Acoustic Design with Regard to Human Perception

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ACOUSTIC DESIGN WITH REGARD TO HUMAN PERCEPTION

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DOCTORAL THESIS

ACOUSTIC DESIGN WITH REGARD TO HUMAN PERCEPTION

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Preface

This thesis is the final part of the doctoral programme in Engineering Acoustics, Faculty of Engineering LTH at Lund University. The work presented in this thesis was started in spring 2018 and completed in May 2022. The work was performed under the supervision of Delphine Bard Hagberg, Senior Lecturer at Lund University, Erling Nilsson, Adjunct Professor at Lund University and Acoustic Specialist at Saint-Gobain Ecophon AB, and Ola Karlsson R&D and Innovation Director at Saint-Gobain Ecophon AB. Saint-Gobain Ecophon AB funded the project.

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Abstract

Ordinary public rooms, such as classrooms and offices where complex tasks such as learning or following long chains of thought are performed, require a good acoustic environment. The acoustic design in these types of rooms were studied in this PhD, taking both objective and subjective perspectives into account.

Experiments were performed in a classroom mock-up using different configurations of absorbers and diffusers. The effects on the room acoustic parameters reverberation time, T_{20}, speech clarity, C_{50}, and sound strength, G, were measured. Further, the subjective experience of the different configurations was investigated. From listening tests, people's experience of uniformity, using pairwise comparison, as well as preferences of speech, in terms of sound quality, attributes and ratings, were evaluated. From an objective perspective, a calculation model was evaluated with a focus on its sensitivity in quantifying the scattering from objects, an aspect that can greatly affect the acoustic environment.

The results show that an absorbent ceiling is a good acoustic baseline. However, additional treatment was needed in order to achieve a satisfactory sound environment for people. People's preferences of sound was best reflected in C_{50}, with increasing values being more appreciated. In addition to the ceiling, absorbing treatment was most efficient at increasing C_{50}. However, diffusers were important for the uniformity throughout the room. It should be noted that diffusers also contribute to higher C_{50} values.

This research shows how different solutions alter different room acoustic parameters and thus the experience for people in these ordinary public rooms. The choice of solution depends on the requirement, i.e., the activity. The effects that the different solutions have can be calculated using the model investigated, which was shown to give estimations of the acoustics that related well to the acoustic measurements and was sensitive to the scattering of objects.

Popular Summary

In schools and offices complex tasks are performed that involve processing new information or performing long chains of thought. To be able to perform these tasks, appropriate acoustic surroundings are critical as they affect our ability to concentrate and to hear properly without extra effort as well as involving aspects of wellbeing.

In this research programme the acoustics in environments such as schools and offices were studied using different solutions that included sound absorbers and diffusers. Both types of treatment affect room acoustics; absorbent material will reduce the sound energy, while the sound energy can be conserved in a room when diffusers are used. Diffusers can further be used to point sound in certain directions.

The investigation included an evaluation of objectively measured room acoustic parameters as well as subjective aspects, in terms of listening tests. Further, the relation between objective and subjective measures was studied.

Installation of an absorbent ceiling in the rooms was a good first acoustic step that significantly improved all room acoustic parameters measured. However, people's responses in listening tests showed that additional acoustic treatment was needed in order to achieve a satisfactory sound environment. To achieve a better acoustic experience for people it was found that an increase in the room acoustic parameter speech clarity, C_{50}, was needed.

To improve the values in C_{50}, either absorbers or diffusers could be used in addition to the ceiling. Absorbers were more efficient at increasing C_{50}, calculated per square metre of material used. Thus, another aspect of the subjective experience is uniformity of sound, meaning everyone should have the same possibility to hear properly, irrespective of their position in the room. This was best achieved when diffusers were used, in combination with the ceiling. The use of diffusers as a complement to the ceiling is thus a good solution in rooms for speech activities, such as classrooms or conference rooms. If the only requirement is to lower the sound level, a solution involving only absorbers is recommended.

It is important for architects and other practitioners to have the possibility to estimate the acoustics in advance in order to create the acoustics required. For that reason, this research has included the investigation of a calculation model adapted for rooms with absorbent ceiling and of the sound field occurring in these rooms. It was found that the model produced results that corresponded well to the measured values. Furthermore, the results could be used to quantify the effect of how diffusers, or other objects, distribute or scatter sound. Scattering can cause significant changes in room acoustics and is therefore important to consider in calculation models. The fact that it is a calculation model means that relatively fast estimations can be made.

Altogether, the results show how different solutions can be used to adjust different acoustic parameters, thus improving people's acoustic experience. It is important to understand the relation between objective and subjective measures in order to make the correct acoustic demands, and solutions. One such finding from this study is the good relation between the parameter C_{50} and people's acoustic experience. This parameter was shown to best relate to people's experience of the sound quality and is therefore recommended for consideration in the acoustic design of ordinary public rooms. Another aspect is that diffusers are an appropriate treatment for improving uniformity in these rooms. Such knowledge, together with models that estimate the acoustic properties in advance, accurately and time-efficiently, such as the one investigated in this study, increases the ability to create satisfactory acoustics in rooms where complex tasks are performed. That in turn results in the possibility to achieve good performance and a high level of wellbeing.

Populärvetenskaplig sammanfattning

I miljöer som klassrum och arbetsrum utför människor komplexa uppgifter så som att ta in ny kunskap, bearbetar information och utför långa tankekedjor. Akustiken har stor betydelse för utförandet av sådana uppgifter, bland annat genom att påverka möjligheten till koncentration men också hur väl vi hör informationen när den talas. I ett vidare perspektiv påverkar akustiken vårt välbefinnande i stor utsträckning.

I det här forskningsprogrammet har akustiken för miljöer i skolor och kontor studerats. Olika akustiska lösningar har använts och utvärderingen har bestått i hur dessa lösningar påverkat objektiva parametrar men också hur den subjektiva upplevelsen för människor har påverkats av dessa olika lösningar. Vidare analyserade relationen mellan de objektiva och subjektiva resultaten.

De olika lösningarna har inkluderat akustiska absorbenter och diffusorer. Båda typerna av material påverkar akustiken, men på olika sätt. En grundläggande skillnad är att absorbenter minskar ljudenergin i rummet, medan diffusorerna påverkar akustiken utan att minska energin. Diffusorerna kan även användas för att rikta ljudet mot en önskad position i rummet.

Resultaten visade på att ett absorberande undertak är en bra grund för att förbättra flera akustiska parametrar. För att skapa en akustisk miljö som ansågs tillfredställande behövdes ytterligare akustikbehandling på väggarna. Hur tillfredställande människors upplevelse av akustiken var kunde relateras till en av de rumsakustiska parametrarna som utvärderades. Denna parameter var taltydlighet, C_{50}. Med högre värde i C_{50} bedömdes akustiken som mer tillfredställande.

Den akustiska behandlingen på vägg som påverkade C_{50} mest effektivt i form av störst effekt per kvadratmeter material, var ytterligare absorbenter. Även diffusorer påverkade C_{50} signifikant även om effekten inte var lika stor som för absorbenterna. En fördel med diffusorerna var att de också skapade en mer homogen akustik i rummet, vilket innebär mer likvärdig upplevelse till alla. Detta är en viktig aspekt för den typ av rum som studeras, i synnerhet i ett klassrum där alla elever ska erbjudas samma möjlighet att höra tydligt för att ta in information och inhämta ny kunskap. Att addera diffusorer till det absorberande undertaket kan därmed vara lämpligt i rum som används för tal, som klassrum och konferens rum. Vid behov att endast sänka ljudnivån är en lösning med mer absorption att föredra.

Det behövs beräkningsmodeller som är tidseffektiva och välfungerande för de ljudfält som finns i dessa miljöer så att arkitekter och andra aktörer som specificerar akustiska lösningar kan göra uppskattningar av akustiken på förhand. Därför undersöktes användandet av en beräkningsmodell för de akustiska lösningarna som har testats i denna studie. Modellen visade resultat som väl stämde överens med gjorda mätningar. Vidare kunde den användas för att på förhand kvantifiera effekten av hur diffusorerna eller andra objekt, sprider ljud, vilket är viktig indata då denna spridning av ljud signifikant kan påverka akustiken. Det faktum att det är en beräkningsmodell gör att uppskattningar av akustiken kan göras relativt snabbt.

Tillsammans visar resultaten hur olika akustiska lösningar kan användas för att justera olika akustiska parametrar och därmed upplevelsen för människor. Specifikt en parameter är viktig för upplevelsen, C_{50}. Med ökad kunskap om denna relation tillsammans med modeller för att beräkna akustiken på förhand ökar möjligheterna för att skapa bättre akustik i rum där komplexa uppgifter utförs. Det ger i förlängningen möjligheter för goda prestationer med gott välbefinnande.

Nomenclature

DIN	Deutsches Institut für Normung e, V.
ISO	International Organization for Standardization
UNI	Ente Italiano di Normazione
T_{20}	Reverberation time in s, evaluated over dynamical range of 20 dB
C_{50}	Early-to late Index in dB, evaluated for 50 ms, expressed as speech clarity
G	Sound strength, in dB
SNR	Signal-to-Noise ratio, in dB
α	Absorption coefficient
α_p	Practical absorption coefficient
α_w	Weighted absorption coefficient
$p(t)$	Impulse response
JND	Just Noticeable Difference
A	Equivalent absorption area in m^2
A_{sc}	Equivalent scattering absorption area, in m^2
r	Pearson correlation coefficient

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PART IV – APPENDED PAPERS

Paper A

The Effect on Room Acoustical Parameters Using a Combination of Absorbers and Diffusers—An Experimental Study in a Classroom.

Emma Arvidsson, Erling Nilsson, Delphine Bard Hagberg, Ola J.I. Karlsson, Acoustics 2020, 2, 505–523.

Paper B

The Difference in Subjective Experience Related to Acoustic Treatments in an Ordinary Public Room: A Case Study.

Emma Arvidsson, Erling Nilsson, Delphine Bard Hagberg, Ola J.I. Karlsson, Acoustics 2021, 3, 442–461.

Paper C

An Energy Model for the Calculation of Room Acoustic Parameters in Rectangular Rooms with Absorbent Ceilings.

Erling Nilsson, Emma Arvidsson, Applied Sciences. 2021, 11, 6607.

Paper D

Subjective Experience of Speech Depending on the Acoustic Treatment in an Ordinary Room.

Emma Arvidsson, Erling Nilsson, Delphine Bard Hagberg, Ola J.I. Karlsson, International Journal Environmental Research and Public Health 2021, 18, 12274.

Paper E

Quantification of the Absorption and Scattering Effects of Diffusers in a Room with Absorbent Ceiling.

Emma Arvidsson, Erling Nilsson, Delphine Bard Hagberg, Ola J.I. Karlsson, Buildings 2021, 11, 612.

Part I
Framework

1 Introduction

The aim and objective of the project is presented in this introductory chapter. There is a summary of the background studies, followed by the motivation and outline of the project. The limitations are also presented.

1.1 Aim and Objective

Ordinary public rooms such as classrooms and offices are environments where large groups of people spend a lot of time. Cognitive tasks are performed there, new information is processed and chains of thoughts are followed.

Acoustics is one of the environmental aspects that must be considered in the design of these rooms to ensure that people can perform complex tasks while maintaining a high level of wellbeing.

The aim of this research has been to improve room acoustics for people in ordinary public rooms, such as classrooms and offices. In these environments people should be able to concentrate, process information and perform cognitive tasks. Thus, these environments should not only provide the possibility for concentration but also allow dialogue between people.

To realize the aim, to improve room acoustics for people, the objective of the research has been to increase knowledge regarding room acoustic design in ordinary public rooms. To achieve sustainable solutions, it was deemed that such knowledge must include both objective and subjective aspects of the room acoustic design.

In this research the objective aspects concern different types of treatment and how these affect different room acoustic parameters. The subjective perspective relates to how people experience the room acoustics depending on the treatment used. Within the scope of the objective, tools for estimating acoustic properties have also been considered.

1.2 Background

The activities in the research programme were based on the outcomes of previous studies, which are summarized below.

1.2.1 Room Acoustics and the Performance of Tasks

It is known that noise causes stress and disturbs concentration. It is also widely accepted that environmental noise has negative effects on learning and the performance of cognitive tasks [1, 2]. From a study of the indoor environment in 51 secondary schools in Italy it was found that the students rated visual and acoustic quality as the most important factors influencing their performance. The main effect of poor acoustic quality was a decreased ability to concentrate, with intermittent noise being more disturbing than continuous noise [3]. From a study by Shield et al. [4] of 13 secondary schools in England that included 185 spaces, it was apparent how acoustics can cause disruption of lessons and affect students' behaviour. The authors emphasize the importance of including acoustics in the design phase of schools.

Studies on the relation between acoustics and cognitive tasks show that test results can be affected by the room acoustic properties. However, not only the results are affected; it is also apparent that a longer response time and increased effort is required to perform a task in a unsatisfactory sound environment [5-10]. Visentin et al. investigated speech intelligibility in terms of correctly recognized words showing no relation to the different room configurations investigated, but with a relation to response time and subjective judgement [11]. This further strengthens the observation that scores may be correct but greater effort may be needed in order to process information. Another cognitive task is reading. Reading speed has been found to be related to acoustic properties, with significant correlation to the ratio of early reflections but not to reverberation time [12]. Sato et al. showed a strong correlation between early reflections and listening difficulty ratings [13-15]. It has also been found that the effect of acoustics on speech is age-dependent, with children being more sensitive than adults. It is indicated that ability at the age of 14 is comparable to the ability of an adult [16, 17]. Non-native speaking or disorders affecting concentration imply even higher demands on the acoustic environment [5, 7, 16-18]. Furthermore, a relation between children's perception of wellbeing and acoustic quality can be seen [19].

Lochner and Burger studied the effect of reflections as early as 1964 [20]. Early reflections contribute to direct sound and Lochner and Burger stress the importance of considering early reflections during room acoustic design. Studies by Bradley et al. show how noise affects speech intelligibility but also how an increase in early reflections can compensate for a low Signal-to-Noise Ratio (SNR) and enhance a speaker's voice [21-24]. Bradley et al. recommend, in rooms for speech, focusing on increasing the early reflections rather than on low reverberation time [25]. The importance of early reflections was further emphasized in a study by Yang and Bradley that showed improved speech intelligibility with an increase in early reflections [26]. An effect of the SNR was also seen on intelligibility; however, associating intelligibility with reverberation time showed lower values. It is appropriate to bear in mind in this discussion that, as has already been mentioned above, reading speed could be related to the ratio of early reflections [12]. It has been indicated that a difference in speech clarity, C_{50}, of 3 dB is needed for a sustainable improvement in speech intelligibility in classrooms [27]. In ISO 3382-1 [28], which concerns performance spaces, the just noticeable difference, JND, is 1 dB. However, a review by Bradley shows how the JND differs depending on frequency as well as type of music [29].

The acoustic parameter sound strength, G, provides information about how the reflections in a room contribute to the sound level. This is a parameter typically used for the acoustic design of performance spaces [30-32]. Room acoustics and noise levels can affect the way speakers adapt their voice effort [33, 34]. It was found by Åhlander et al. [35], which studied the voice comfort of teachers in Sweden, that this group report voice problems to a greater extent than the rest of the population. Such problems not only cause sick leave but also the risk of having to take early retirement from work. Methods for describing voice support have been developed [36-38].

Even if several parameters exist to describe the acoustic properties in rooms, reverberation time is still a common descriptor for specifying the demands regarding acoustic quality [39]. However, it is known that two rooms with the same reverberation time are not necessarily perceived in the same way [40, 41]. In a study of two small rooms it was seen how the reverberation time was similar while other parameters differed, indicating the need to measure several acoustic parameters [42]. Other parameters have recently been introduced in some standards for ordinary rooms such as in the Italian standard UNI 11532-2 for education [43, 44] and in a recently published standard for open spaces ISO 22955 [45]. It should also be mentioned how the need for both diffusion and absorption is observed in the German standard DIN 18041 [46].

1.2.2 Effects of Room Acoustic Treatments

The application of absorbing material is a common treatment in ordinary rooms. The effect on acoustic parameters depending on the placement of the material has been studied [47, 48] as well as the angle dependency [49]. Nolan et al. have worked on measurement methods in situ, taking angle dependency into account [50, 51].

Diffusing elements can be used for voice support and to improve the uniformity of sound in a room but also to direct sound to an absorbent surface [52]. The effects on objective parameters and perception depending on the placement and distance to a diffuse element have been studied for concert halls [53-55]. Choi has investigated the effect, in a 1/10 scale, of combining these two types of treatments in different configurations, adjusting different parameters depending on the placement of treatment [56-58]. Labia investigated different quantities and placement of absorbers and diffusers for a meeting room using simulations [59]. Sanavi investigated the effect of absorbers and diffusers in meeting rooms including a listening test, with a suggestion, however, to look deeper into this aspect [60]. In [61] it was shown that a diffuse reflection improved speech intelligibility with the listener perceiving the source to be closer compared to a specular reflection. In this study too, the author comments on the need for further studies on the effects of diffusers.

1.2.3 Estimation of Acoustic Properties in Ordinary Rooms

An important aspect in acoustic design is knowledge of acoustics and usability of the tools for estimating acoustic properties. From a review on acoustic performance-based design by Badino et al. [62] one of the conclusions was a need to improve practitioners' acoustic knowledge and programming skills in order to apply acoustic performance-based design. Another important aspect highlighted in the study was the need for integration and interoperability between different tools. To include the scattering and diffusion from difference surfaces is difficult in simulations. Two different models were investigated in [63], considering objective descriptors as well as subjective aspects and showing how one model better corresponded to perception in listening tests. Marbjerg et al. [64, 65] showed difficulties in the use of simulation models, as simulated results for energy-based models deviated from measured values. Better results could be obtained with a phased geometrical model; however, this model has the drawback in that it is time-consuming.

Using the Sabine formula to calculate the acoustic properties of a room presumes a diffuse sound field. However, the sound field in ordinary rooms is typically non-diffuse. In fact, even in reverberation chambers it is difficult to obtain a diffuse sound field [66]. It is important to consider the effect of scattering objects in ordinary rooms. With the assumption of a diffuse sound field, predicted reverberation times are often shorter than those measured [67, 68]. The decay processes in ordinary rooms with absorbent ceiling has been studied in [69, 70]. From this has a statistical energy analysis, SEA, model been developed, SEA models are typically used as prediction tools on a system level [71].

1.3 Motivation

It is well accepted that noise has negative effects on health and wellbeing. Noise can also disturb concentration, with disruptive noise having a more severe effect than continuous noise. This implies a need for control of sound levels.

In ordinary rooms the transfer of information is critical; the speech should clearly reach the listeners. Further, it is critical that speech reaches everyone in the audience. The acoustic treatment must balance the reduction of noise but still ensure good speaking and listening conditions.

Studies presented in previous sections show the importance of early reflections in relation to listening effort, reading speed and speaking conditions. Early reflections should thus be considered in the choice of acoustic treatment in order to ensure appropriate acoustic conditions for everyone in the room.

Absorbent treatment is often chosen for ordinary public rooms. However, in performance spaces such as theatres and concert halls, acoustic treatments that reflect sound, such as diffusers, are normally used. This treatment is used as voice support for the artist on stage and to direct the sound to everyone in the audience. Everyone listening should have an equally favourable sound experience. Diffuser treatment also provides voice support for the artist on stage. The two arguments, voice support and proper listening conditions for everyone, are also applied for ordinary rooms, even if the roles are defined differently. In that case, the teacher is the person who needs voice support and the audience are the students requiring comfortable listening conditions. In a working environment the same situation could apply, such as when an employee presents information to colleagues or customers.

To increase the range of materials used in these types of rooms, the inclusion of diffusers could thus be useful for improving the acoustic environment. Research on how diffusers can be applied in the acoustic design of ordinary rooms was seen to be limited and was therefore of interest for studying in this research. Different acoustic treatments can affect different room acoustic parameters and, in turn, people's subjective experience. It is critical to understand this relation if the acoustical design of ordinary rooms is to be sustainable.

With increased knowledge of how different treatments can be used and how they can affect people, the acoustic environment in ordinary rooms can be improved. However, architects and other practitioners must be able to estimate in advance how different treatments will affect room acoustic properties. The different objects in ordinary rooms, such as furniture and other interiors, cause scattering, which affects room acoustic properties significantly. It is therefore essential to consider the effect of these objects during the acoustic design and in the choice of acoustic treatment. Furthermore, the inhomogeneous sound field in these rooms also affects the acoustic properties and must be accounted for. Studies previously reported on show that simulation models often become complex when all of these aspects are considered. It has also been shown how the modelling, in addition to the acoustic parameters, also affects perception. Work on developing these models has contributed to more accurate models, although often with time demands being a drawback. Time is a critical aspect in the acoustic design of ordinary public rooms. However, an estimation of room acoustic properties in ordinary rooms is important in order to make the correct choice of acoustic treatment.

1.4 Project Outline

Based on the challenges identified, the research programme was structured into four studies;

a) Treatments and Parameters

b) Subjective Differences

c) Subjective Preferences

d) Estimation of Acoustic Properties

The outline of the work with the different studies is depicted in Figure 1. To the left in the figure, the objective studies are presented and, to the right, the subjective studies. The main activity of each study is presented in the green boxes. The studies resulted in the papers A-E, see the blue boxes.

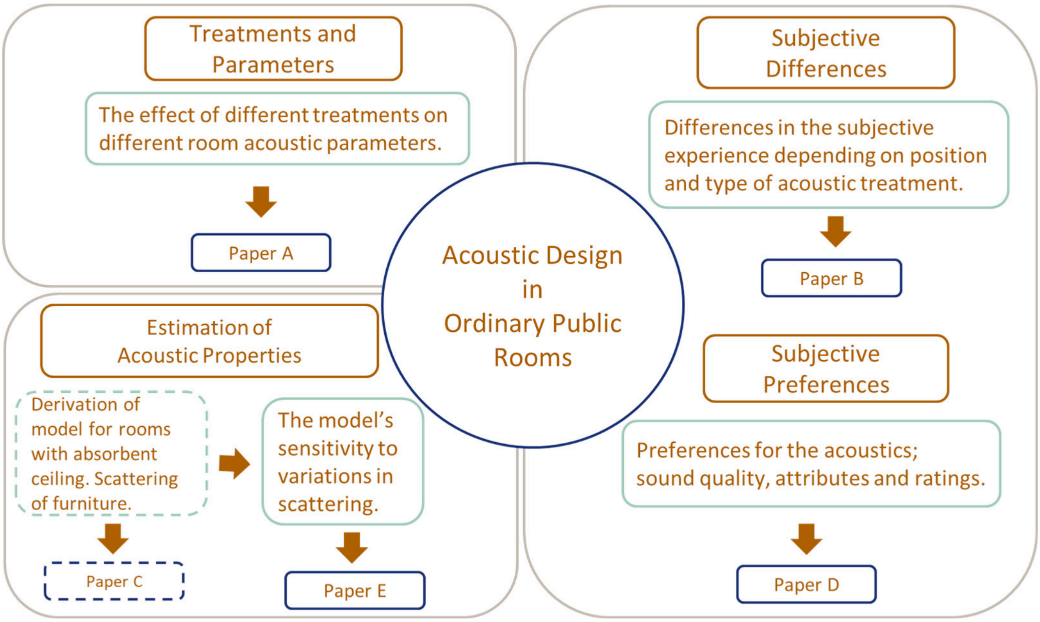

Figure 1 Outline of the thesis based on four different studies, marked in brown and all connected to the central question of the research: the acoustic design in ordinary rooms. In the green boxes the objective of each study is described. The dashed line indicates a sub-study to this research project, the author of this thesis is not the main contributor.

The starting point for *a) Treatments and Parameters* was the choice of room acoustic parameters. The parameters used should include different aspects of the acoustics and together contribute to an understanding of the entire acoustic environment of the room. It was important to study different types of acoustic treatments, i.e., absorbers and diffusers, and how these affect different room acoustic parameters depending on the set-up.

Identifying and understanding how the different treatments affect the subjective experience is necessary. In the study *b) Subjective Differences*, it was investigated whether people could perceive differences between different treatments. It was important to study differences between configurations that used varied treatments as well as differences within one configuration, i.e., whether people experienced one configuration more or less uniformly.

Not only differences are of importance; preferences regarding the sound environment also need to be considered. In *c) Subjective Preferences,* people's preferences were investigated as regards environments where they have to listen to information. It was further investigated whether people's preferences could be related to a room acoustic parameter and the type of acoustic treatment.

Knowledge of how different treatments affect room acoustics and people should be used in acoustic design in order to improve people's sound environment. To apply such knowledge, architects and other practitioners who specify acoustic treatment must have convenient tools for estimating acoustic properties in advance. This means tools suitable for the particular type of room in question. Tools must be time-efficient, i.e., give realistic estimations without being time-consuming. For this reason, application of a calculation model was investigated in the study *d) Estimation of Acoustic Properties.* A statistical energy analysis, SEA, model was used, developed for rooms with absorbent ceilings. Development of the model was not part of the research presented in this thesis but was to investigate its sensitivity to scattering objects. In the first part, scattering from furniture was investigated and the second part involved scattering from diffusing elements, with the latter part being the main part of the study.

The studies have resulted in five papers. Summary of those papers can be found in the Part II, Research, and the whole papers can be found in the Part IV, Appended Papers.

1.5 Limitations

The study is limited to ordinary public rooms. Examples of ordinary public rooms are classrooms and offices. Open areas are not studied. Regarding the subjective studies, the listener's perspective is investigated.

2 Acoustic Terms and Definitions

Acoustics, the science of sound, includes a wide range of concepts. In the following chapter the acoustic terms and definitions, used in this research are presented.

2.1 Room Acoustics

In room acoustics is the sound within an enclosed room considered. The activity and layout between rooms can differ widely, which implies a need for grouping rooms into different types. Commonly used are the three types; performance spaces, ordinary rooms and open plan, visualised in illustrations below.

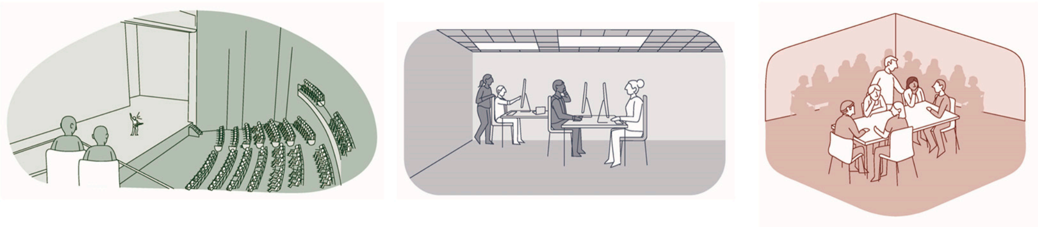

Figure 2 Illustrations of different room types, performance space, open plan, and ordinary room.

The standard ISO 3382-1/2/3 [28, 72, 73], dealing with measurements of room acoustic parameters, is divided into these three room types. Performance spaces are room such as theatres and concert halls, rooms were the sound typically is emitted from a specified area, usually without any dialog between people. The audience has high demands on the acoustics and should be fulfilled independent of position. In the acoustic design of these rooms are often several different parameters considered.

Ordinary rooms, such as classrooms, must provide an acoustic environment supporting both dialog, and concentration. As for performance spaces, it is critical that the acoustic demands are satisfactory in all positions, all students in a classroom must have good possibilities to hear properly.

With different room acoustic parameters can different aspects of the acoustics be considered. Thus, in the standard ISO 3382-2 [72], for ordinary rooms, is only one parameter considered, the reverberation time. However, there are national standards were also other parameters are considered for these rooms, for example in the Italian standard UNI-2 [44] for educational spaces.

As regards open plan must people have the possibility to concentrate and perform cognitive tasks, while at the same time inspire people to interact. The open areas for interacting can also be challenging in creating environments for concentration.

In this work has ordinary rooms been considered. The study is focusing on rooms where people work or study. To avoid that this is mixed with residential premises was “public” added to the description of room type evaluated in this project, i.e., ordinary public rooms.

2.2 Reflections

The acoustics in an ordinary room will be affected by how the sound is reflected in the room. Different terms are used to describe different reflection pattern and behaviours.

If a sound wave hit an ideally flat surface, it will be specular reflected, the angle of reflection is the same as the angle of incidence. If the surface is uneven the sound wave will change direction, this is called scattering. Per definition, scattering is the non-specular reflections that occur when a sound wave hits a surface [74]. For scattering to occur, the wavelength of the sound waves is comparable to or shorter than the object hit [71]. Examples of specular reflections and scattering is seen in Figure 3.

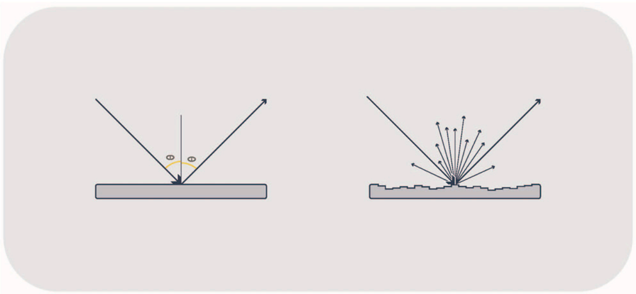

Figure 3 Left illustration; Specular reflected sound wave. Right illutration; Incident sound wave is reflected in different directions, scattering.

In ordinary rooms, scattering is caused by furniture and other objects. Furniture used in ordinary public rooms typically contributes to scattering in mid-frequencies and can significantly affect the room acoustic properties, which also is shown in this research in following chapter.

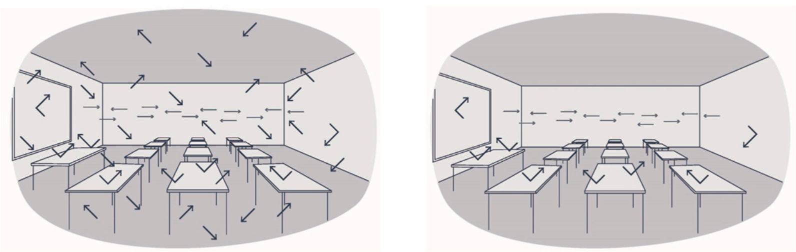

Figure 4 Furniture contributing with scattering. The left illustrating steady state while right illustartion shows a decay.

Introducing objects, such as furniture, in rooms often creates a more diffuse sound field. Per definition is a sound field diffuse when the energy is the same at each point in the room; the sound field is isotropic [74]. A completely diffuse sound field cannot be achieved in practice [66]. For the measurement of sound absorption in a reverberation room, the target is to have a diffuse sound field. This is dealt with by using different types of reflectors.

The scattering from an object can be quantified with the scattering coefficient, defined in ISO 17497-1 [75]. The scattering coefficient is the ratio of sound energy that is reflected in a non-specular manner in relation to the total amount of reflected energy [71].

Another descriptor for the reflection pattern from an object is the diffusion coefficient which describes how evenly distributed an incident sound wave is dispersed when hitting a surface. In ISO 17497-2 [76], methods for measurement of diffusion coefficients are described. The distribution of reflections is measured by positioning microphones in a hemispherical shape around the object. The measurement is conducted in an anechoic chamber, either with one source giving the directional diffusion coefficient or with several source directions giving the random incidence diffusion coefficient. Further, the two coefficients can be normalized to a flat surface, giving the normalized directional diffusion coefficient and normalized random incidence diffusion coefficient [76].

2.3 Room Acoustic Parameters

There are a number of different room acoustic measurements that can be used to objectively describe the acoustics in a room. For the work presented in this thesis it has been important to consider how the room contributes to early and late reflections as well as to the sound energy in the room. Three parameters relating to these aspects have been measured and are presented in the following sections.

2.3.1 Reverberation Time, T_{20}

Reverberation time, T, is the time in seconds it takes for the sound pressure level to decrease 60 dB after the sound source has been turned off [77], meaning that the reverberation time describes how fast the sound energy decreases in a room, after turning off the source. The measurement of reverberation time is described in ISO 3382-2.

The reverberation time can be evaluated during a shorter range than 60 dB. T is in that case extrapolated to correspond to a decay of 60 dB. The shorter range used is denoted with the index of the used range. For example, a range of 20 dB is denoted T_{20} [72].

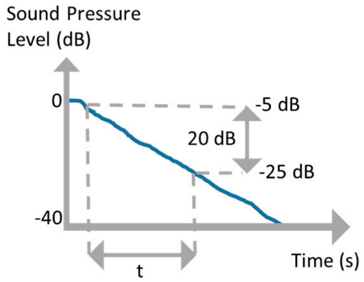

Figure 5 Reverberation time is the time it takes for the sound to decrease 60 dB, can also be measured over a shorter interval, for example 20 dB, in that case denoted T_{20}, 3t=T_{20}. Evalution starting after 5 dB decrease.

2.3.2 Speech Clarity, C_{50}

The sound reaching our ears can either come direct from the source or after being reflected in a surface. The reflections are divided into early and late reflections. The early reflections can be perceived as strengthen the direct sound, also described as useful. In Figure 6 direct sound, early and late reflections are illustrated.

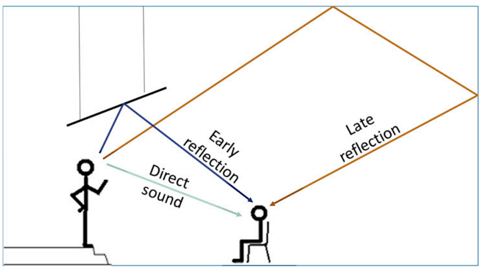

Figure 6 Illustartion of direct sound, early and late reflections.

The ratio between early and late arriving energy can be described by using the early-to-late index, C_{t_e} [71]. C_{t_e} is the logarithmic ratio between the energy arriving within t_e divided by the energy arriving after t_e. C_{t_e} is expressed in dB, defined in ISO 3382-1 and given by [28]

$$C_{t_e} = 10lg\frac{\int_0^{t_e} p^2(t)dt}{\int_{t_e}^{\infty} p^2(t)dt} \qquad (1)$$

where
$p(t)$ is the instantaneous sound pressure of the impulse response measured at the measurement point
t_e is the early time limit, for speech is $t_e = 50$ ms, for music is $t_e = 80$ ms

As this research focuses ordinary public rooms, speech, rather than music, is of importance and, consequently, t_e=50 ms has been used. C_{50} is often expressed as speech clarity. This expression will be used in the thesis.

2.3.3 Sound Strength, *G*

Sound strength, G, is a measure that is related to how the reflections contribute to the sound level in the room.

Sound strength is defined by the logarithmic ratio in sound pressure between the room investigated and a free field, i.e., an environment where sound is not reflected in any surfaces. Sound strength is included in ISO 3382-1 and given by [28]

$$G = 10lg\frac{\int_0^\infty p^2(t)dt}{\int_0^\infty p_{10m}^2(t)dt} \qquad (2)$$

where
$p(t)$ is the instantaneous sound pressure of the impulse response measured at the measurement point;
$p_{10}(t)$ is the instantaneous sound pressure of the impulse response measured at a distance of 10 m in a free field

2.4 Sound Absorbers

Sound absorbers are used to adjust room acoustic properties by reducing energy. There are different types of sound absorbers. In order to group them two broad classes can be used: porous absorbers and resonant absorbers. These two groups are described below, followed by a description of how the absorption properties are usually evaluated.

2.4.1 Porous Absorbers

In a porous absorber the sound energy is reduced when it propagates between the interconnected pores in the media, i.e., there must be an open pore structure. Viscous and thermal effects will cause dissipation of the sound energy; however, the viscous effects are the greatest. The sound propagation in the pores causes movements in the viscous fluid air appearing in the pores. When the air moves it enters the walls of the pores, friction occurs and the energy is dissipated [74].

Examples of porous absorbers are foam, textiles, granules and mineral wool such as stone wool or glass wool. The typical acoustic treatment in ordinary public rooms is the application of mineral wool tiles. The absorption properties of porous absorbers are typically better in high rather than low frequencies [74].

2.4.2 Resonant Absorbers

Resonant absorbers are typically used for low frequency absorption. The resonance absorbers contain a mass and a spring. By adjusting either of these two properties, the absorber can be tuned to operate in a specific frequency range. Absorption is attained at the system's resonance frequency. Normally the resonance absorber operates over a narrow range of frequencies [71, 74].

2.4.3 Reverberation Room Method for Absorption Coefficient

A common way to describe the absorption properties of a material is to use the absorption coefficient measured in a reverberant room. The absorption coefficient α is the ratio between the equivalent absorption area of a sample and the total area that the sample covers [74]. The equivalent absorption area is given by

$$A = \frac{55{,}3V}{cT} - 4Vm \tag{3}$$

where

V is the room volume

c is the propagation speed of sound

T is the reverberation time

m is the power attenuation coefficient

This method is defined in ISO 354 [77]. The reverberation time is measured for the empty room and for the room with the sample tested. The difference in A for the two measurements is the equivalent absorption area for the sample, called A_T. The absorption coefficient of the sample α_s is calculated by

$$\alpha_s = \frac{A_T}{S} \tag{4}$$

where

A_T is the equivalent sound absorption area of the test sample

S is the area of the test sample

2.4.4 Air Flow Resistivity

The amount of energy that is reduced in the porous absorber will depend on how easily the sound wave can enter the material and how difficult it is for the sound to continue to propagate within the material. One way to measure this is with airflow resistivity. The method is defined in the standard ISO 9053-1/2 [78, 79]. In this method, air is sent through a sample and the pressure before and after the sample is measured. The flow resistivity σ expressed in $\frac{\mathrm{Pas}}{\mathrm{m}^2}$ or as MKS units $\mathrm{Nm}^{-4}\mathrm{s}$ is given by [74]

$$\sigma = \frac{\Delta P}{Ud} \qquad (5)$$

where

ΔP is the pressure drop

d is the thickness of the material

U is the mean steady flow velocity

The air flow resistivity of porous materials is used in the calculation model evaluated in this thesis.

2.5 Diffusers

Diffusers can be used to adjust the acoustics in a room, though not by absorbing the sound energy but by dispersing the sound waves. With this type of treatment the energy is conserved. Diffusers are commonly used in performance spaces, for example to treat echoes, support the performance on stage and to promote spaciousness [74].

The term diffuser is not clearly defined. Cox and d'Antonio describe a diffuser in "Acoustic Absorbers and Diffusers" as an element that causes a large amount of sound waves entering the surface to be temporally or spatially dispersed [74]. Elements used to make a sound field more diffuse are also often called diffusers; however, it cannot always be guaranteed that they contribute with both temporal and spatial dispersion of sound waves. In order to describe the uniformity of the diffuser, the diffusion coefficient has been introduced, described earlier in this chapter.

Part II
Research

3 Research Studies

The following chapter presents the studies made in this research programme. In the first section is the general experiment set-up presented, valid for all the studies. Thereafter is each study presented with method and principal results. For detailed results, see respective paper in Part IV of this thesis, Appended Papers.

3.1 Experimental Set-Up

The different studies are based on experiments, all carried out in the same mock-up of a room, located in a laboratory environment. The area of the test room was approximately 52 m^2. Height from floor to soffit was 3.50 m. Ceiling was installed at a height of 2.70 m from the floor. A sketch of the room with dimensions is presented in Figure 7.

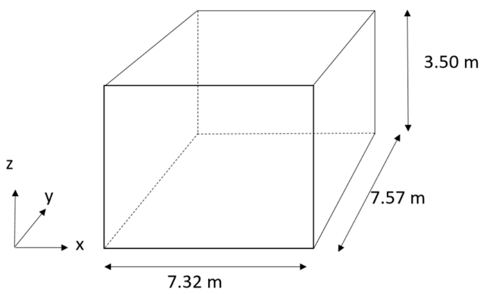

Figure 7 Sketch of mock-up room.

Since different objects in a room contributes with scattering, which effect the acoustic properties, has furniture been used. In the experiments including furniture were 11 tables and 18 slightly upholstered chairs used, see Figure 8.

Figure 8 Mock-up room with furniture and absorbent ceiling.

3.1.1 Acoustic Materials

Acoustic materials used were porous absorbers and diffusers, installed in different set-ups.

The porous absorber had a thickness of 40 mm and an air flow resistivity of 40 kPa*s/m^2 measured in accordance with ISO 9053-2 [79]. The weighteabsorption coefficient, measured in an accredited lab according to ISO 354 [77] and evaluated according to ISO 11654 [80] was $\alpha_w = 1$, with most absorption in the higher frequency range. The product was used in the suspended ceiling as well as the walls. Regarding the latter, the absorbers were mounted directly on the walls. The practical absorption coefficient for the standardized overall depth of system 200 mm as well as for ODS of 50 mm from measurement in accredited lab can be seen in Figure 9.

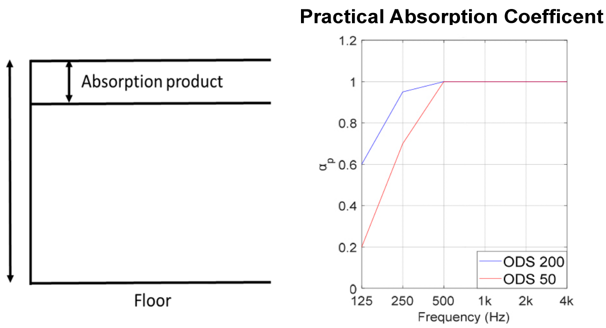

Figure 9 Sketch of overall depth of system (ODS) set-up. Practical absorption coefficient of the porous absorber for ODS 200 mm, which is the standardized ODS and 50 mm, corresponding to direct mounting on the wall.

The diffusers were prototypes made of wood in a semi-circular shape. This prototype was used to create a more diffuse sound field and also to direct the sound in a certain direction. Depending on the orientation of the diffuser, the main direction of reflections will be either vertical or horizontal. The direction in which a diffuser directs most of the sound waves gives rise to its designation in this thesis: vertically oriented diffuser or horizontally oriented diffuser depending on direction. The orientations are depicted in Figure 10.

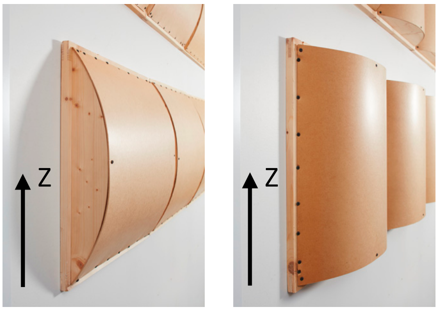

Figure 10 Diffusers used in the studies. Left picture: vertically oriented diffuser, directing majority of sound waves vertically. Right picture: Horizontally oriented diffuser, directing majority of sound waves horizontally.

Diffusion characteristics for the diffusers were measured in a semi-anechoic room. Energy in the reflections were measured for every 10 degrees, from 0 to 90 degrees. The diffuser characteristics for 500 Hz, 2000 Hz and 4000 Hz are presented in Figure 11.

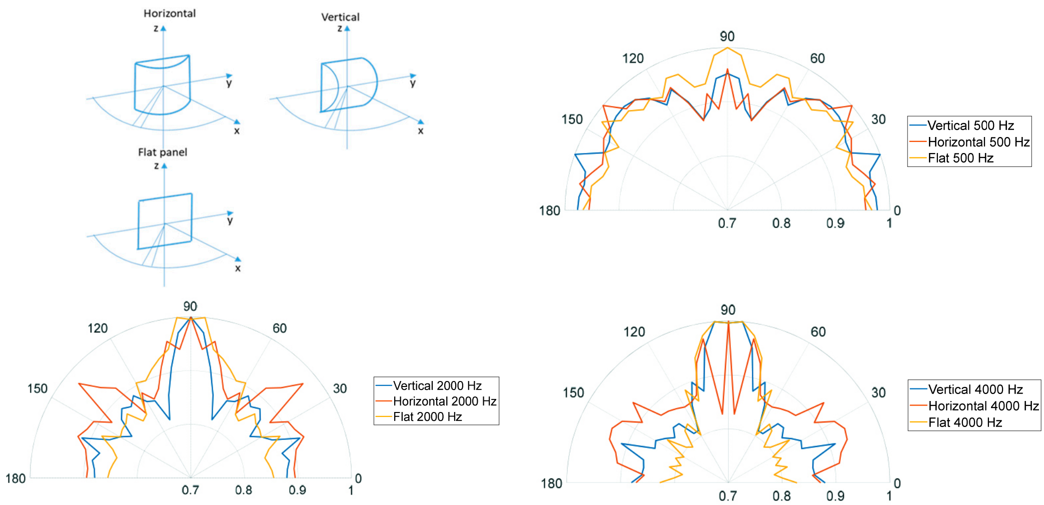

Figure 11 Diffusion characteristics for the diffusers. The two different orientations, horizontal and vertical, as well as comparison to a flat panel. Upper left: diffusers with coordinate system. Upper right: 500 Hz. Lower left: 2000 Hz. Lower right: 4000 Hz.

The prototype has resonance absorption properties in the low frequencies, these properties are independent of the orientation of the diffuser.

3.1.2 Room Acoustic Measurements

A package of room acoustic parameters characterizing different aspects of the acoustics was chosen;

- Reverberation time, T_{20}
    - Evaluated for 20 dB of the dynamical interval typically used for in-field measurements in order to avoid the effect of background noise.
- Speech clarity, C_{50}
    - *Early-to-late index,* C_{t_e}, *with* t_e=50 ms used for speech.
- Sound strength, G

Measurements were performed using a DIRAC system (DIRAC type 7841, Ver.6.0). An exponential sweep signal was used as excitation for the measurement of T_{20} and C_{50}. An omnidirectional loudspeaker with dodecahedron geometry, as in Figure 12, was used. The centre of the loudspeaker was 1.55 m from the floor. G was measured using a constant sound power source placed on the floor. An omnidirectional microphone was used as a receiver at 1.20 m from the floor. All receivers were placed a minimum of 1 m from hard surfaces.

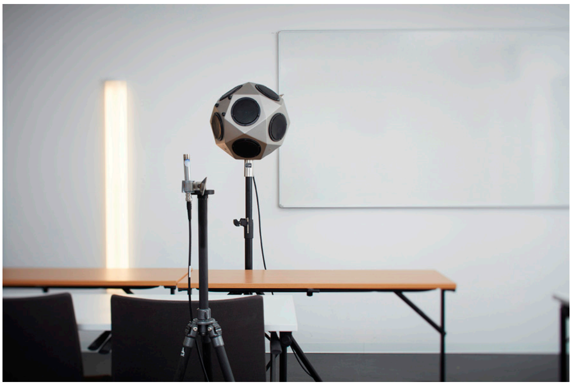

Figure 12 Loudspeaker with dodecahedron geometry and omnidirectional microphone in the mock-up room.

An evaluation of repeatability of the room acoustic measurements was performed. For two source positions and six receiver positions the repeatability for a 95% confidence interval was lower than the just noticeable difference, JND, defined in ISO 3382 [28]. This set-up was therefore used for the objective studies, i.e., two source positions and six receiver positions, giving twelve measurements in total for each configuration. Sources were placed in the area corresponding to that where a teacher is typically positioned. The positions of sources and receivers are depicted in Figure 13.

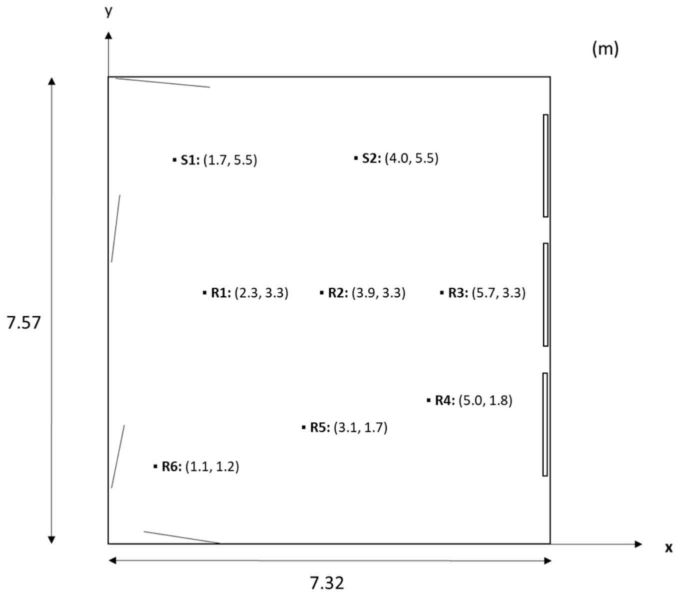

Figure 13 Two sources and six receivers were shown to give repeatability lower than JND. The positions in this figure were used in the objective studies. In the subjective studies were the positions slightly adjusted, and one more receiver was used to suit those studies.

3.2 Study: Treatments and Parameters

In the first study of this research programme the aim was to investigate how different acoustic treatments affect different room acoustic parameters.

3.2.1 Configurations

It was of interest, firstly, to obtain information regarding how an absorbent ceiling and furniture affect room acoustic parameters. It was then investigated how additional wall treatment affects the acoustics, with additional absorption and two versions of diffusing treatment on the walls. In all cases with wall treatment, the same wall area was covered. It was also investigated how diffusers placed above the source affect the acoustics, with twelve absorptive tiles being replaced with diffusers. Table 1 shows all configurations investigated. The configurations are depicted in Figure 14.

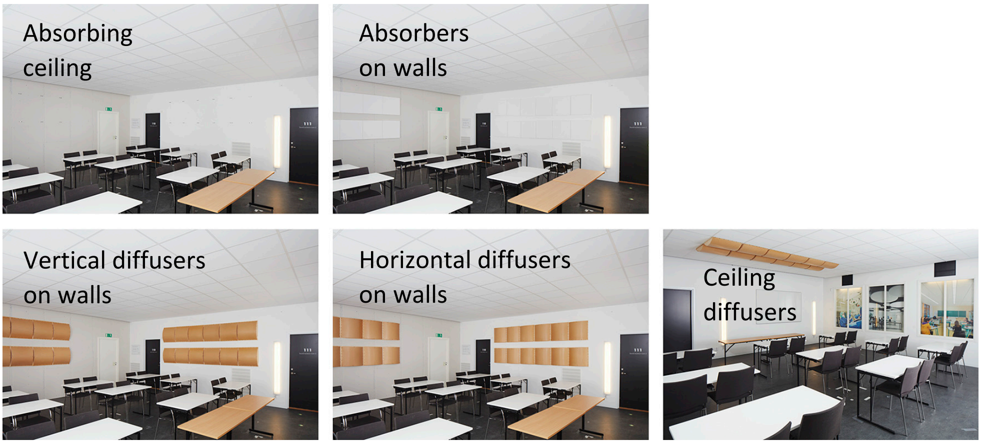

Figure 14 Configurations with absorbent ceiling and furniture. Upper right figure with absorbent wall treatment. Lower figures with diffusers; left figure with vertically oriented diffusers, middle figure with horizontally oriented diffusers, right figure with ceiling diffusers.

Table 1 Description of test configurations in study of treatments and parameters.

Configuration	Ceiling	Walls	Furniture
1	No	No	No
2	52 m^2 Absorbing ceiling	No	No
3	52 m^2 Absorbing ceiling	No	Yes
4	52 m^2 Absorbing ceiling	9 m^2 Absorbers	Yes
5	52 m^2 Absorbing ceiling	9 m^2 Diffusers, vertically oriented	Yes
6	52 m^2 Absorbing ceiling	9 m^2 Diffusers, horizontally oriented	Yes
7	48 m^2 Absorbing ceiling, 4 m^2 diffusers above source position	9 m^2 Absorbers	Yes

3.2.2 The Effect on Room Acoustic Parameters

The absorbent ceiling significantly affects all the evaluated room acoustic parameters. As regards the furniture, the effects are mainly seen for the parameters reverberation time, T_{20}, and speech clarity C_{50}, in the mid frequencies, minor effects on sound strength, G, in low frequencies.

From the baseline of an absorbent ceiling and furniture, wall treatment was used. It was seen how this additional treatment can individually fine-tune the different parameters, depending on the treatment used. With additional absorbers, all the measured parameters were affected.

Regarding the different solutions using diffusers, mainly T_{20} and C_{50} were affected, meaning this solution can be used for cases in which energy needs to be conserved, such as in rooms where the primary activity involves speech. It should also be observed how the low frequency absorption of the diffusers affected all parameters measured. Results, in average over all measurement positions, on T_{20}, C_{50} and G for the different configurations are seen in Figure 15.

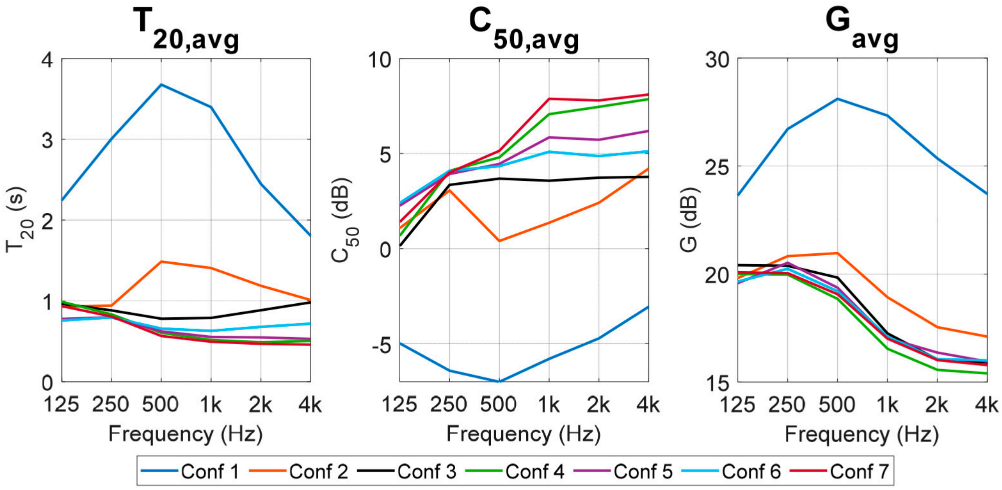

Figure 15 Room acoustic parameters for configurations 1–7. Average values over 2 sources and 6 receivers.

Using diffusers in the ceiling increased speech clarity in the rear part, position R5 in Figure 13, of the room by 3 dB in the higher frequency range. On average, across the twelve measurements, only minor changes were seen. The results for average values, positions close to the speaker, R2, and in the rear part of the room, R5, with and without ceiling diffusers, are presented in Figure 16.

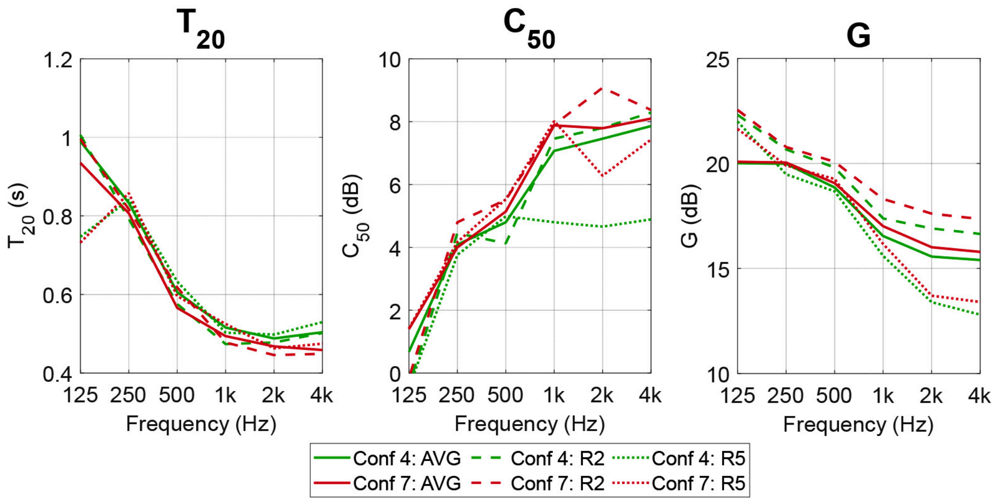

Figure 16 Comparison of configurations with and without ceiling diffusers on average, in position close to source, R2, and position further away from source, R5. Significant difference in position R5.

A comparison was also made between the measurements and a calculation using diffuse sound field theory, the Sabine formula. Configuration three were considered, meaning absorbent ceiling and furniture. This comparison showed significant differences, see Figure 17. This results indicates the need of using calculation models adapted to the room type and treatment used in the room.

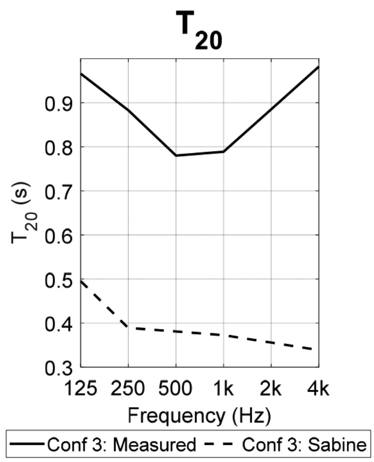

Figure 17 Measurement and calculation, using diffuse sound field theory, of reverberation time for Conf 3.

3.3 Subjective Testing

The same room was used for the experiments in subjective tests as for the objective studies. It was of interest to compare the experience as regards a position close to the speaker, further away on the same line as the speaker, and in a corner, one source position and three receiver positions were used. These positions were also evaluated for the room acoustic parameters. Source and receiver positions used in the subjective testing can be seen in Figure 18.

Figure 18 One source / speech postion, S2, three receiver positions, R2, R4 and R5, used in the listeing test.

Binaural headphones, BHS II from HEAD Acoustics, were used for the listening tests. The headphones had calibrated microphones for the sound sampling and were equipped with equalizer, SQuadriga, for correct playback, see Figure 19.

Figure 19 Headphones used for sound sampling and playback in listening tests.

The test was conducted using Software ArtemiSuite with testing module SQala from HEAD Acoustics supporting binaural recordings.

A group of 29 people participated in the listening tests. The group represented variations in age, experience and types of work in order to represent a variety of people in a workplace.

None of the participants had any insight into the ongoing study. The sounds were recorded in the mock-up but the listening test group did the evaluation in another, neutral room, see Figure 20, in order to not affect judgement relating to any aesthetic features.

Figure 20 The room where listening test group evaluated the sounds.

All sounds listened to were uncoded, meaning that the participants could not make any connections between the different sounds. Other aspects that can affect responses in listening tests are mood and health. Before starting the test, the participants filled out a questionnaire including these types of questions. The information was to be used to analyse any outlying results.

For the reliability of the results it was important that participants were able to concentrate throughout the whole test. The test was therefore designed to be finished within 20 minutes. Further, after completing the listening test, the participants rated how well they had been able to concentrate throughout the test. The aim was to use this information to evaluate whether anyone could be identified as giving outlying results. The information was also used with regard to test reliability; a high ratio answering with a high figure would indicate that the test design was too extensive, with the reliability of the outcome consequently being low.

Also in relation to reliability, the questions must be adequate, meaning they should correspond well to the objective of the study and the participants must understand the questions correctly; clear instructions are critical. Every participant therefore had a training session before the real test started. The training included all the different types of questions included in the listening test, and further instructions on how to manage the software. In addition, after the completed test, every participant rated the clarity of the instructions. As with the concentration aspect, this information was to be used in any case of outlying results; and if a high ratio answered that the instructions were unclear this would indicate low test reliability. A summary of the aspects relating to uncertainty and test reliability is presented in Figure 21.

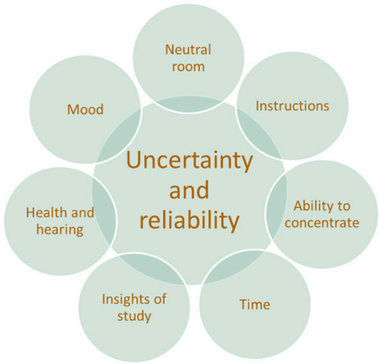

Figure 21 Uncertainties and reliability aspects considered in the listening test design.

A pilot test was performed testing the different aspects discussed above relating to test uncertainty and reliability. Responses from the pilot group were not included in the evaluation presented as results.

3.4 Study: Subjective Differences

Pairwise comparison was used to study differences. Five different configurations were evaluated, all with absorbent ceiling and furniture as a baseline. Configurations with different wall treatments were investigated: wall absorption, vertical and horizontal diffusers. Configurations with ceiling diffusers were also used. The configurations correspond to numbers 3–7 in Table 1 in the Configurations section.

It was found that the configurations with diffusers produced the most similar experience. In second place came the configuration without any wall treatment. This result can be explained by the reduction of energy occurring at the walls when absorbers are used, causing less uniformity of the acoustic energy. Position R5 was particularly close to the wall where absorbers or diffusers were mounted. The results are shown in Figure 22. It should be noted that the configuration numbering used corresponds with the descriptions in Table 1 of this thesis.

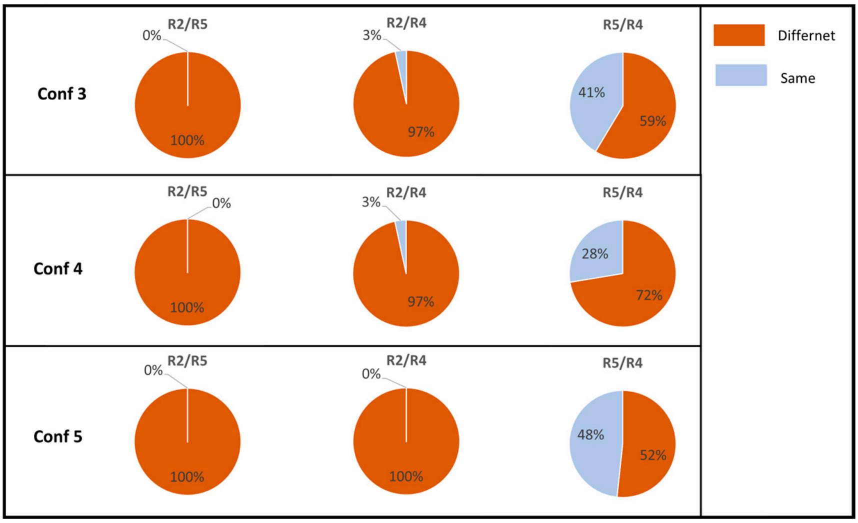

Figure 22 Observed differences between different positions within one configuration.

Using the different orientations of diffusers (Conf 3/Conf 4), the experience was the same for most of the participants. The differences in room acoustic measurements between these two configurations were small. The differences in T_{20} and C_{50} were in the range of JND according to ISO 3382-1 [28]. The difference in C_{50} in the position in rear part of the room, R5, due to ceiling diffusers (Conf 2/Conf 5), was perceived by about 40% of the participants. This indicates that the JND for speech should be investigated further. It should however be mentioned that more people perceived a difference in position R5 than the other positions, meaning that an effect of the diffusers is perceived subjectively. The results are seen in Figure 23.

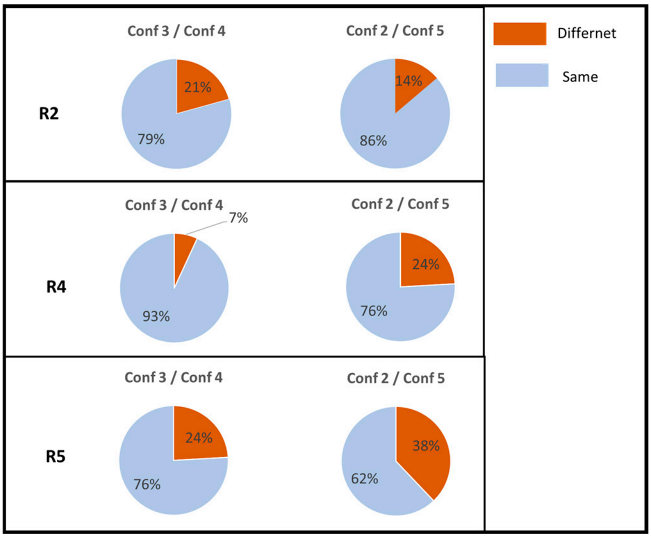

Figure 23 Observed differences between different configurations in the positions R2, R4, R5.

Comparing the results in subjective testing with the room acosutic measurements indicate that the subjective perception of differences in sound more often relates to C_{50} than T_{20}. Sound strength, G, could also be associated to the perceived differences.

3.5 Study: Subjective Preferences

In this study preferences of the acoustics were investigated, three different evaluations were included: sound quality, attributes and rating.

3.5.1 Description of Investigated Preferences

For the three evaluations used in this study the participants were asked to consider being in a room and listening to information. Three configurations were evaluated, configurations 3–5 in Table 1. All three had absorbent ceiling and furniture, one had no wall treatment and two had wall treatment, absorbent and vertical diffusers respectively.

Sound quality was judged using a rating scale, 1–10, where 1 corresponds to intolerable and 10 to excellent. In the evaluation of sound quality these were further grouped into three levels: Satisfactory, corresponding to points 8–10, Acceptable, corresponding to points 5–7, and Unsatisfactory, corresponding to points 1–4.

The attributes were related to how the speech was experienced. Four different attributes were used

- Echoic - Echo/tendencies of echo.
- Unclear - No echo, but indistinct; extra concentration required to hear.
- Clear - The sound is clear but not comfortable to listen to.
- Pleasant - The sound is clear and comfortable to listen to.

The rating was a third way of investigating how people experienced the sound environment depending on the type of treatment. In this investigation people rated the same position for the different configurations.

3.5.1.1 Evaluation Subjective Preferences

The Pearson correlation, evaluating the linear relation between two variables, was used to study sound quality and attributes, with the room acoustic parameters representing one of the variables. The strength between the two variables is expressed as r, varying from -1 to +1. Complete correlation is obtained when r=1 or r=-1. Whether r is positive or negative shows the direction for the dependency between the variables. A positive dependency means that if one of the variables increases, the other variable will also increase. With negative correlation, one variable increases while the other decreases. It should be noted that the correlation provides information about the association between two variables, but not the cause. If r=0, no dependency is found between the variables [81].

Regression was also used for the evaluation of sound quality and attributes, in order to better understand the relation between the variables; not only how strong the relation is, as with correlation coefficient, but also how the variables relate to each other. With regression, an equation is calculated for the line that best describes the relationship between an explanatory, dependent variable and the response variable. The coefficient of determination, R^2, presents how well the equation explains the response variable. This value can vary between 0–1, or be represented as a percentage 0–100%. With R^2=1 or 100%, all responses can be explained by the equation of the regression line [82]. R^2 can also be expressed as degree of explanation, i.e., how well the explanatory variable can explain the response variable. R^2 is the square of the correlation coefficient, r. The application decides which value of R^2 is appropriate; for the calibration of two balances, the R^2 should be close to 1, or 100 %. For subjective testing, lower values are normally obtained [82].

3.5.2 Responses to Sound Preferences

There were ten levels in the scale for sound quality, grouped into satisfactory, acceptable and unsatisfactory. The results of this test show that to use only absorbent ceiling (Conf 3) is not sufficient to attain an acceptable, levels 5–7, sound environment in a whole room. In position R5, the rear part of the room, the majority of people experienced the sound environment to be unsatisfactory.

The configuration with wall absorption, additional to the absorbing ceiling (Conf 4), was perceived as the best. More than 80% of the participants deemed that configuration to be acceptable or satisfactory across all the positions. In the position close to the speaker, 100% of the participants deemed it satisfactory. This was also the case for the configuration with diffusers (Conf 5), with 100% deeming this position as acceptable or satisfactory. For the other positions the sound quality was perceived to be slightly lower for the configuration with diffusers compared to the configuration with wall absorption. However, a majority of the participants found the configuration with diffusers acceptable or satisfactory. It should be noted that this number was the same, 69%, for both positions in the rear part, R4 and R5, for this configuration. From the previous study, Subjective Differences, this configuration was perceived to be most similar between the same two positions. The results on perceived sound quality for the different configurations and positions are shown in Figure 24.

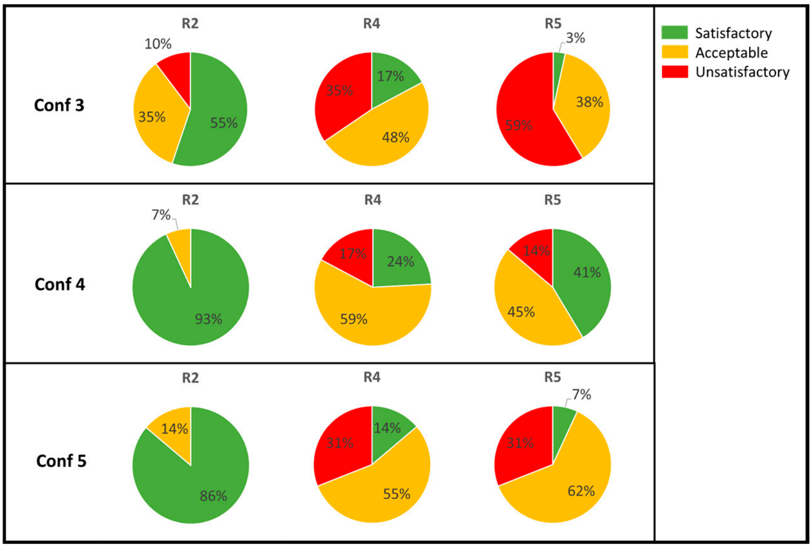

Figure 24 Sound quality grouped into satisfactory, acceptable and unsatisfactory.

Investigating the relation between room acoustic parameters and sound quality showed a good, positive, correlation to speech clarity, C_{50}. In the high frequency range, 1000 Hz–4000 Hz, the correlation coefficient was $r > 0.8$ for $p < 0.05$, meaning a good correlation and statistical significance. Correlation to reverberation time, T_{20}, and sound strength, G, did not show as clear a relation. The relation between the room acoustic parameters and sound quality can also be represented in regression. Expressing the relation between C_{50} to perceived sound quality in R^2 gives a degree of explanation of 65% and above for the high frequencies, using simple regression, linear relation. Using the result on regression with the different levels presented above, satisfactory, acceptable and unsatisfactory, indicates that to achieve the level of acceptable C_{50} >2 dB for frequencies 1000 Hz and 2000 Hz, and C_{50}>3 dB for 4000 Hz was needed. To achieve a satisfactory sound environment, the results indicated that C_{50}>8 dB or more was needed for frequencies 1000 Hz and 2000 Hz, and C_{50}>9 dB was needed for frequency 4000 Hz.

Reverberation time is often used as a specification parameter for ordinary public rooms. This study shows that C_{50} is a parameter that better explains the relation to perceived sound quality. With regression between perceived sound quality and T_{20}, time, at the high frequencies, the degree of explanation was around 30%. Scatterplots with regression for sound quality relating to the two parameters T_{20} and C_{50} are shown in Figure 25.

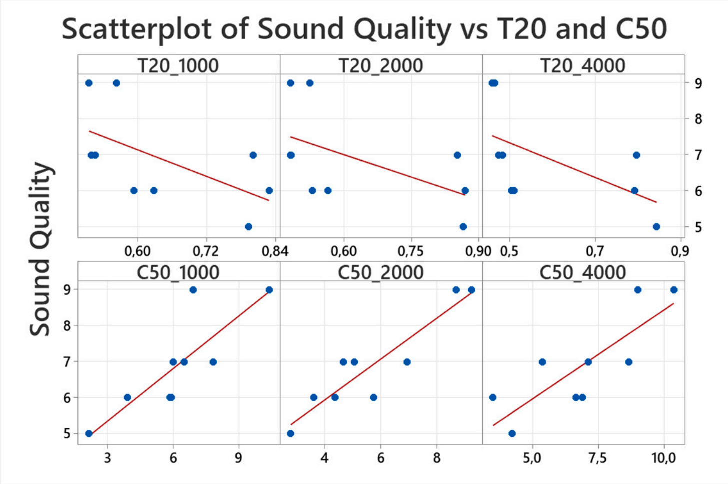

Figure 25 Scatterplot with linear regression for T_{20} and C_{50}, on the x-axis, relating to perceived sound quality, on y-axis.

In evaluating the attributes echoic unclear, clear and pleasant in relation to different acoustic treatments, the configuration with absorbent ceiling only was deemed as echoic by a majority of the participants, in all positions, implying that an absorbent ceiling (Conf 3) is not sufficient for good speech perception. The configuration with wall absorption (Conf 4) has highest level of pleasant and clear. The majority perceived configuration with diffusers (Conf 5) as clear or pleasant, but it should be noted that some people find the environment with diffusers to be echoic, see Figure 26.

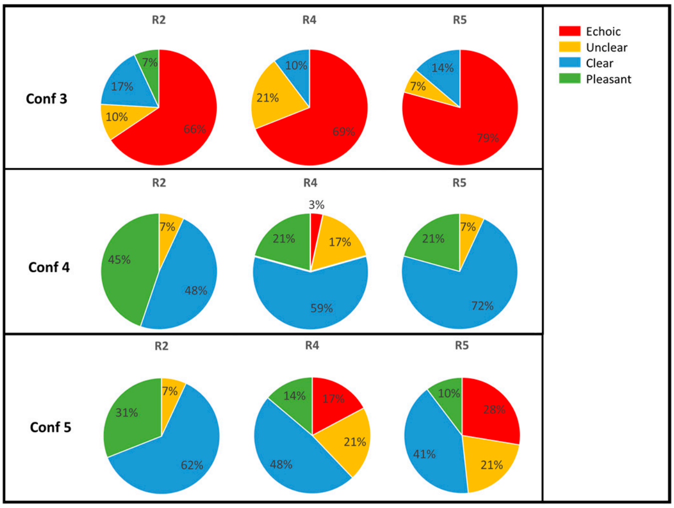

Figure 26 Attributes echoic, unclear, clear and pleasant for the different configurations.

A study of the correlation of attributes to room acoustic parameters showed a relation to T_{20}. From frequency 500 Hz and above, a good, correlation coefficient of 0.9, was found, with $p<0.05$, showing statistical significance. However, a fairly good correlation to C_{50}

was also found for frequencies 1000 Hz to 4000 Hz, a positive correlation with $r>0.7$ for these frequencies, with $p<0.05$.

The ratings showed the configuration with most absorption to be the best, the configuration with diffusers came in second place and the configuration with absorbent treatment only in the third place. This was the case for all three positions in the room. These results follow the same trend as seen for sound quality and attributes, confirming the results of the study, that C_{50} relates well to subjective experience of sound environment.

3.6 Study: Estimation of Acoustic Properties

In this study a statistical energy analysis, SEA, model was investigated, developed for rooms with absorbent ceiling.

3.6.1 Evaluation of Scattering using SEA model

The work performed in this study has been related to the scattering effect of diffusers, when used in combination with an absorbent ceiling. The study is based on a statistical energy analysis, SEA, model derived in a sub-study to this research program.

In the SEA model the assumption is that the sound field in these rooms comprises a grazing and non-grazing sound field. The grazing sound field accounts for the sound waves propagating parallel to the ceiling.

Energy can be transferred from the grazing to the non-grazing sound field by the introduction of scattering objects such as furniture, or as in this case diffusers. The effect of scattering on the decay curve is visualized in Figure 27.

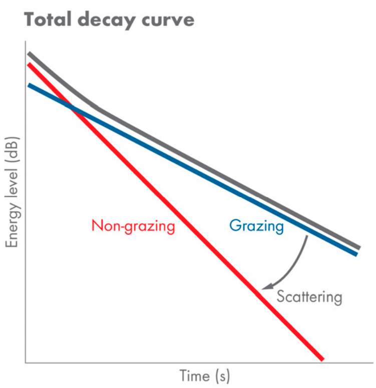

Figure 27 Total decay in gray, built up of the modes in the grazing and non-grazing fields. the later part of the decay is dominated by the grazing modes, blue curve, determining the reverberation time. Energy can be transformed from grazing to non-grazing due to scattering.

In the SEA model, the effect of the scattering can be calculated by using the reverberation time with and without the objects. The effect is expressed in equivalent scattering absorption area, A_{sc}, given by

$$A_{sc} = 0.127V\left(\frac{1}{T_{20,with}} - \frac{1}{T_{20,without}}\right) \qquad (6)$$

where

V is the volume of the room

$T_{20,with}$ is the reverberation time with objects

$T_{20,without}$ is the reverberation time without objects

The scattering of diffusers was investigated from two perspectives:

- the sensitivity of different diffuser configurations, i.e., can the differences in configurations be observed in the parameter A_{sc} and
- the possibility of quantifying the diffusers in a laboratory scale, important to enable calculation of the acoustic properties in advance.

A number of different set-ups of diffusers in combination with absorbent ceiling were investigated. These set-ups involved different diffuser properties by changing their orientation, as in Figure 10, by using different quantities of diffusers, and by using different installation patterns. These types of variations could typically be found in real rooms and it is therefore important that a model is sensitive to such variations. The different set-ups were tested with and without furniture. A total of 34 different configurations were investigated.

The data on each element must be available for use as input parameters in the calculation model. It was therefore investigated whether the diffuser could be quantified in terms of A_{sc} in a reverberation chamber. The A_{sc} measured in the mock-up room in the laboratory and in a reverberation chamber were compared. The comparisons were made for configurations with absorbent ceiling, with no furniture and with the two different diffuser orientations. The reverberant room used had an area of approximately 14 m^2; for dimensions see Figure 28. The height from floor to soffit were 4 m. The ceiling was installed at the same height as in the mock-up room, i.e., 2.70 m.

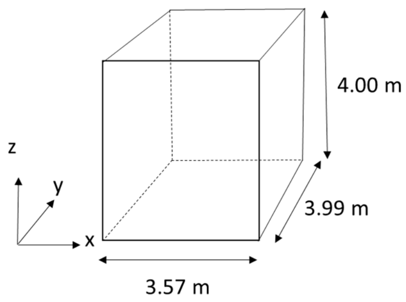

Figure 28 Dimensions of reverberant room used in study comparing the A_{sc} of diffusers in the mock-up room.

3.6.2 Quantification of Scattering

The parameter equivalent scattering absorption area, A_{sc}, showed clear differences, in the higher frequency range, between the two different orientations. The evaluation for different quantities of diffusers showed a decrease in A_{sc} per element when the number of elements increased. Testing the installation pattern showed that the effect on A_{sc} per element increased when the full diffuser was exposed, compared to when the diffusers were mounted directly beside each other. The results of variations in effect per element can be seen in Figure 29, which presents a selection of configurations.

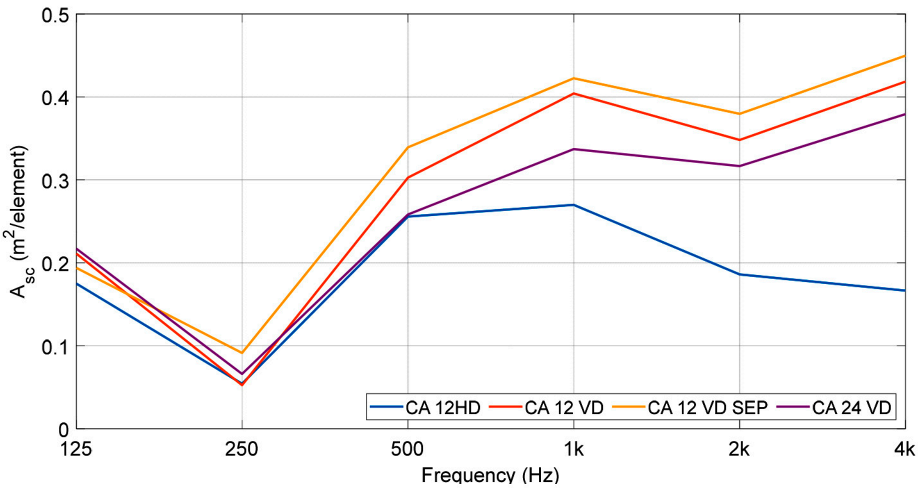

Figure 29 The effect on A_{sc} per element depending on orientation, quantity and installation pattern. All configurations have an absorbing ceiling (CA), 12 and 24 diffusers are used. Vertically oriented diffusers are denoted VD, horizontally oriented diffusers are denoted HD. Installation pattern where the diffusers are sepratared from each other are denoted SEP.

It was also found that the combination of furniture and diffusers resulted in a greater effect on A_{sc} than with only the addition of the two separate objects, see Figure 30. This is an important aspect to take into account in the calculations of room acoustics.

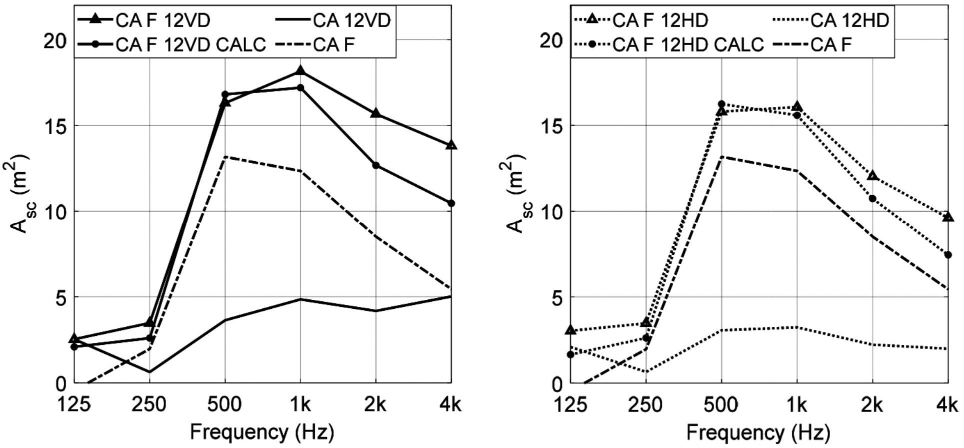

Figure 30 The effect on A_{sc} of configuration with absorbent ceiling and furniture (CA_F) and 12 diffusers, vertically oriented in the left graph and horizontally oriented in the right graph. Adding the contribution (calculated) for the two separate objects diffusers and furniture is denoted “CALC”. A_{sc} from measured values, CA_F_12VD/12HD, shows higher values than the separate contribution to A_{sc}, i.e., an additional effect on A_{sc} is achieved when combining furniture and diffusers.

Tests were also performed to investigate whether the diffusers could be quantified in a laboratory scale, in a reverberation chamber. The values obtained in the reverberation chamber and in the full-scale mock-up were similar at higher frequencies. Greater differences were seen in the lower frequency range; this could be explained by the small dimensions of the reverberation chamber used being smaller than typical sizes of reverberation chambers in accredited labs, where measurements of absorption according to ISO 354 are made. The results indicate that diffusers could be quantified in terms of A_{sc} in a laboratory environment. The A_{sc} could then be used as an input parameter in the calculation model for estimations of room acoustic properties.

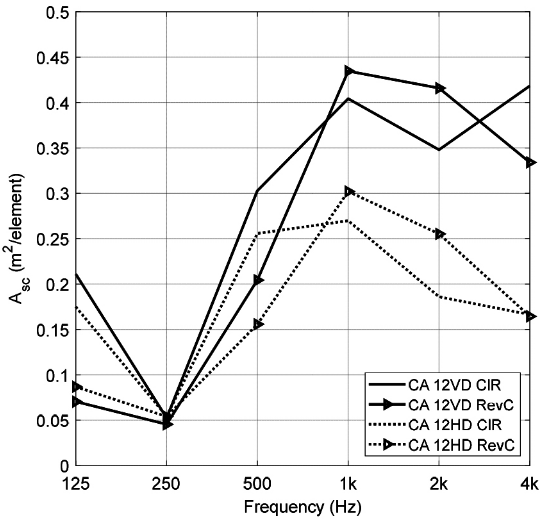

Figure 31 Effect in terms of A_{sc} per element for measurement in a classroom mock-up (CIR) and reverberation chamber (RevC). Absorbing ceiling (CA) in all cases, 12 diffusers mounted vertically (VD) or horizontally (HD). The diffusers were mounted in connection to each other in rows.

4 Summary of Results

Study *a) Treatments and Parameters* showed how an absorbent ceiling gives a good baseline by reducing reverberation time, T_{20}, and sound strength, G, and, and increasing speech clarity, C_{50}. However, wall treatment can be used to fine-tune the acoustics. Depending on type of treatment different parameters are adjusted. For a further decrease in T_{20} and G, absorbent wall treatment is a good choice, while diffusers can be appropriate when there is a need for improved speech conditions while the sound energy is conserved. The two different wall treatments, absorbers and diffusers, affect both T_{20} and C_{50}. Placing diffusers in the ceiling, located in a typical speaking position, increased speech clarity significantly in the rear part of the room and increased G slightly at the speaking position. Furthermore, diffusers can be designed to have absorption properties. The low frequency absorption of the diffusers used in this research affected all the room acoustic parameters that were measured.

Study *b) Subjective Differences*, showed that the acoustics were perceived more uniform with diffusers on the walls as compared to absorbent panels. People could also perceive a difference with the ceiling diffusers in the rear part of the room.

In study *c) Subjective Preferences*, people judged speech in terms of sound quality, chose predefined attributes and rated different environments. The sound quality could be related to the room acoustic parameter C_{50}, in the higher frequency range. The attributes were best related to T_{20}; however, a relation to C_{50} could also be seen. In the ratings the configuration with the most absorption was rated as the best. This configuration had the highest C_{50}.

The above-mentioned results provide information on how acoustic treatments can affect objective and subjective measures. In study *d) Estimation of Acoustic Properties,* a SEA model adapted for rooms with absorbent ceiling was investigated. It was found in that study how calculations from the model correlated well with measurements. In addition, it was found how the scattering and absorption properties could be quantified, in a laboratory environment. This data can be used as input parameters in the SEA model for the estimation of room acoustic parameters.

The information from the different studies shows how different treatments can be used to alter different room acoustic parameters. The subjective studies show that diffusers contribute to a more uniform acoustic experience. They also show how speech clarity relates well to people's experience of the sound environment. To control C_{50} is therefore recommended in the room acoustic design of ordinary rooms.

5 Description of Published Papers

5.1 Paper A

The Effect on Room Acoustical Parameters

Using a Combination of Absorbers and Diffusers

– An Experimental Study in a Classroom

Acoustics, Special Issue: Innovative Design and Applications of Materials for Acoustically Performative Indoor and Outdoor Environments.

Authors: Emma Arvidsson, Erling Nilsson, Delphine Bard Hagberg, Ola J.I. Karlsson

Published: 4 July 2020

Summary: This paper evaluated the room acoustic parameters reverberation time (T_{20}), speech clarity (C_{50}) and sound strength (G) in a classroom where different acoustic treatments were used. The effect of adding an absorbing ceiling, furniture, and absorption as well as diffusers on the walls was evaluated. Diffusers were also used in the ceiling, replacing absorbent tiles in the area above the speaker. The diffusers had low frequency absorption and were compared to a porous, low-frequency absorber.

The results showed how an acoustic ceiling was a good baseline and also how furniture clearly affected room acoustics in mid frequencies. As regards different treatments on walls, the results demonstrated how these treatments could be used to further adjust different room acoustic parameters. Adding diffusers or absorbers affected T_{20} and C_{50}; however, sound absorbers also affected G. An important finding was also how the ceiling diffusers clearly affected speech clarity in the rear part of the room. The addition of diffusers is therefore useful in rooms for speech. If there is a need for a further decrease in sound energy, a solution with additional absorption should be chosen. The low frequency comparison showed higher efficiency with the use of diffusers.

Contribution: The author of this thesis designed and accomplished the experiments together with supervisor Erling Nilsson. The author of the thesis prepared the original draft of the paper with significant contribution from Erling Nilsson to the Introduction paragraph. Erling Nilsson, Delphine Bard Hagberg and Ola J.I Karlsson supervised the study and reviewed the paper.

5.2 Paper B

The Difference in Subjective Experience

Related to Acoustic Treatments in an Ordinary Public Room: A Case Study

Acoustics, Special Issue: Room Acoustics.

Authors: Emma Arvidsson, Erling Nilsson, Delphine Bard Hagberg, Ola J.I. Karlsson

Published: 18 June 2021

Summary: The results from Paper A showed how the room acoustic parameters could differ depending on the acoustic treatment used. However, these differences are only of interest if people can also experience a difference subjectively. The objective of this paper, Paper B, was to investigate whether people could experience a difference between different configurations. This involved not only differences between configurations but also internally within a configuration, i.e., different positions in the room were investigated.

Room acoustic measurements and listening tests were conducted. In the listening tests people were asked to judge whether they perceived that speech sounded the same or different. Speech was recorded in different configurations of acoustic treatments as well as in different configuration positions.

It was found that people found configurations with diffusers on the walls to be most similar, meaning that the diffusers resulted in a more uniform acoustic experience. Configurations with no wall treatment were experienced as being more uniform than configurations with absorption on the walls. The effects of ceiling diffusers were perceived more often in the rear part of the room, where the greatest effect on room acoustic parameters was attained.

Contribution: The author of this thesis designed, performed and analyzed the experiments and also prepared the original draft of the paper. Erling Nilsson, Delphine Bard Hagberg and Ola J.I. Karlsson supervised the study and reviewed the paper.

5.3 Paper C

An Energy Model for the Calculation of Room Acoustic Parameters in Rectangular Rooms with Absorbent Ceilings

Applied Sciences, Special Issue: Advances in Architectural Acoustics.

Authors: Erling Nilsson, Emma Arvidsson

Published: 18 July 2021

Summary: An absorbent ceiling is typical treatment in ordinary rooms. This treatment results in the sound field becoming non-uniform, and diffuse sound field theory becomes inappropriate. In addition, the scattering due to furniture and other objects must be accounted for. This paper presents the development of a calculation model based on statistical energy analysis, SEA.

The model accounts for the sound fields that occur in rooms with absorbent ceiling by introducing two subsystems into the model, a grazing and a non-grazing. In the grazing field the sound waves travel parallel to the ceiling. The model also includes a method for estimating the scattering effect of furniture. Predictions from the model are compared with a diffuse sound field theory and also compared to measurements. The three room acoustic parameters reverberation time, speech clarity and sound strength were investigated. The SEA model showed better relation to measurements than diffuse sound field theory.

Contribution: The main author of the paper is Erling Nilsson, who developed the SEA model presented. The author of this thesis was involved in the parts relating to estimations of the scattering due to furniture.

5.4 Paper D

Subjective Experience of Speech

Depending on the Acoustic Treatment in an Ordinary Room

MDPI International Journal of Environmental Research and Public Health, Covered in PubMEd, Special issue: Speech Communication in Complex Auditory Scenes and Effects on Voice Behaviour and Health, Listening Comfort, Well-being, and Learning. Included in the section "Health, Behaviour, Chronic Diseases and Health Promotion".

Authors: Emma Arvidsson, Erling Nilsson, Delphine Bard Hagberg, Ola J.I Karlsson

Published: 23 November 2021

Summary: Paper B investigated whether people could experience a difference depending on the type of acoustic treatment. In this study the subjective preferences were investigated. People were asked to judge how well they experienced the different speech samples, and this was called sound quality. They were also asked to assign predefined attributes to the different speech samples. Ratings between different configurations were also performed.

The results showed that speech clarity, C_{50}, could be related to the perceived sound quality. Reverberation time, T_{20}, was best related to the attributes, but also a relation to C_{50} could be seen, although not as strong. The relations to room acoustic parameters were valid for the higher frequency range. The configuration with the most absorption was rated the best for all positions. This configuration had the highest C_{50} values. No relation between sound strength G and subjective experience were found in this study. It should be noted that the attributes used did not correspond to sound levels. Further, only minor changes were seen in G for the different configurations. These two aspects could explain why no relation to G was found in this study.

Contribution: The author of this thesis designed, performed and analysed the experiments and also prepared the original draft of the paper. Erling Nilsson, Delphine Bard Hagberg and Ola J.I. Karlsson supervised the study and reviewed the paper.

5.5 Paper E

Quantification of the Absorption and Scattering Effects of Diffusers in a Room with Absorbent Ceiling

MDPI Buildings, special issue Computational and Experimental Evaluation of Architectural Acoustics in Enclosures.

Authors: Emma Arvidsson, Erling Nilsson, Delphine Bard Hagberg, Ola J.I Karlsson

Published: 4 December 2021

Summary: It is important that architects and other practitioners have appropriate tools for acoustic design that specifies room acoustic treatment. From the studies presented in previous papers it has been found that diffusers can be sufficient acoustic treatment in rooms such as classrooms and offices. In the study presented in this paper, Paper E it was investigated whether the absorption and scattering properties of diffusers could be quantified by using the parameter equivalent scattering absorption area, A_{sc}. Several different configurations in a classroom were investigated. For the different configurations, different diffuser characteristics, and quantity and the installation pattern of diffusers were tested. It was found that the parameter A_{sc} and the model were sensitive to these changes. Furthermore, it was tested whether it was possible to make the quantification in a laboratory environment, a reverberation chamber. It was found that A_{sc} can be an appropriate way of estimating the effect of diffusers in a reverberant room as well. The A_{sc} values can be used as input parameters in the model presented in Paper C for estimations of room acoustic parameters.

Contribution: The author of this thesis designed, performed and analysed the experiments and also prepared the original draft of the paper. Erling Nilsson, Delphine Bard Hagberg, Ola J.I. Karlsson supervised the study and reviewed the paper.

Part III
Research Sum-Up

6 Concluding Remarks

The research presented in this thesis includes both subjective and objective aspects of room acoustic design. It was deemed that this approach was required in order to attain the aim of the project – to improve room acoustics for people in ordinary public rooms. In the following paragraphs the output of the different studies is related and discussed.

6.1 Reliability in the Subjective Testing

The aspect of uncertainty, and bias in particular, is critical with regard to reliability in subjective testing. None of the participants had any underlying insights into the study; they could not visually relate any of the sounds to the configurations, and all sounds were uncoded. These actions lower the risk of bias.

After the listening test, the test persons could respond regarding their ability to concentrate throughout the test and whether the instructions had been clear. In the survey there was also a free field to fill out for reflections and comments about the test. People responded with high ratings regarding clarity of instruction and their ability to concentrate throughout the tests. These responses together with the actions counteracting bias demonstrate reliability in respect of the outcome of the test.

Some people responded with higher points relating to the evaluation of the speech, meaning in general that they were more positive to the sounds they heard. Prior to the test, self-ratings on mood, health and hearing were included. From that questionnaire, no relation could be found to the higher points. It cannot be concluded whether higher points depended on a natural variation in preferences or on a question reflecting something particular for this group of people that they were lacking.

The individuals in the listening tests represented a cross-section of people in a workplace, with differences in education, age and experience. Against the background of this variation, the outcome of the study should be interpreted as the experience of a general group of people working in ordinary public rooms. For the aim of a more specific environment, such as university premises, a group of students could be more relevant.

6.2 Room Acoustics Relating to Human Perception

There are several parameters to describe room acoustics properties. In the Introduction, it can be seen how late reflections, early reflections and sound levels all affect the sound environment. To deal with these aspects, three parameters were chosen for this study: reverberation time, T_{20}, accounting for the late reflections; speech clarity, C_{50}, accounting for early reflections; and sound strength, G, accounting for how the room contributes to the sound energy. The package of these parameters together provides a good overview of the acoustic properties of a room.

This research programme has shown that, in order to create good acoustics in ordinary rooms, an absorbent ceiling is a good baseline, significantly adjusting several room acoustic parameters. However, to obtain satisfactory room acoustics, additional treatment was needed. The parameter shown to be most important for the subjective experience was speech clarity, C_{50}.

In the study of perceived sound quality, the degree of explanation from C_{50} was high at the high frequencies. This means that people's experience of sound quality was related to the value of C_{50}, with a higher value being more appreciated. In the investigation of attributes, which covered clarity and comfort of speech, reverberation time, T_{20}, was best related, but a relation to C_{50} could also be seen. When people were asked to rate which configuration they found best, again the one with the highest C_{50} was chosen, and this was the case for all positions evaluated.

There could of course be other parameters that would also give a good correlation to the subjective preferences of sound. However, the good relation found between the subjective experience and the parameter speech clarity, C_{50}, in all the studies regarding preferences, indicates that this parameter is highly relevant for inclusion in the acoustic design of ordinary rooms. More work on defining target values of C_{50} is however required. Furthermore, a study of different attributes relating to the acoustic requirements of these types of rooms would be of interest going forward.

The fact that C_{50} related well to people's perception of sound shows the importance of considering how this parameter can be adjusted. In this research both absorbers and diffusers were used, and both types affect C_{50}, but the effect on C_{50} per square metre of treatment was higher using additional absorbers. Thus, the diffusers do also have other advantages, namely to contribute to more uniform acoustics throughout the room, which is an important aspect to consider for ordinary rooms; everyone should have the same opportunity to hear information properly. Furthermore, the results show the importance of considering different positions in a room, and not only average values.

Another aspect to consider in the choice of additional treatment is whether there is a need to reduce or conserve sound energy. For the latter, diffusers should be chosen. This could for example be in rooms for speech where it is important that the sound energy reaches everyone, even those sitting far away from the speaker. If the need is only to reduce energy, i.e., in noisy environments, absorbers should be used.

It should be noted that the variations in sound strength, G, were low in the configurations included in the subjective testing. This could be a reason for the low correlation to perception. Further, the attributes were not designed to reflect the sound level in particular. So even though G was not contributing to the perceived acoustics the result of this study cannot exclude the importance of G in the acoustic design of ordinary rooms. To evaluate the need for sound strength, a test altering absorption properties and attributes relating to sound levels could be performed.

6.3 Scattering and Estimation of Room Acoustics

For support in choosing appropriate acoustic treatment, it is important that architects and other practitioners have tools for estimating the acoustic properties in a room depending on the treatment to be used. The calculation model investigated in this thesis gave results that related well to the measured values of room acoustic parameters, both for absorbing and diffusing treatment.

The model was sensitive to different diffuser characteristics and installation patterns that could be applicable in the room acoustic design of ordinary rooms. Sensitivity was measured in terms of the parameter equivalent scattering absorption area, A_{sc}.

To estimate the acoustics in advance, the A_{sc} must be quantified for the treatment. Evaluating the A_{sc} for the diffusers gave similar results per element in the laboratory environment as in the real mock-up room. This is an indication that the method could be used to quantify diffusers. However, such a method must be clearly defined, with the absorption properties of the ceiling, the quantity of diffusers and the room dimensions of the test environment being examples of parameters requiring further investigation.

The measurements of room acoustic parameters showed significant effects from the furniture used. It was also seen how the effect of the diffusers was greater when used in combination with furniture. It is important to understand the effects of furniture for the correct estimation of the acoustics. Thus, only one set-up of furniture was used for the measurements in this research programme. Studying the effect of different furniture set-ups on acoustics was not within the scope of the programme. However, investigating different set-ups would be of interest for further studies, which would include investigations of the maximum scattering effect that furniture can contribute with.

The model investigated was shown to produce results well related to measured room acoustics in rooms with absorbent ceiling where the sound field is non-diffuse. Furthermore, the parameter used for quantifying absorption and scattering of objects, denoted A_{sc}, was sensitive to changes in directivity and installation set-up. These aspects, together with the fact that the model investigated is a calculation model providing rapid estimations, make it convenient in the acoustic design process for these types of rooms. It is thus suggested that further research should be carried out into room set-ups and definitions of quantification methods, as previously discussed.

7 Contributions

This research has focused on ordinary public rooms such as classrooms and offices. In these types of rooms large groups of people spend many working hours.

A sound absorbent ceiling is a good acoustic baseline in these rooms. Typically, they are characterized by the reverberation time. Further, it is assumed in calculation models that the sound field is diffuse, such as in the classical Sabine formula. However, in rooms with absorbent ceiling treatments, the assumption of a diffuse sound field is not valid. Furthermore, the single use of reverberation time as a descriptor of acoustics is not sufficient. Two rooms with the same reverberation time can be perceived differently, and there is obviously a need for complementary descriptors for proper characterization. It is important to understand the relation between the different parameters and people's experience of sound, therefore this has been studied in this research.

The measures speech clarity, C_{50}, and sound strength, G, have been investigated together with reverberation time, T_{20}. With these additional parameters, early reflections are also taken into account, as they are missing in the evaluation of T_{20}. The parameter G is mainly dependent on the total absorption in the room; a full wall to wall covering ceiling will thereby determine the value of sound strength. Additional acoustic treatment on walls or the presence of furniture in the room usually only have a minor effect on G. However, due to the non-diffuse sound field and presence of lateral sound energy, absorbent or diffusing treatment on walls can significantly affect parameters such as reverberation time and speech clarity. It is therefore important to be able to quantify the absorption as well as the scattering effect of such treatment. This quantification has been part of this thesis.

For the room types studied in this research, the following can be concluded:

- C_{50} was the parameter best reflecting people's experience of different sound environments
- Diffusers, in addition to an absorbent ceiling, contributed to a more uniform acoustic experience throughout the room
    - The directional characteristics of the diffusers are important when used in combination with a sound absorbing ceiling
    - Placing the directional diffusers in the ceiling, above the speaking position, effectively improved C_{50} in the rear part of the room
- The measure equivalent scattering absorption area, A_{sc}, evaluated for quantifying scattering and absorption, was shown to be
    - sensitive to directivity, quantity and installation pattern of diffusers
    - possible to measure in a reverberant laboratory setting.

8 Directions for Future Work

Findings from the research presented in this thesis can contribute to improvement of acoustics in ordinary rooms. The work is based on a holistic approach, which can be useful going forward. A continuation of the different studies performed for this doctoral thesis is also of interest for the future. The following are suggestions for such studies:

- Defining target values of speech clarity, C_{50}, in ordinary rooms. The outcome from the study *Subjective Preferences* indicated target values for C_{50}. These were related to the experience of sound quality. To define target values, the preferences from a larger group of individuals should be investigated. Cognitive tasks could also be included in such an investigation.
- Investigation of just noticeable difference, JND, for speech. The outcome from study *Subjective Differences* showed that a higher JND than recommended in ISO 3382-1 was needed to recognize a difference. A study of JND for speech over different frequencies for different room acoustic parameters would be valuable.
- Quantification method definition for scattering objects. The study *Estimation of Acoustic Properties* showed that the SEA model was suitable for ordinary rooms. Using the model requires input values of the parameter equivalent scattering absorption area, A_{sc}. In the above-mentioned study, it was indicated that quantification of A_{sc} could be performed in a reverberant room. A future study could investigate the conditions for such a method. This would include investigation of the absorption properties of the ceiling, how to transform the values from lab scale to real rooms, with the effect of furniture as well as quantity of objects to be tested.
- Variation of room set-up altering treatments, scattering objects and room dimensions. Furniture affects room acoustic properties. It was also seen how the effect of diffusers increased when combined with furniture, and this combined effect is of interest for further study.

Thus, in order to really improve the room acoustics in ordinary rooms, it is critical that information from these types of studies reaches the people involved in defining up the specifications relating to room acoustic design. Consideration of communication aspects is thus also of high importance going forward.

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Part IV
Appended Papers

A

acoustics

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Article

The Effect on Room Acoustical Parameters Using a Combination of Absorbers and Diffusers—An Experimental Study in a Classroom

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Abstract: Several room acoustic parameters have to be considered in ordinary public rooms, such as offices and classrooms, in order to present the actual conditions, thus increasing demands on the acoustic treatment. The most common acoustical treatment in ordinary rooms is a suspended absorbent ceiling. Due to the non-uniform distribution of the absorbent material, the classical diffuse field assumption is not fulfilled in such cases. Further, the sound scattering effect of non-absorbing objects such as furniture are considerable in these types of rooms. Even the directional characteristic of the sound scattering objects are of importance. The sound decay curve in rooms with absorbent ceilings often demonstrate a double slope. Thus, it is not possible to use reverberation time as room parameter as a representative standalone acoustic measure. An evaluation that captures the true room acoustical conditions therefore needs supplementary parameters. The aim of this experimental study is to show how various acoustical treatments affect reverberation time T_{20}, speech clarity C_{50} and sound strength G. The experiment was performed in a mock-up of a classroom. The results demonstrated how absorbers, diffusers and scattering objects influence room acoustical parameters. It is shown that to some extent the parameters can be adjusted individually by using different treatments or combination of treatments. This allows for the fine-tuning of the acoustical conditions, in order to fulfill the requirements for achieving a high-quality sound environment.

Keywords: room acoustics; sound diffusion; sound absorption; sound scattering; sound strength; speech clarity; reverberation time

1. Introduction

In ordinary public rooms, the typical acoustic treatment is a suspended absorbent ceiling. Examples of ordinary public rooms are classrooms, offices, health care premises and restaurants. Many people spend their working days in those spaces performing a variety of different activities. The acoustical conditions are crucial for people's wellbeing and while supporting their activities.

1.1. Room Acoustic Parameters in Classrooms

The importance of good acoustical conditions in schools, with classrooms that support speech communication, as well as concentrated work, is well documented. Several surveys in school environments have emphasized the detrimental effects of insufficient acoustic treatment in classrooms [1,2]. The effect on cognitive functions, such as working memory, have been investigated [3], as well as on academic attainment [4]. Acoustical treatment in classrooms should not only secure good listening conditions; it has been reported that teachers suffer from voice disorders to a greater degree than the rest of the population [5]. Objective measures for voice support in medium-sized classrooms have therefore been developed [6–8].

The most common way to specify room acoustical target values in standards and regulations is to use reverberation time T_{60} [9]. The reverberation time is often evaluated as T_{20}, i.e., evaluating the range −5 to −25 dB of the decay curve. Validation is defined in ISO 3382-2 [10]. Due to the procedure for evaluation of T_{20}, early reflections are ignored. As stated in textbooks on acoustics [11,12], it is known that two rooms with the same reverberation time can still be perceived as different, and that the reverberation is not solely enough to characterize room acoustical conditions. The fact that early reflections are ignored in evaluating T_{20} is a plausible explanation for the occasionally bad correlation between the perceived condition. Furthermore, in rooms with ceiling treatment, the decay curve is often double-sloped, with a steep slope at the start of the decay and a less steep slope towards the end of the decay [13]. Thus, there is an ambiguity in the evaluation of the reverberation time, due to the non-linear behavior of the decay curve. Consequently, complementary room acoustic parameters are needed, in order to capture the subjective experience of the acoustical conditions.

Lochner and Burger [14] emphasized the importance of early reflections for the subjective impression of an auditorium, stating that it is the sound field and pattern of reflections that will affect how the sound environment is experienced, rather than one single parameter. The early reflections will contribute to the direct sound and thereby to the clarity of speech. The importance of parameters including early reflections, such as speech clarity C_{50}, have also been investigated in several studies [15–20]. Another parameter for speech intelligibility is the Speech Transmission Index (STI). The parameters C_{50} and STI have been introduced in some national standards [21,22]. STI is defined in IEC60268-16 [23] and C_{50} in ISO 3382-1 [24]. C_{50} is an energy ratio for early-to-late arriving energy expressed in dB. The time limit between early and late energy is set at 50 ms for speech. Another parameter describing the relation between early and late reflections is definition, $D_{50,}$ which is expressed as a percentage. These two parameters, C_{50} and D_{50}, are exactly related. In this study C_{50} has been investigated.

In a recent study [25], the reading speed for Italian second graders was investigated. The study indicates a relation between reading speed and C_{50}. No correlation to reverberation time was identified.

Bradley et al. [26] investigated speech intelligibility in classrooms, examining the relation between signal-to-noise ratio and room acoustic parameters. The results from [26] show that the effect on signal-to-noise ratio is very important for speech intelligibility, and useful-to-detrimental ratios are proposed and recommended, instead of only focusing on the reverberation time. Further, they concluded that an increase in early reflections could improve signal-to-noise ratio by up to 9 dB [27].

The non-linear decay curve in a room with absorbent ceiling treatment also implies that there is a difference in the character of the sound field at steady-state and during the latter part of the decay. It is therefore also of interest to use the parameter sound strength G defined in ISO 3382-1. This parameter is measured during steady state, and relates to how sound reflections in a room contribute to the sound pressure level. Sound strength has mainly been used for concert halls and other performance spaces [28,29], but also for the evaluation of acoustical conditions in classrooms [15].

1.2. Room Acoustic Treatment in Classrooms

The most common acoustic treatment in ordinary public rooms is a sound absorbent ceiling and traditionally, as mentioned above, the required target values are defined by the reverberation time. When most of the absorption in ordinary rooms is predominately located at the ceiling, the scattering properties of furniture and other interior equipment will affect the acoustical conditions [30]. In fact, even the directional characteristics of sound scattering objects in a room with a suspended absorbent ceiling will be significant. If the sound scattering objects redirect the energy up onto the absorbent ceiling or in a direction towards other sound reflecting surfaces, such as walls, the outcome will be different. This circumstance also presents the possibility of using sound scattering objects in order to fine tune acoustical conditions. Diffusers have long been used and applied in concert halls and studios [31]. The purpose of diffusers is to avoid flutter echoes and to decrease the grazing sound field, but this type of treatment can also be used to direct the sound in preferable directions [32]. Absorbers reduce echoes but also decrease the sound energy levels, which can be negative in rooms such as classrooms.

The influence of the location of sound absorbing materials on room acoustical parameters has been studied by Cucharero et al. [32]. The effect on reverberation time, speech clarity and STI of sound absorbing material, and its placements in educational rooms, was calculated in a study by Berardi et al. [33]. Choi has studied the combination of diffusers and absorbers on a 1/10 scale, testing different placements of absorbers and diffusers [34,35]. Evaluating the room acoustic parameters of reverberation time, speech clarity and sound strength showed that a combination of those two different types of acoustic treatment was the most preferable when considering several acoustic parameters.

Another aspect of classroom acoustics is the absorption of low frequencies. Listening tests show preferences for configurations with good low frequency absorption, especially in cases where a high ratio of low frequency sound is emitted [36].

1.3. Study Objective and Principal Conclusion

The findings in the references cited above imply that the acoustic treatment in a room needs to deal with different acoustics parameters in order to achieve good acoustic quality, both for the speaker and listener. The objective of this study is to investigate the effect of different types of acoustic treatment on several room acoustic parameters. The investigation was made as a series of experiments in a mock-up of a classroom. Configurations with porous absorbers and diffusers both in the ceilings and on the walls have been evaluated. Combinations of resonant absorbers and diffusers were also tested, in order to further investigate the possibility of improving classroom acoustics. The effect on the room acoustic parameters T_{20}, C_{50} and G is evaluated.

2. Materials and Methods

2.1. Room Mock-Up

The experiments were conducted in a mock-up of a classroom with dimensions 7.32 m × 7.57 m × 3.5 m. The ceiling covers 7.2 m × 7.2 m and was installed at height 2.70 m. Dimensions and coordinate system are shown in Figure 1. The room has a concrete soffit, linoleum floor and gypsum walls. One of the walls represents a facade with three windows included. There are doors on the other walls, see Figure 2.

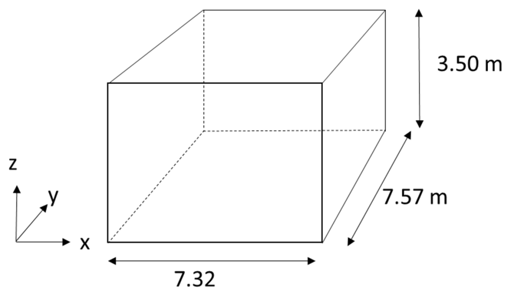


Figure 1. Dimensions of room used in the experiments. Coordinate system where x is the width, y is the length and z is the height of the room.

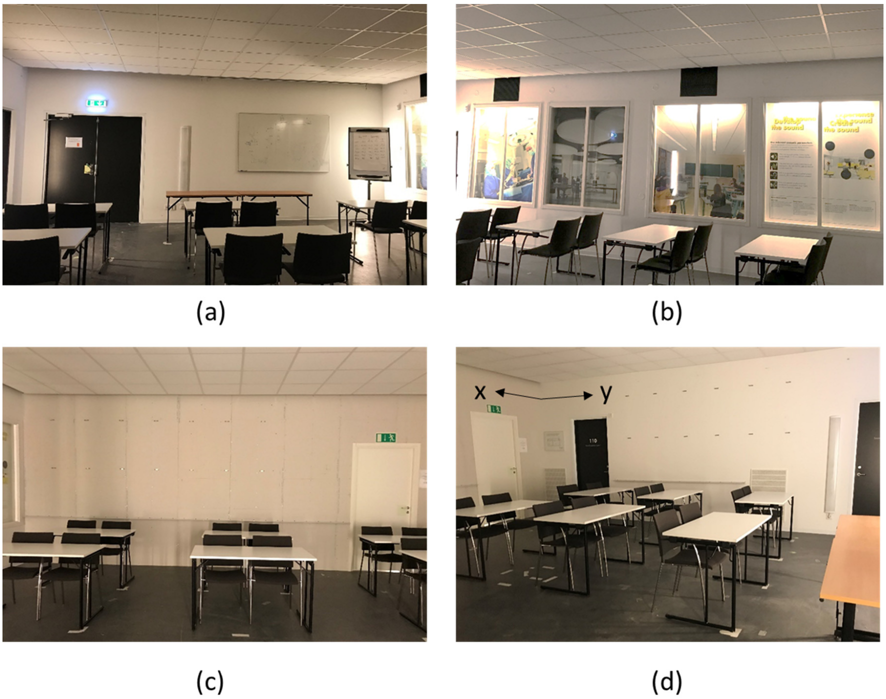


Figure 2. The classroom with furniture, (**a**) from the back, (**b**) from the corner, (**c**) from the front, (**d**) from the upper corner, including coordinates for the room.

The room of 55 m^2 was furnished with 11 tables and 18 slightly upholstered chairs, but no other furniture. The room was equipped with a whiteboard, a flip board screen and luminaires on the walls (see Figure 2).

2.2. Room Acoustic Parameters and Measurements

The room acoustic parameters evaluated are sound strength (G) Equation (1), speech clarity (C_{50}), Equation (2) and reverberation time (T_{20}). Measurements were performed using the DIRAC system (DIRAC type 7841, v.6.0). G was measured using a constant sound power source placed on the floor. An exponential sweep signal was used as excitation for evaluation of C_{50} and T_{20}. In the latter, an omnidirectional loudspeaker with dodecahedron geometry was used. The center of the loudspeaker was at 1.55 m from the floor. An omnidirectional microphone was used as a receiver at 1.20 m from the floor. Two source positions and six receiver positions have been used; for positions see Figure 3.

Sound strength G is defined as

$$G = \frac{\int_0^{\infty} h^2(t)dt}{\int_{0ms}^{t_{dir}} h_{10m}^2(t)dt} \tag{1}$$

Speech clarity C_{50} is defined as

$$C_{50} = \frac{\int_0^{50ms} h^2(t)dt}{\int_{50ms}^{\infty} h^2(t)dt} \tag{2}$$

where $h(t)$ is the impulse response; h_{10m} is the impulse response at 10 m in a free field.

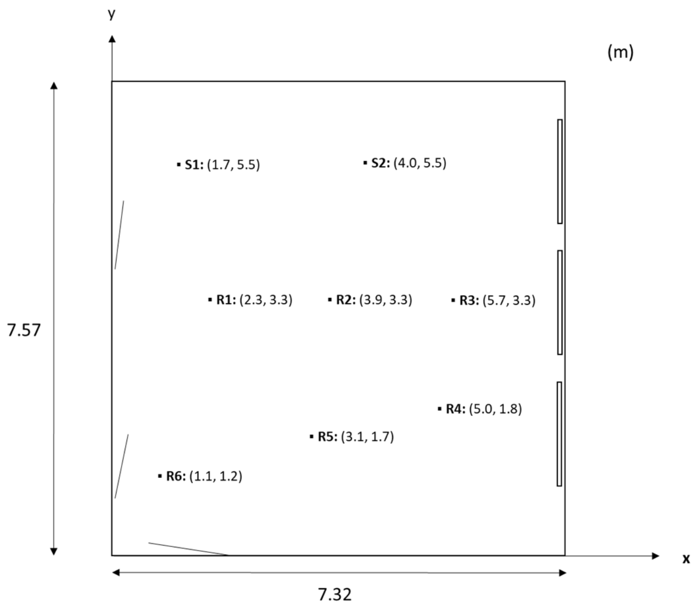


Figure 3. Room dimensions, source positions S1–S2 and receiver positions R1–R6.

In both speech clarity and sound strength, the early reflections are included. When evaluating $T_{20,}$ according to ISO 3382-2, the evaluation interval is −5 to −25 dB, given that the early reflections are excluded. The evaluation concerns octave bands in range 125–4000 Hz averaged over source and microphone positions.

The measurements were performed over the course of two days, with stable temperature and humidity conditions. It was secured that there was no influence of background noise in the measurements.

2.3. Repeatability Test of Measurement Method

A repeatability test for the measurement procedure used was performed. Impulse response measurements in the classroom mock-up, shown in Figure 2 were repeated five times. The room was furnished and had a suspended absorbent a ceiling. The practical absorption coefficients for the ceiling are shown in Figure 4. Between each measurement, the equipment i.e., the loudspeaker and the microphone, was taken out from the room and reinstalled at different positions. Further, the loudspeaker was rotated, as this too can influence the measurements [37]. The measurement was performed during the course of one day. Temperature and humidity were kept stable during the measurement procedures. However, with regards to the loudspeaker, it was always located at the front of the room in the vicinity of the teacher's desk. Two loudspeaker positions and six receiver positions for each loudspeaker position were used. Thus, a total of twelve observations were collected for each measurement. The loudspeaker and microphone were always at least one meter from the surrounding walls, and the receiver positions were no less than two meters from the loudspeaker.

The purpose of the repeatability test was to establish the variation in the *averaged* room acoustical parameters reverberation time T_{20}, speech clarity C_{50} and sound strength G, when averaged over the twelve combinations of loudspeaker and receiver positions. Knowing this variation gives an indication of the measurement procedure's influence when comparing different scenarios of acoustical treatment and the significance of the results. The spatial variation over positions, see Appendix A, are naturally much larger than the variation of the averaged values in the repeatability test. It can, however, be noted that the spatial variation in rooms with ceiling treatment probably differ from what is expected under diffuse field conditions [38].

The repeatability test was performed for the basic configuration, i.e., the classroom with the furniture and ceiling treatment in Figure 4. The results of the five measurements of T_{20}, C_{50} and G are presented in Table 1. The standard deviation for each pair of possible combinations, i.e., ten different combinations, from the five measurements was calculated and averaged. These results are also shown in Table 1 with the relative standard deviation is presented in the last column. Assuming normal distribution, an approximate uncertainty limit corresponding to a 95% confidence interval is presented in Table 2.

Table 1. Results of repeatability test of the measurement method used in the study. Average values over the five different measurements, columns 2–6, average for each octave, column 7 and relative standard deviation, column 8.

(a) Sound Strength G (dB)							
Test	1	2	3	4	5	$G_{,avg}$	$\sigma_{avg}/G_{,avg}$
125 Hz	21.4	21.6	21.9	21.5	20.5	21.4	0.45
250 Hz	20.8	20.7	21.3	20.8	20.8	20.9	0.16
500 Hz	19.8	19.8	19.5	19.6	20.2	19.8	0.09
1000 Hz	19.3	19.0	19.0	19.2	19.5	19.2	0.04
2000 Hz	18.0	17.8	18.4	18.6	18.4	18.2	0.07
4000 Hz	18.0	17.7	18.5	18.2	18.4	18.2	0.05
(b) Speech Clarity C50 (dB)							
Test	1	2	3	4	5	$C_{50.avg}$	$\sigma_{avg}/C_{50.avg}$
125 Hz	−0.7	−0.4	−0.8	−1.3	−1.7	−1.0	−0.02
250 Hz	1.3	1.1	1.2	1.5	1.7	1.4	0.01
500 Hz	3.0	3.4	3.1	2,7	3.5	3.1	0.01
1000 Hz	4.6	4.4	4.0	4.4	4.2	4.3	0.01
2000 Hz	3.7	3.7	3.9	4.6	3.8	3.9	0.02
4000 Hz	5.0	4.4	5.3	5.1	5.0	5.0	0.01
(c) Reverberation Time T20 (s)							
Test	1	2	3	4	5	$T_{20.avg}$	$\sigma_{avg}/T_{20.avg}$
125 Hz	1.50	1.43	1.44	1.40	1.56	1.47	0.038
250 Hz	1.45	1.43	1.47	1.44	1.45	1.45	0.009
500 Hz	0.81	0.81	0.82	0.82	0.83	0.82	0.009
1000 Hz	0.77	0.77	0.76	0.76	0.76	0.76	0.006
2000 Hz	0.91	0.89	0.89	0.91	0.90	0.90	0.008
4000 Hz	0.88	0.89	0.88	0.89	0.89	0.89	0.007

Table 2. Uncertainty interval related to repeatability, corresponding to a 95 % confidence interval, for the measurement procedure used in the experiments.

	G_{avg} (dB)	$C_{50,avg}$ (dB)	$T_{20,avg}$ (s)
125 Hz	±0.61	±0.56	±0.077
250 Hz	±0.30	±0.29	±0.018
500 Hz	±0.40	±0.29	±0.010
1000 Hz	±0.25	±0.27	±0.006
2000 Hz	±0.37	±0.38	±0.010
4000 Hz	±0.36	±0.36	±0.008

It is concluded that the variations in repeated measurements are less than just noticeable differences (JND), according to ISO 3382-1. This supports the discussion of significant differences in the measurements.

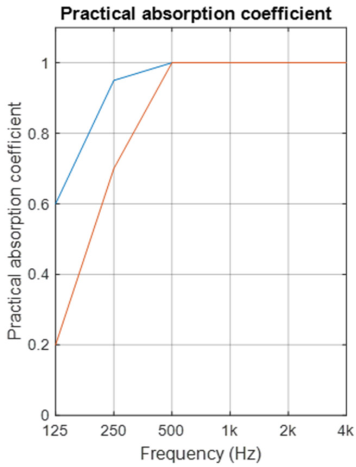


Figure 4. Absorption coefficient for a 40 mm glass wool product used as absorbing material in the experiments. Blue: Absorption coefficient for overall depth (ODS) 200. Red: ODS 50 mm.

2.4. Acoustic Treatment

2.4.1. Absorbing Material

The absorbing material used in the form of ceiling panels and wall panels is a glass wool product with a thickness of 40 mm and air flow resistivity of 40 kPa*s/m^2. The practical absorption coefficient, α_p, for the material according to ISO 11654 [39] can be seen in Figure 4 below. The absorption performance is shown for overall depth (ODS) 200 mm, according to specification in standard as well as for ODS of 50 mm, which represents the behavior of the material when mounted directly on the wall. This will be explained in a further section on configurations. The weighted absorption coefficient α_w is equal to 1 for both ODS set-ups.

For evaluation of the effect of low frequency absorption, experiments were carried out with added absorption on top of the suspended ceiling. The product used was a 50 mm glass wool product with air flow resistivity of 10 kPa*s/m^2 encapsulated in a plastic foil.

2.4.2. Diffusers

The diffusers used were made of a wood frame with a surface of a curved hardboard. All diffusers tested had the same geometry and dimensions 600 mm × 600 mm × 100 mm, see Figure 5. Air gaps on the sides in combination with the enclosed volume gives the diffuser a Helmholtz resonance in the frequency range of 125–250 Hz.

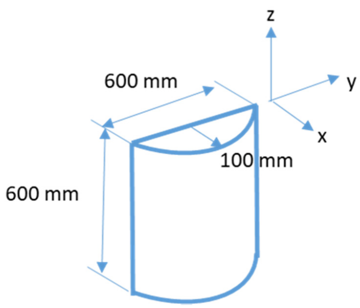
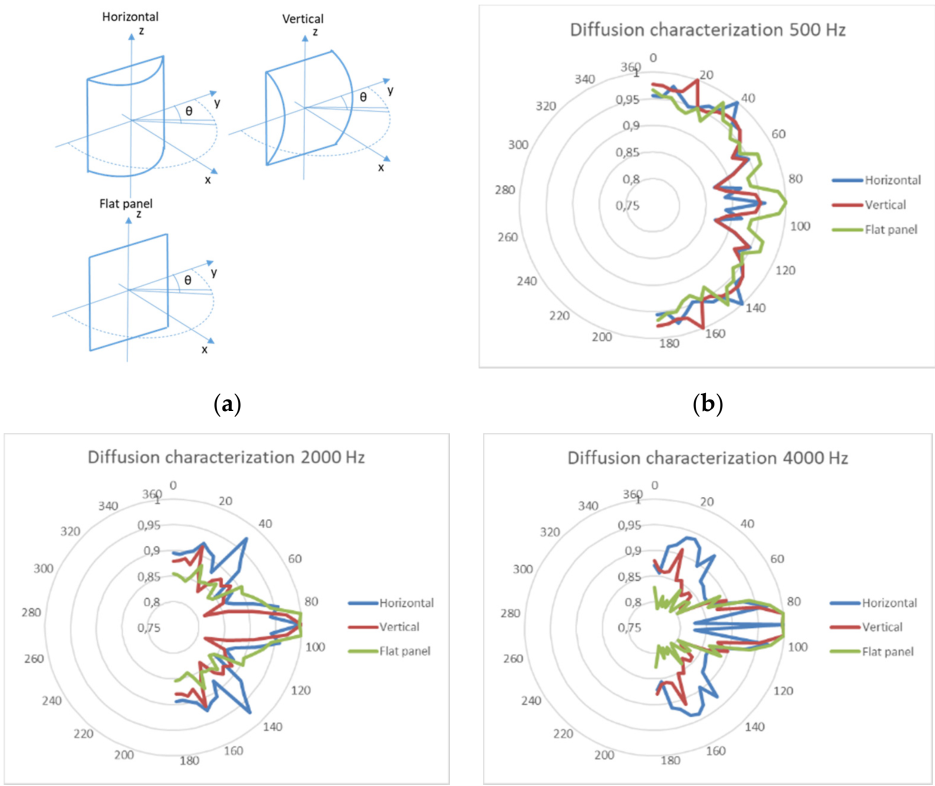


Figure 5. Sketch of diffuser used in the study, horizontally oriented.

Diffusion characteristics were measured in a semi-anechoic chamber. The energy in the reflections were estimated from impulse responses using windowing techniques, excluding the direct sound. The reflections were measured for azimuthal angles (θ) 0–90 degrees. Figure 6 presents the diffusion characteristics for 500, 2000 and 4000 Hz, and the assumption of symmetrical properties has been applied.



(**a**) (**b**) (**c**) (**d**)

Figure 6. Diffusion characteristics at (**b**) 500, (**c**) 2000 and (**d**) 4000 Hz. The upper left figure (**a**) shows the orientation of the diffusers relative room coordinates, see Figure 1.

The diffusers were tested in a vertical and a horizontal direction. In the vertical the majority of sound waves were directed in z-direction, Figure 7. while for horizontal is the majority of waves directed in x-y plane, Figure 8.

Figure 7. Vertically oriented diffusers, majority of reflections will be sent in z-direction.

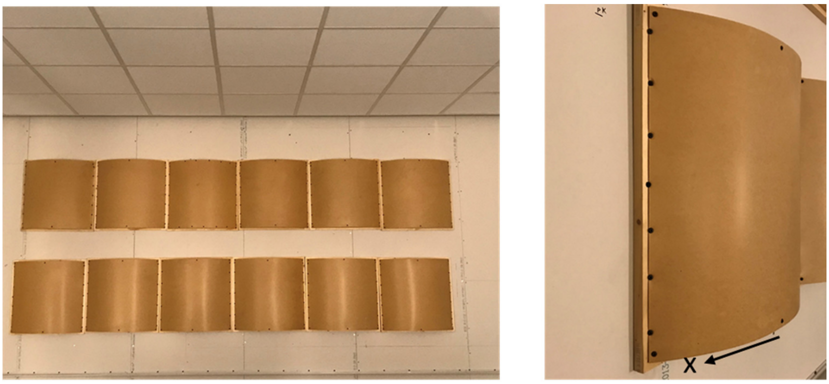


Figure 8. Horizontally oriented diffusers, majority of reflections will be sent in x-direction.

2.5. Configurations

For this experimental series, nine different configurations were tested, starting from the empty room. Thereafter, there was an absorbent ceiling, with properties according to Section 2.4.1. added and further was the room furnished. From this configuration was different type of wall treatment added, three different configurations: absorbing material, according to Section 2.4.1; vertically oriented diffusers, as in Figure 7; and horizontally oriented diffusers, as in Figure 8. Additional diffusers were installed in the ceiling. These diffusers were located in the front area of the room, i.e., in a typical speaker position. In the last configurations, low frequency absorption was investigated; Helmholtz resonance absorption by diffusers, compared to a porous absorber with properties for good absorption properties in this frequency range (see the last section of Section 2.4.1). All configurations are described in Table 3. For full abbreviations and definitions see Abbreviations.

Table 3. Configurations in the test series: Configuration number, definition with abbreviations and description of the configurations.

Configuration	Configuration Definition	Configuration Description
1	Empty	No acoustic treatment
2	51.8CA	51.8 m^2 absorptive ceiling
3	51.8CA_F	(2) + furniture
4	51.8CA_F_8.64WA	(3) + 8.6 m^2 wall absorbers
5	51.8CA_F_8.64VWD	(3) + 8.6 m^2 vertical wall diffusers
6	51.8CA_F_8.64HWD	(3) + 8.6 m^2 horizontal wall diffusers
7	47.5CA_4.3CD_F_ 8.6WA	47.5 m^2 absorptive ceiling, 4.3 m^2 ceiling diffusers, furniture and 8.6 m^2 wall absorbers
8	51.8CA_8.6VWD	(2) + 8.64 m^2 vertical wall diffusers
9	51.8CA_25.0LFMA	(2) + 25.0 m^2 low frequency absorptive mineral wool added in the ceiling

3. Results

The following section is divided into four different subsections, presenting the room acoustic parameters for different configurations. Section 3.1. represents the effect of traditional acoustic treatment and furniture. Section 3.2. includes the effect of acoustic treatment, absorbers and diffusers, on the walls, using the diffusers in different orientations. Section 3.3 describes how the diffusers were placed on the ceiling and Section 3.4. includes the effect of additional low frequency absorption. The results are presented in the form of diagrams, evaluated over octave frequency bands. All values for the room acoustic parameters with the corresponding standard deviation are presented in Appendix A.

3.1. Effect of Absorbent Ceiling and Furniture

The graphs presented in Figure 9 show the room acoustic parameters for a room without treatment (Empty), a room with absorbent ceiling (51.8CA) and a room with absorbent ceiling and furniture (51.8CA_F). For description of furnishing see Section 2.1. Room mock-up. Comparing the empty room with a configuration using acoustic ceiling shows a clear difference for all acoustic parameters over the entire frequency range, with the strongest change from 500 Hz and upwards, which can be correlated to the acoustic performance of the ceiling (see Figure 4). The sound strength in Figure 9a decreases by as much as 8 dB at these frequencies, and speech clarity, in Figure 9b, by 7 dB. The reverberation time, in Figure 9c, decreases to approximately half the value. The reason for the short reverberation times at low frequencies, in an already empty room, is due to the fact that the surrounding walls in the classroom were lightweight walls of plaster board.

Adding furniture contributes by scattering the sound and is effective from 500–2000 Hz, with the largest differences at 500–1000 Hz, resulting in an additional change in curve shapes for the room acoustic parameters. The sound strength value is mainly dependent on the absorption area, but a decrease of about 1 dB for the frequencies 500–4000 Hz can still be found for this parameter, due to scattering and minor absorption from the upholstered chairs. It should be noted that 1 dB is considered a just noticeable difference (JND) for sound strength, according to ISO 3382-1 [24]. The speech clarity and reverberation time is affected in a more limited frequency range, 500–1000 Hz, with significant differences. Regarding speech clarity, an increase of 3 dB is achieved at 500 Hz, and 2 dB at 1000 Hz. As for sound strength, 1 dB difference in speech clarity is considered to be JND, according to [24]. The reverberation time decreased by nearly half at 500 Hz, from 1.5 s to 0.8 s, with less reduction at 1000 Hz and 2000 Hz, although still a noticeable difference, a decrease of 0.6 s at 1000 Hz, and 0.3 s at 2000 Hz. JND for a reverberation time is a change of 5% [24].

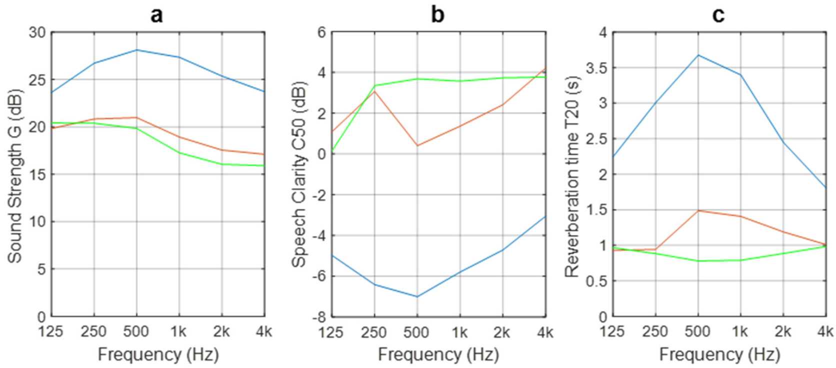


Figure 9. Room acoustic parameters, (**a**) sound strength (G), (**b**) speech clarity (C_{50}) and (**c**) reverberation time (T_{20}). In blue: room with no treatment (Empty). Red: room with absorbent ceiling (51.8CA). Green: room with absorbent ceiling and furniture (51.8CA_F). Installation of ceiling gives solid differences for the entire frequency range while furniture has highest efficiency at 500–2000 Hz. All parameters are affected by the furniture; thus, the greatest differences are seen for C_{50} and T_{20}.

Comparing the measured value to calculation with assumption of diffuse sound field using Sabine's formula shows substantially lower values for calculation over the entire frequency range compared to the measurement, see Figure 10. Note also that the shape of the two curves differs. The slight increase at higher frequencies in the measured curve often appears in sparsely furnished rooms, due to the lateral reflections from walls. The frequency-dependent effect of scattering is not included in the Sabine calculation, but appears as a valley in the measured curve. Measured absorption from furniture is taken into account in the calculation.

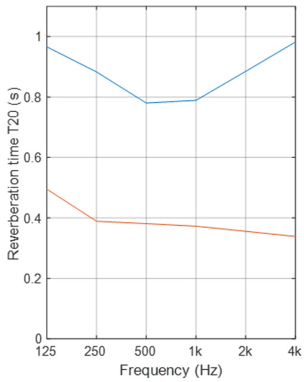


Figure 10. In blue measured and in red calculated reverberation time for the room with absorbent ceiling and furniture.

3.2. The Effect of Acoustic Treatments on the Walls

The following graphs in Figure 11. present the room acoustic parameters for configurations with acoustic treatment placed on the adjacent walls. Two walls are used, 4.3 m^2 is covered with the treatment on each wall for all three configurations presented in this section, i.e., coverage of 8.6 m^2 in total. The configurations are with wall absorption (51.8CA_F_8.6WA), vertically oriented wall diffusers (51.8CA_F_8.6VWD) and horizontally oriented wall diffusers (51.8CA_F_8.6HWD) (see Figures 7 and 8). For all configurations in this section, a full covering absorbent ceiling is installed and the room is sparsely furnished, as in configuration 51.8CA_F, which is also included in graphs below for comparison.

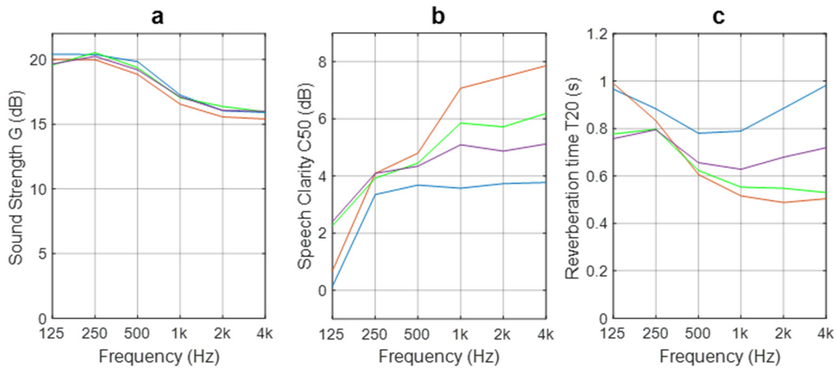


Figure 11. Room acoustic parameters, (**a**) sound strength (G), (**b**) speech clarity (C_{50}) and (**c**) reverberation time (T_{20}). Blue: base configuration with only ceiling treatment and furniture (51.8CA_F) to be compared with configurations having acoustic treatment on the walls. Red: porous absorbers (51.8CA_F_8.6WA). Green: vertically directed diffusers (51.8CA_F_8.6VWD). Violet: horizontally directed diffusers (51.8CA_F_8.6HWD). The different types of acoustic wall treatment cover the same area in all three cases. The strongest impact on G is achieved with wall absorbers. Diffusers also had a minor effect on this parameter, with similar values obtained independent of orientation. For C_{50} and T_{20}, the orientation of diffusers is critical, with a greater effect achieved by vertically directed diffusers.

The configuration with wall absorbers results in lower sound strength values in a frequency range of 250 Hz to 4000 Hz, both in comparison with diffuser configurations, as well as with configurations with no wall treatment; a decrease is seen for the entire frequency range in this comparison. The differences are small, but a clear trend is apparent (see the graph in Figure 11). Up to 0.8 dB, lower values are obtained for the configuration with absorbing wall treatment and the diffusing wall treatment within the frequency range of 250–4000 Hz. Thus, G is still lower for configurations with diffusers, compared to no wall treatment (51.8CA_F). Further, a similar G is obtained for configurations with diffuser treatment (51.8CA_F_8.6VWD) and (51.8CA_F_8.6HWD), i.e., the values for this parameter are independent of the direction of diffusers. Note also from this graph, that the lower values in G for configurations with diffusers is at a frequency of 125 Hz. This decrease is not correlated to scattering, but it is due to the resonance absorption for this frequency included in the design of the diffusers used in the study. This is shown further in Section 3.4.

Speech clarity increases for all configurations with any type of wall treatment. The largest increase is seen for configuration with wall absorbers (51.8CA_8.6WA) at a frequency of 500–4000 Hz. In comparison with diffusers, the change is largest at 4000 Hz, with a 1.7 dB and 2.8 dB difference for vertically oriented and horizontally oriented, respectively.

The two configurations with diffusers have similar C_{50} values in octave bands 125 Hz to 500 Hz, i.e., in the range where these diffusers are not designed to be effective. However, at 1000 Hz to 4000 Hz, clearly higher C_{50} values are obtained for the vertically oriented diffusers—about 0.8–1.0 dB higher, compared to horizontally oriented diffusers. This is a frequency range where the diffusers are effective, but the vertically oriented diffusers, to a greater degree, distract the lateral sound field and redirect the sound to the absorbent ceiling. The same behavior between the different configurations is seen for reverberation time. In addition to this, for the higher frequencies, similar results are achieved in T_{20} for configuration with vertical diffusers and wall absorbers. A change in the behavior is obtained for frequency 125 Hz for both C_{50} and T_{20} in configurations with diffusers. As for sound strength, this is due to resonance absorption in the diffusers.

3.3. Ceiling Diffusers

The following section presents the effect of diffusers installed in the ceiling. Six of the absorbent panels in the front of the room, typical speaker position, were replaced with diffusers, corresponding to 4.3 m^2, see Figure 12. The walls are covered with 8.6 m^2 of absorbers and the room is sparsely furnished (47.5CA_4.3CD_F_8.6WA).

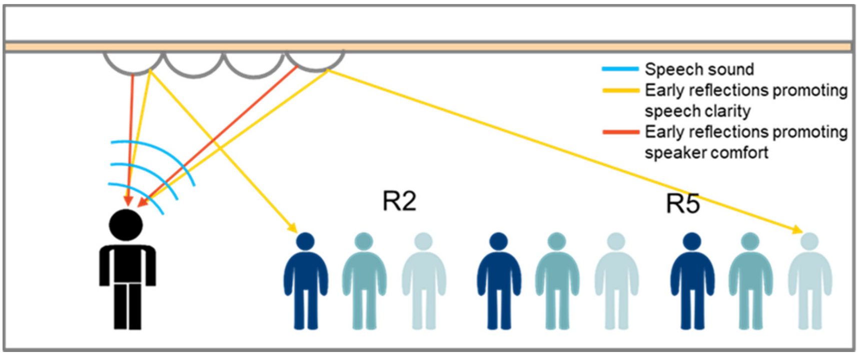


Figure 12. Location of ceiling diffusers above assumed speaker position. R2 corresponds to position for listener close to the speaker, R5 corresponds to listener in the rear area of the room.

The results for the average values over the twelve measurements show a general decrease in G and T_{20}, and an increase of C_{50}. The difference is small but a clear trend is obtained, see Figure 13. Ceiling diffuser configurations were also tested with no wall treatment or wall diffusers, with equivalent trends being obtained (for the results, see Appendix A).

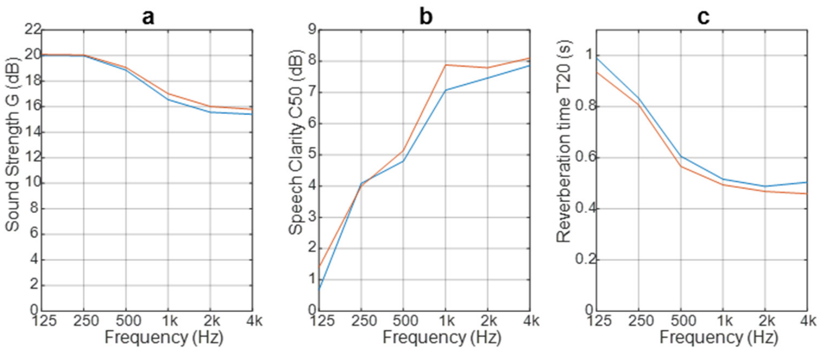


Figure 13. Global figures, averaged over all source and receiver positions. In (**a**) sound strength (G), (**b**) speech clarity (C_{50}) and (**c**) reverberation time (T_{20}). Blue: room with absorbent ceiling, furniture and wall absorbers (51.8CA_F_8.6WA). Red: room with partly absorbent ceiling, partly ceiling diffusers, furniture and wall absorbers (47.5CA_4.3CD_F_8.6WA). Configuration with ceiling diffusers gives lower value in G, with a clear trend apparent even if the difference is small. In terms of C_{50} ceiling diffusers give an increase from frequency 500 Hz and upwards, with the greatest difference being 0.8 dB, at 1000 Hz. The reverberation time decreased in configuration with ceiling diffusers over the entire frequency range, with the change being small but the trend clear.

The effect of ceiling diffusers was further evaluated for different positions in the room by comparing the room acoustic parameters for receiver positions R2 and R5, source position S2. Positions are described in Figure 3 and further visualized in Figure 12.

Sound strength decreases with distance from the source, but a comparison to 51.8CA_F_8.6WA show higher values for configuration with ceiling diffusers 47.5CA_4.3CD_F_8.6WA. In addition to the increased energy level, a significant increase is obtained for C_{50}. In R5, i.e., in the back of the room, a difference can be seen for the entire frequency range, with strongest effect at 1000–4000 Hz, an increase of 1.5–3.2 dB. The reverberation time is also affected, mainly in the higher frequency range. Results are shown in Figures 14 and 15.

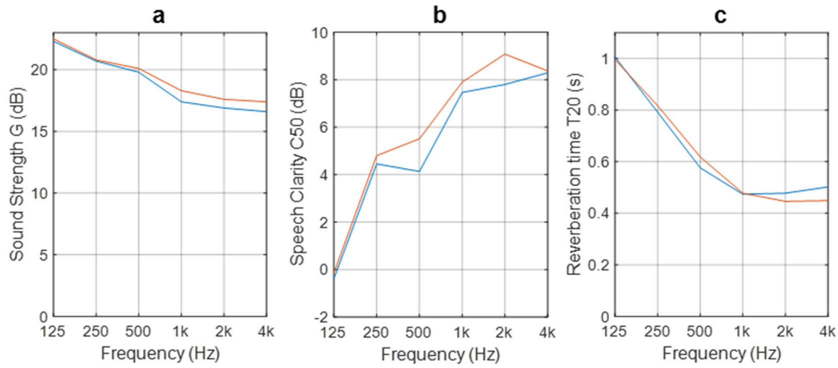


Figure 14. In (**a**) sound strength (G), (**b**) speech clarity (C_{50}) and (**c**) reverberation time (T_{20}) in position R2. Blue: without ceiling diffusers (51.8CA_F_8.6WA). Red: with ceiling diffusers (47.5CA_4.3CD_F_8.6WA). Small increases in G and C_{50} are achieved in configurations with diffusers in combinations with slightly lower T_{20}.

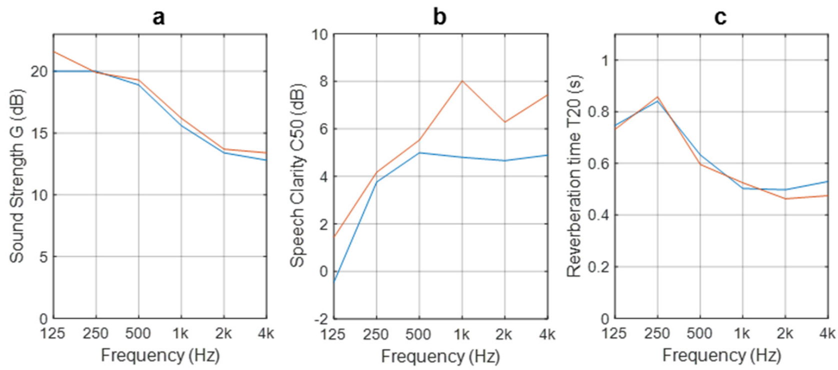


Figure 15. In (**a**) sound strength (G), (**b**) speech clarity (C_{50}) and (**c**) reverberation time (T_{20}) in position R5, back of the room. Blue: without ceiling diffusers (51.8CA_F_8.6WA). Red: with ceiling diffusers (47.5CA_4.3CD_F_8.6WA). A small increase is seen for G. A significant increase in C_{50} is achieved with slightly lower T_{20}. The strongest improvements are seen in position R5 and in the frequency range of 1000–4000 Hz.

3.4. Combining Diffusers with Helmholtz Absorption

One way to obtain good absorption in a certain frequency is to use resonance absorbers. The diffusers used in this study were designed to operate as Helmholtz resonator at frequencies 125–250 Hz. The result of its effect in configuration 51.8CA_F_8.6VWD is compared with configuration with a porous low frequency absorber, configuration 51.8CA_25.0LFMA, described in Section 2.4.1. Evaluation of reverberation time shows a clear effect for both configurations at low frequencies. It could be noted that 8.6 m^2 diffusers were used while the area of porous low frequency absorber was

25 m^2. Additionally, the diffusers affect the higher frequency range to a greater extent. The results are presented in Figure 16.

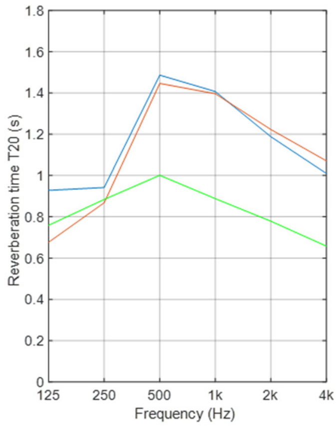


Figure 16. Reverberation time (T_{20}), in blue only absorbent ceiling (51.8CA), in green vertical wall diffusers (51.8CA_8.6VWD) and in red low frequency porous absorber (51.8CA_25.0LFMA). The two latter configurations affect the lower frequencies significantly; thus, the areas used for the different low frequency treatments are different. In addition, the diffusers affect the higher frequency range to a greater extent.

4. Discussion

Installing the fully covering absorbent ceiling in the empty room, as a first step, affected all the room acoustic parameters. This treatment can be seen as a good baseline for a classroom, since it significantly decreases the sound strength and reverberation time, and increases the speech clarity. The addition of furniture also affected the results, mainly due to increased scattering, as only a small amount of absorption is involved. The furniture affects the parameters particularly at frequencies of 500–1000 Hz. This configuration, an absorbent ceiling and a sparsely furnished room, could be seen as a normal classroom situation. It is important to note the difference in result between measurement and calculated T_{20} by using diffuse sound field theory for this configuration. The much lower values achieved in calculation demonstrate that the lateral sound field must be considered in acoustic models dealing with ordinary, furnished rooms.

The additional acoustic treatment in different configurations using absorbers and diffusers contributed important effects for fine-tuning the acoustics. The general finding was that higher sound energy levels were obtained for configurations with diffusers, and lower energy levels for configurations with absorbers. Both types of treatment affected speech clarity and reverberation time.

With the diffusers, the energy is conserved, compared to the absorbers where the energy is reduced, explaining why both horizontally oriented and vertically oriented diffusers have similar values in terms of sound strength. A reason for the effect on speech clarity and reverberation time is the scattering of the diffusers. Significant differences are found between the vertically and horizontally directing diffusers, where the vertical affected C_{50} and T_{20} to a greater extent. The vertically oriented diffusers reduced the sound waves in the horizontal plane and directed the sound into the ceiling, showing the importance of directional scattering in rooms with ceiling treatment, which correlates well to the diffusion characteristics of the diffusing elements.

In the experiments using diffusers in the ceiling, important improvements for receivers located outside the direct sound field could be achieved. Keeping the sound energy level, a significant increase in speech clarity was found for the receiver at the back. This is an important application for use in classrooms where a teacher gives instructions at the front of the room. An interesting finding with all the ceiling diffuser configurations was that a decrease in T_{20} was obtained while G increased, and this finding also applied when evaluating the results on an average basis for the twelve different measurements. This raises, again, the question of the importance of considering the effect of scattering.

It should be observed that C_{50} only gives information about the early-to-late ratio of the reflections, and does not explain anything about the sound energy. This means that high C_{50} can be achieved without guaranteeing sound energy will be sufficiently high for the listener, or supporting the speaker. A case with high C_{50} and low sound energy can result in:

(1) Too low a sound level reaching listeners in the rear area of the classroom;
(2) Greater voice effort for the speaker.

In the configurations with diffusers, an increase in C_{50} could retain the sound strength, i.e., the sound energy.

In choosing the acoustic treatment, it is important to consider the type of room acoustic properties required for the specific room. With diffusers, reverberation time can be lowered and the ratio of early reflections increase with sound energy conserved. Thus, for environments where complex tasks requiring concentration are performed or in a very noisy environment, sound energy reducing treatment should be used. It is thus of importance to define the activity taking place in the room when choosing the acoustic treatment.

In the discussion of acoustic design, it is important to note that the diffusers used in this study were designed to operate as scattering objects for the higher frequency range, which is important for speech, and for absorption at low frequencies. It is possible to design the diffusers to operate at the requested frequencies.

It has been mentioned above that only small effects were seen for some configurations. It should be noted that only a small part of the wall area was covered, for example, the ceiling diffusers covered 8% of the ceiling area. An increased area of acoustic treatment would, to a certain degree, affect the values further. However, realistic conditions must be considered, e.g., a real classroom can have more furniture affecting the scattering properties. Other factors that can influence the perception of the acoustics, not studied in this investigation, are background noise, the people and their activities.

An observation from the results is the importance of using several room acoustic parameters to characterize a specific acoustic environment (see e.g., Figure 15). For example, T_{20} and C_{50} can be varied with diffusers, but still maintain the sound strength. However, using absorbers, the sound strength can be varied as well. The outcome of these two scenarios will be different experienced, and needs to be considered to obtain the correct acoustic balance for low and high frequencies in ordinary public rooms.

5. Conclusions

A clear trend in how different types of acoustic treatment affect room acoustic parameters has been demonstrated where, as a baseline, an acoustic ceiling should be used to decrease the energy level, increase the ratio of early-to-late reflections and lower the reverberation time. However, in a sparsely furnished room, it can still be difficult to achieve a high-quality sound environment with only an absorbent ceiling. The room acoustic parameters can be fine-tuned by using diffusers and absorbers on the walls and/or in the ceiling. The two different types of treatment operate differently and create distinctive experiences for the people in the room. With additional porous absorbers, G and T_{20} are decreased and C_{50} is increased, while diffusers affect C_{50} and T_{20}, keeping G stable or increased, depending on placement and amount.

The diffusers used in this study where efficient in absorbing sound at the frequency of 125–250 Hz, but the frequency range within which it operates as a resonant absorber can easily be adopted. Additionally, the frequency ranges for which it operated most efficiently as a scattering object can be adjusted, depending on the demands.

This study provides information on how different acoustic treatments can be used to obtain different room acoustic qualities, and can be used to improve the sound environment in ordinary public rooms. However, the target values of the room acoustic parameters must be defined for the specific environment and activity, in order to use this information for correct the fine-tuning of acoustic environments.

6. Patents

Patent pending, European Patent Office, 20170667.8.

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Abbreviations

Acoustic Configurations

CA	Ceiling absorptive
CD	Ceiling diffuser
F	Furniture, the room is sparsely furnished
WA	Wall absorbers
VWD	Vertical wall diffusers
HWD	Horizontal wall diffusers
LFMA	Low frequency mineral wool absorber

Appendix A

Table A1. Number together with any of above written abbreviations describes the m^2 of the specified acoustic treatment.

Acoustic Parameters	
G	Sound Strength
C_{50}	Speech Clarity
T_{20}	Reverberation time, evaluated over 20 dB decrease

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The Difference in Subjective Experience Related to Acoustic Treatments in an Ordinary Public Room: A Case Study

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Abstract: In ordinary public rooms absorbent ceilings are normally used. However, reflective material such as diffusers can also be useful to improve the acoustic performance for this type of environment. In this study, different combinations of absorbers and diffusers have been used. The study investigates whether a test group of 29 people perceived sound in an ordinary room differently depending on the type of treatment. Comparisons of the same position in a room for different configurations as well as different positions within one configuration were made. The subjective judgements were compared to the room acoustic measures T_{20}, C_{50} and G and the difference in the values of these parameters. It was found that when evaluating the different positions in a room, the configuration including diffusers was perceived to a greater extent as being similar in the different positions in the room when compared to the configuration with absorbers on the walls. It was also seen that C_{50} was the parameter that mainly affected the perception, with the difference needing to be 2 dB to recognize a difference. However, the room acoustic measurements could not fully explain the differences obtained in perception. In addition, the subjective sound image created by different types of treatments was also shown to have an important impact on the perception.

Keywords: acoustic perception; subjective acoustics; speech clarity; sound strength; reverberation time; room acoustic design

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1. Introduction

1.1. Room Acoustics in Ordinary Rooms

In ordinary public rooms—such as classrooms—there is often sound absorbing material chosen as the only acoustic treatment. A high degree of absorbent material, normally used in order to lower the reverberation time, can risk attaining a too low speech level. In the acoustic design of performance spaces, the sound strength is normally controlled [1–3]. The sound strength describes how the room responds to the sound source and is described in the ISO standard 3382-1 for performance spaces [4].

In a room for speech, such as a classroom, is it important that the sound energy level is sufficiently high to ensure that everyone in the audience receives the information being transmitted [5]. It is also important that the speaker can be provided with vocal support. Teachers report voice problems to a greater extent than the rest of the population [6]. A parameter room gain, G_{RG}, has been developed in order to evaluate speaker comfort [7–9].

Another important parameter to consider in rooms for speech is the speech clarity, C_{50}, accounting for the ratio of early reflections. The quality of the speech will be dependent on the reflection pattern and the early reflections will contribute to the direct sound [10]. In a study by Bradley et al. [11] the recommendation for rooms for speech was to focus rather on increasing the early reflections than on lowering the reverberation times. Furthermore, it was found by Bradley and Reich that C_{50} can to some extent complement a low S/N [12].

As mentioned above, too large quantity of absorbers can cause an excessively low sound energy level, providing the speaker with less support and the listener with less information. It has been shown in model scale [13,14] and further in full scale mock-up [15], that a combination of absorbers and diffusers can be used in order to fine-tune different room acoustic parameters. The diffusers can be used to affect the reflection path without decreasing the energy level. The importance of using both absorption and diffusion or scattering has also been recognized in standards [16,17].

In a study by Azad et al. [18] it was tested how room acoustic parameters were affected if the diffusing element directs the sound toward an absorptive area in a non-diffuse room. It was found that the placement of absorptive material is an important factor to consider [19,20]. However, in a study by Shtrepi et al. [21] the location of a diffusive element varied and showed no significant changes in objective room acoustic measurements. Further, it was found in a previous study in this research program [15] that more uniform acoustic properties were obtained using a combination of absorbers and diffusers compared to when only absorptive material was used.

1.2. Room Acoustics and Subjective Experience

It is necessary to understand how different room acoustic properties affect people in order to be able to correctly design acoustic environments. Acoustic properties may differ in different positions in a room, which must also be considered. In terms of diffusing elements, Visentin et al. investigated whether there is a difference in perception for surface responding with diffuse or specular reflections, finding that better speech intelligibility was obtained with a diffuser [22]. In a study by Shtrepi et al. [21] no sensitivity between listening positions could be found with different locations of a diffuse element. However, differences in terms of reverberance, coloration and spaciousness were reported. In another study by Shtrepi et al. [23], it was found that the distance from the diffuser surface did have an effect; a distance of 2.15 m was found to be the threshold for when the listener will no longer perceive the diffusing effect, with the distance depending on the distance to the source position.

Visentin et al. raised the question as to how listening effort could be part of the acoustic design in rooms for speech [24]. In that study it was found how the listening effort differed when room acoustic properties were changed in an Italian university classroom. The question of whether a diffuser and an absorber cause different subjective experience in a conference room was investigated in a study by Sanavi et al. [25] and showed that addition of each of these treatments improved the acoustic experience; however, the absorber was rated better in this study. The room acoustic properties seem to be even more sensitive for non-native listeners; the score can still be good, but rating of effort is higher [26].

Several studies have shown how acoustic properties affect cognitive skills. It is well known that noise disturbs concentration, but cognitive performance is also affected by the sound environment [27–29]. An important finding from these studies is that a more distracting sound environment does not necessarily cause more errors, but greater effort is needed in order to perform the task. The ability to remember and process information is more sensitive than the perception of single words [30]. In specific relation to early reflections, Puglisi et al. examined the effect on the reading ability of Italian second graders, finding that the early reflection ratio could be correlated to reading tasks [31]. The acoustic environment can also be related to well-being [32].

In ISO 3382-1 for performance spaces, the just noticeable differences for different room acoustical parameters are described. It has been found that the just noticeable difference (JND), i.e., the difference needed to experience a difference of the sound, differs for different frequencies and types of music [33]. Further, it is important to consider the values in different positions and not only on an average level. Regarding the importance of good speech clarity, Bradley and Reich investigated [34] the JND for C_{50} in rooms for speech, finding that 3 dB is more relevant for these types of rooms than the 1 dB value stated in the standard 3382-1 for performance spaces. However, JND for speech and in ordinary room is not fully understood.

1.3. Study Objective and Principal Conclusion

In a previous stage of this research [15] it was investigated how different acoustic treatments, affect room acoustic parameters in a classroom. It was concluded from the study that different type of treatments can be used to fine tune different room acoustic parameters, depending on the need. This has been followed up by investigating if people subjectively can experience a difference of a speech, which is presented in this paper. The aim of the study is to investigate whether people can perceive a difference in relation to different positions and different configurations. Furthermore, to investigate if the participant's subjective experiences can be related to the differences in the room acoustic parameters T_{20}, C_{50} and G. To find the preferred solution is not within the scope of this investigation.

A mock-up of a classroom in a laboratory environment was used. In total, five different acoustic treatment configurations were evaluated. All of these have an absorptive ceiling and are sparsely furnished. Variations comprise different acoustic treatment on walls, sound absorbing tiles and diffusing elements, differently oriented. In one configuration, the absorbing ceiling tiles in the area over the source, i.e., speaker, position were replaced with diffusers. Absorbing tiles were applied on the walls in this configuration.

The perception results were compared to room acoustic parameters in order to evaluate whether differences in perception were related to room acoustic parameters or whether the sound image perceived should be related to other descriptors or attributes. It was found that the sound was perceived most similar in configurations with diffusers compared to configuration with only absorbers. To obtain differences in perception, changes mainly in C_{50} were needed. This study does show that the difference should be 2 dB in C_{50} for a significant difference in perception.

2. Materials and Methods

Experiments were performed in a mock–up area in a laboratory environment with dimensions 7.32 m × 7.57 m × 3.50 m. The area was furnished to simulate a typical classroom. Room acoustic measurements were performed in this environment as well as recordings for the listening test. The listening test was made in another, neutral room. In the following section, the acoustic materials used in the study are presented, as well as how these materials are combined in different configurations. This is followed by descriptions of the room acoustic measurements as well as the listening test procedure.

2.1. Acoustic Treatment

2.1.1. Porous Absorber

The absorbing material used in the ceiling panels and wall panels is a glass wool product with a thickness of 40 mm and air flow resistivity of 40 kPas/m^2. The material's practical absorption coefficient, α_p, measured according to ISO 354 [35] and evaluated according to ISO 11654 [36] can be seen in Figure 1. The absorption performance is shown for the overall depth (ODS) of 200 mm, according to specification in standard, as well as for ODS of 50 mm, which represents the behavior of the material when mounted directly on the wall, which is done for Conf 2 and 5 in this investigation, described in Section 2.3 below. The weighted absorption coefficient α_w is equal to 1 for the two different ODS, evaluated in accordance with ISO 11654 [36].

2.1.2. Diffusers

The diffusers used were made from a wood frame with a surface of curved hardboard. All diffusers tested had the same geometry and dimensions: 600 mm × 600 mm × 100 mm, see Figure 2. Air gaps at the sides in combination with the enclosed volume give the diffuser resonance absorption properties in the frequency range 125–250 Hz.

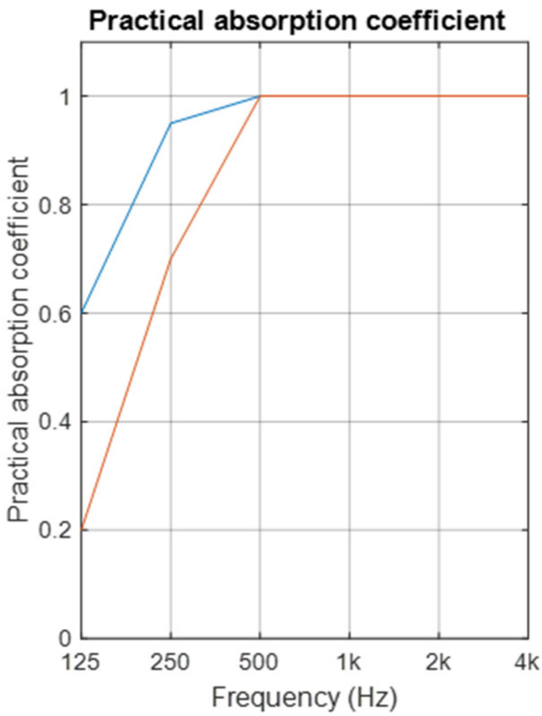

Figure 1. Absorption coefficient for a 40 mm glass wool product used as absorbing material in the experiments. Blue: ODS 200 mm. Red: ODS 50 mm.

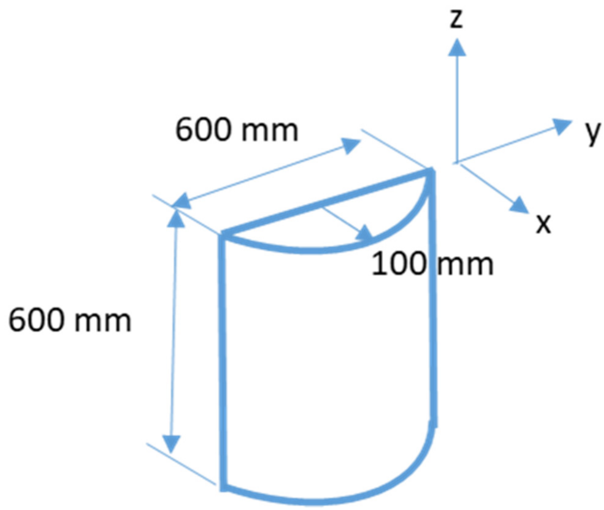

Figure 2. Sketch of diffuser used in the study, horizontally oriented.

Diffusion characteristics were measured in a semi-anechoic chamber. The energy in the reflections was estimated from impulse responses using windowing techniques, excluding the direct sound. The reflections were measured for azimuthal angles (θ) 0–90 degrees. Figure 3 presents the diffusion characteristics for 500, 2000 and 4000 Hz; assumption of the symmetrical properties has been applied.

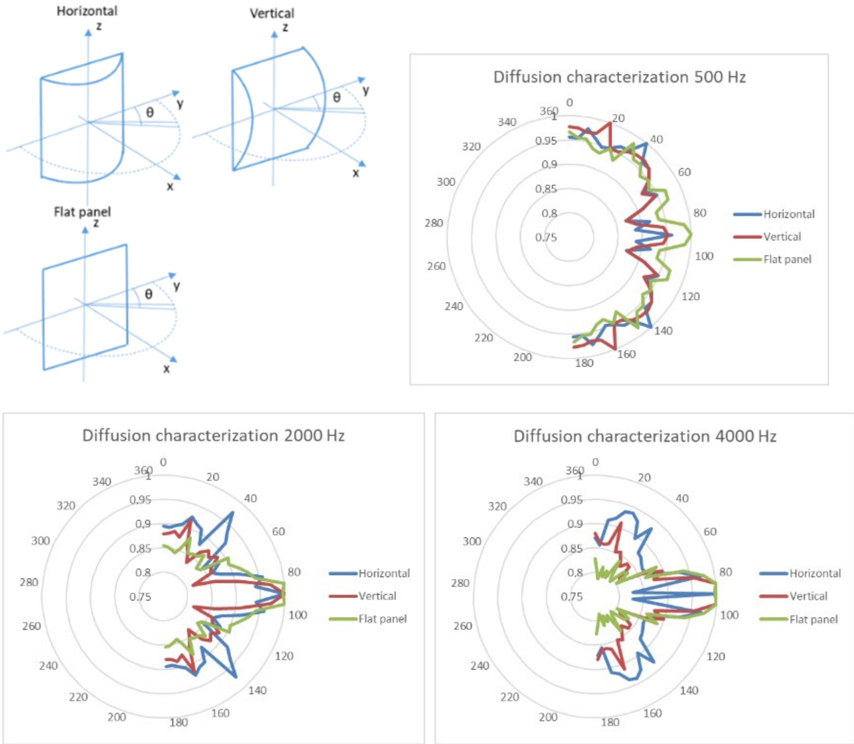

Figure 3. Diffusion characteristics at 500, 2000 and 4000 Hz. Upper left figure shows the orientation of the diffusers relative room coordinates, also visualized in Figures 4 and 5 below.

Figure 4. Vertically oriented diffusers; most of reflections will be sent in z-direction.

The diffusers were tested in a vertical and a horizontal orientation. In the vertical position, most sound waves were directed in the z-direction, Figure 4, while for horizontal, most waves were directed in the x-y plane, see Figure 5.

2.2. Mock-Up and Configurations

The environment where the measurements and recordings were evaluated is a mock-up of a classroom in a laboratory setting. The dimensions of the room were 7.32 m × 7.57 m × 3.50 m, see Figure 6.

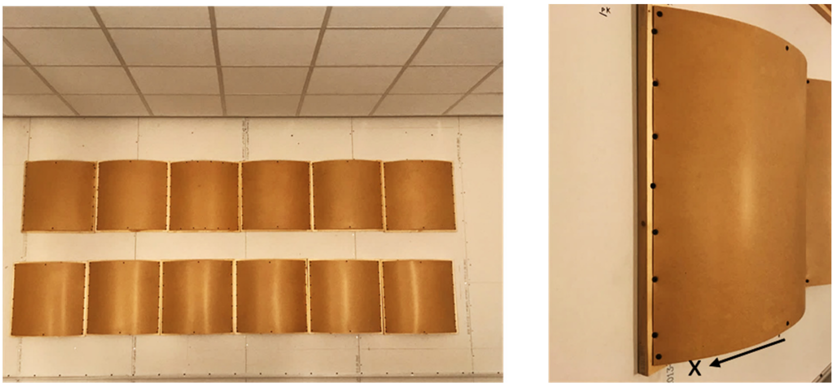

Figure 5. Horizontally oriented diffusers; most of reflections will be sent in x-direction.

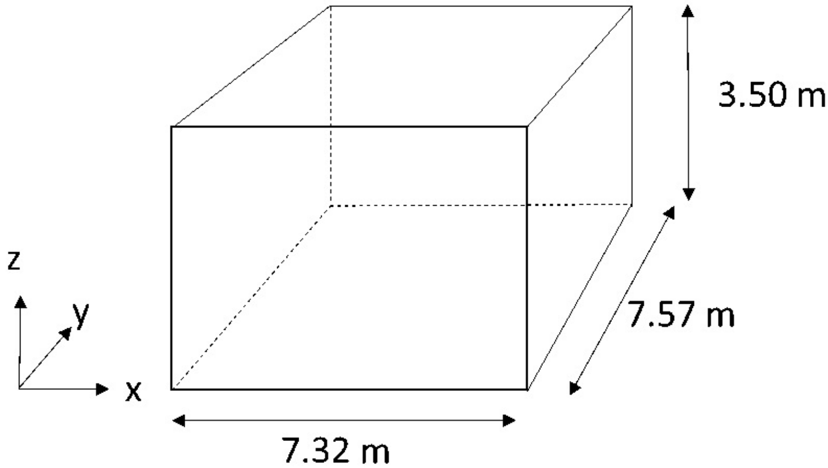

Figure 6. The dimensions of the room used in the experiments: coordinate system where x is the width, y is the length and z is the height of the room.

Five different configurations were evaluated. As a baseline, an absorptive ceiling was installed. All configurations were sparsely furnished, with 11 tables and 18 slightly upholstered chairs being used. The room was equipped with a whiteboard, a flipboard and luminaires on the walls, see Figure 7.

The first configuration had only the acoustic ceiling, covering 52 m^2, as acoustic treatment. For the second configuration, absorptive tiles were added on two walls, with a total of 9 m^2 being covered. In the third and fourth configurations, diffusing elements were used on the walls, vertically and horizontally oriented, respectively. The same placement and coverage areas were used as for the absorptive tiles. The last, fifth, configuration was based on configuration two but with 12 absorbing ceiling tiles replaced by 12 diffusing elements in the source area, i.e., the speaking area, which was covering 4 m^2. Abbreviations has been used to describe the configurations, see Table 1. Full description of configurations, see Table 2. Pictures of the configurations are found in Figure 7 for Conf 1, and in Figure 8 for Conf 2–5.

2.3. Room Acoustic Parameters and Measurements

The room acoustic parameters evaluated are Sound Strength (G) Equation (1), Speech Clarity (C_{50}), Equation (2) and Reverberation Time (T_{20}). Measurements were performed using the DIRAC system (DIRAC type 7841, Ver.6.0). G was measured using a constant sound power source placed on the floor. An exponential sweep signal was used as excitation for evaluation of C_{50} and T_{20}. In the latter, an omnidirectional loudspeaker with dodecahedron geometry was used. The center of the loudspeaker was at 1.55 m from the floor. An omnidirectional microphone was used as a receiver at 1.20 m from the floor. Two source positions and seven receiver positions were used; for positions see Figure 9.

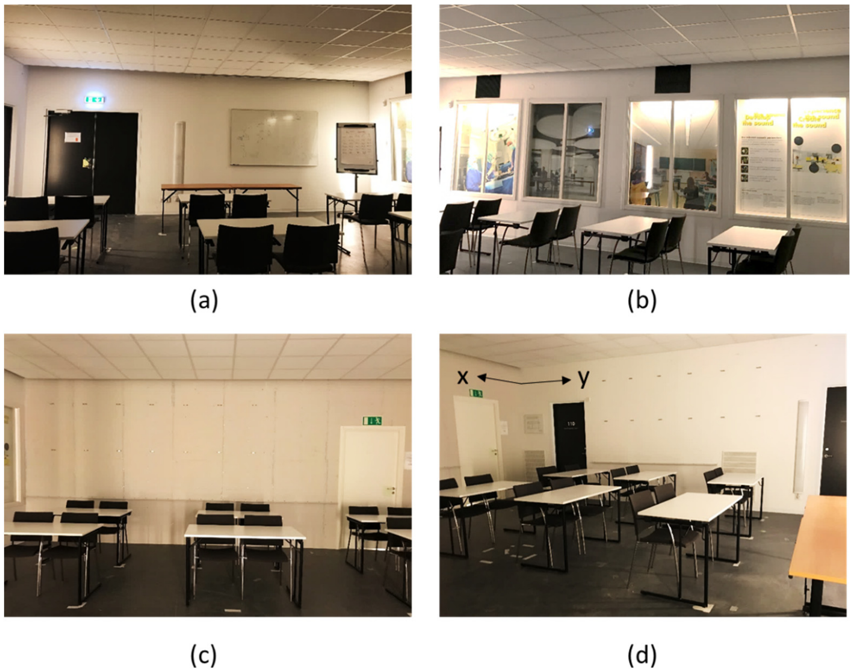

Figure 7. The classroom with furniture: (**a**) from the back, (**b**) from the corner, (**c**) from the front, (**d**) from the upper corner, including coordinates for the room.

Table 1. Abbreviations used to describe the configurations.

Abbreviation	Description	Comments
CA WA VWD HWD	Ceiling absorptive Wall absorption Vertically oriented wall diffusor Horizontally oriented wall diffusor	XX before any abbreviation describes the m^2 used for the material, e.g., 52 CA stands for 52 m^2 absorptive ceiling
F	Furniture	Sparsely furnished

Table 2. Description of the configurations used in the test.

Configuration		Ceiling	Wall Treatment	Furnished
No	Abbreviation			
1	52CA_F	52 m^2 absorptive	-	Sparsely
2	52CA_9WA_F	52 m^2 absorptive	9 m^2 absorptive tiles distributed on two walls	Sparsely
3	52CA_9VWD_F	52 m^2 absorptive	9 m^2 vertically oriented diffusers distributed on two walls	Sparsely
4	52CA_9HWD_F	52 m^2 absorptive	9 m^2 horizontally oriented diffusers distributed on two walls	Sparsely
5	48CA_4CD_9WA_F	48 m^2 absorptive ceiling, 4 m^2 diffusing elements	9 m^2 absorptive tiles distributed on two walls	Sparsely

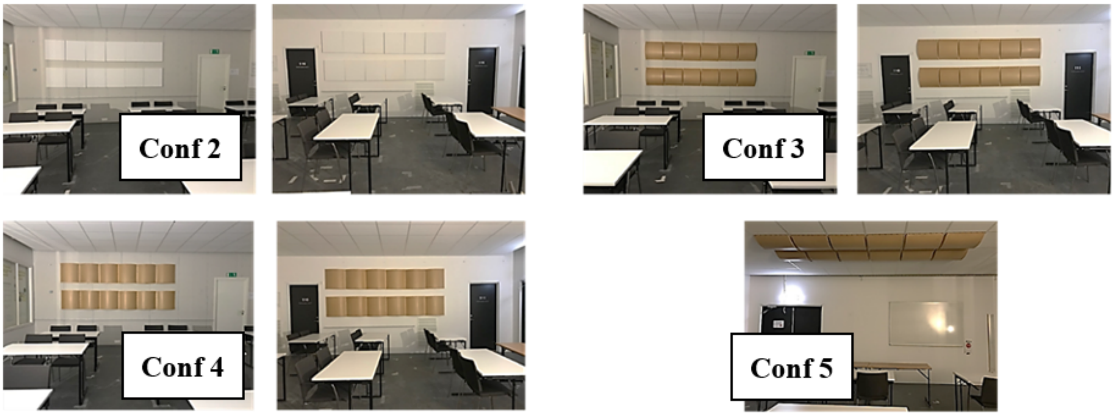

Figure 8. Pictures of configurations. **Upper left corner**: Conf 2 with absorbing tiles on the walls; **Upper right corner:** Conf 3, vertically oriented diffusers on the walls; **Lower left corner:** Conf 4, horizontally oriented diffusers on the walls; **Lower right corner:** Conf 5, ceiling diffusers, absorbing tiles on the walls as in Conf 2 (upper left corner in this figure).

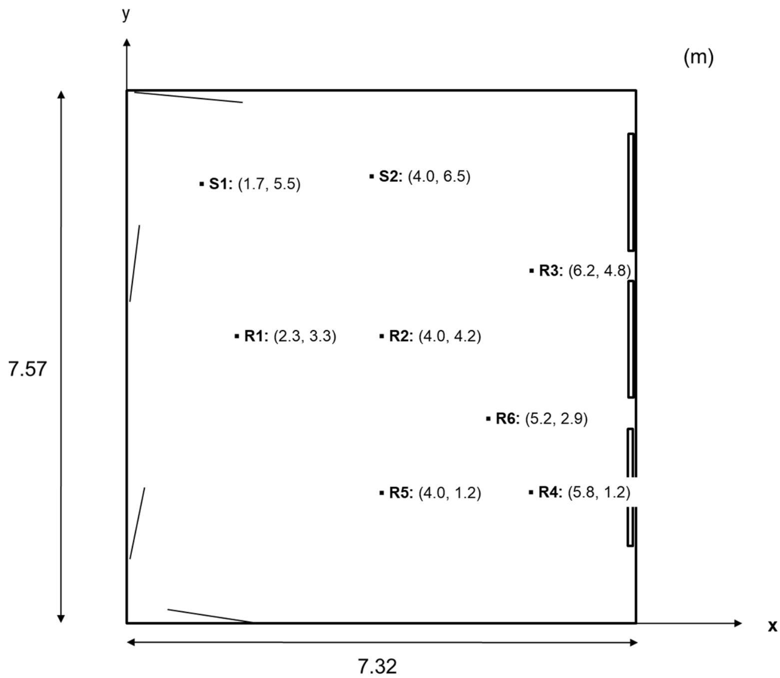

Figure 9. Room dimensions, source positions S1 and S2 and receiver positions R1–R6.

Sound strength G is defined as

$$G = 10lg\frac{\int_0^\infty h^2(t)dt}{\int_{0ms}^{t_{dir}} h_{10m}^2(t)dt}\,dB \tag{1}$$

Speech clarity C_{50} is defined as

$$C_{50} = 10lg\frac{\int_0^{50ms} h^2(t)dt}{\int_{50ms}^{\infty} h^2(t)dt}\,dB \tag{2}$$

where,

$h(t)$ is the impulse response.
h_{10m} is the impulse response at 10 m in a free field.

For both speech clarity and sound strength, the early reflections are included. When evaluating $T_{20,}$ according to ISO 3382-2, the evaluation interval is −5 dB to −25 dB, given that the early reflections are excluded.

The measurements were performed during the course of one day with stable temperature and humidity conditions. The background noise level was <30 dBA. The repeatability of the measurements was evaluated in a previous article [15] and the uncertainty interval for a 95% confidence interval is shown in Table 3.

Table 3. Interval of the uncertainty for the room acoustic measurements.

	$\mathbf{G_{avg}}$ (dB)	$\mathbf{C_{50,\ avg}}$ (dB)	$\mathbf{T_{20,\ avg}}$ (s)
125 Hz	±0.61	±0.56	±0.077
250 Hz	±0.30	±0.29	±0.018
500 Hz	±0.40	±0.29	±0.010
1000 Hz	±0.25	±0.27	±0.006
2000 Hz	±0.37	±0.38	±0.010
4000 Hz	±0.36	±0.36	±0.008

2.4. Listening Test

2.4.1. Sound Sampling Set-Up

Material for the listening tests was collected by recording sounds in the same environment described in the previous section. Female speech, sampled in an anechoic chamber, was played from a loudspeaker, type Genelec 8030 B, placed in S2, with the acoustic center at 1.55 m from the floor. The emitted sound power level was the same for all samplings. Recordings were made with binaural headphones, BHS II (3322) HEAD Acoustics, with calibrated microphones. B2U (3323) HEAD acoustics adapter is used for recording and playback equalization. Each sample lasted 4–6 s and was recorded at a height of 1.20 m from the floor. Recordings were made in positions R2, R4 and R5. Positions are the same as for the room acoustic measurements, described in Figure 9. Source and headphones can be seen in Figure 10. The headphones used for the recordings were also the playback system in the listening test.

2.4.2. Test Design

There is no standard for listening tests in ordinary public rooms. The objective of studies investigating subjective experiences often differs and the design of the test is thereby critical; the test design must relate to the objective of the study and may thereby vary from case to case. However, a common challenge in test design is the risk of bias [37], which must be considered. Aspects of bias can in this case be insights in the study ongoing or preconception. Other risks are lack of concentration, health issues, hearing impairments, duration of the test, whether the questions are adequate and whether the instructions are clear to the participants in the listening jury. Consequently, these aspects have been considered in the design of this listening test, visualized in Figure 11. As regards the duration, the test was designed to enable performance within 20 min. The time needed is related to the ability to maintain concentration. Additionally, in this aspect, the test contained different types of evaluations for the avoidance of monotony. The jury was composed of randomized mix of persons with an age span between 23 to 52 years old. None of the participants had insights into the study. Furthermore, the sounds were randomized. All participants completed training before performing the test.

The test design was evaluated in a pilot study. Five participants with varied experience performed the test and were interviewed on their view of the test. Subsequent modifications were shorter time sequences and clarifications regarding instructions were introduced. The judgements of the five participants in this pilot study are excluded from the evaluation presented in the results section of this article.

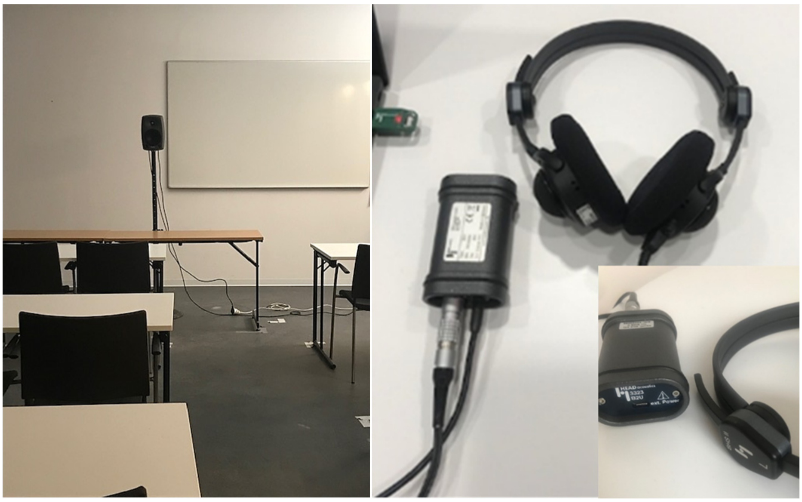

Figure 10. Left: Loudspeaker, Genelec 8030B used as sound source for listening test recordings. The source is placed in position S2. **Right:** Headphones BHS II and adapter B2U for equalization of recordings and for recordings to listening test. Same headphones are used both for recordings and jury evaluation.

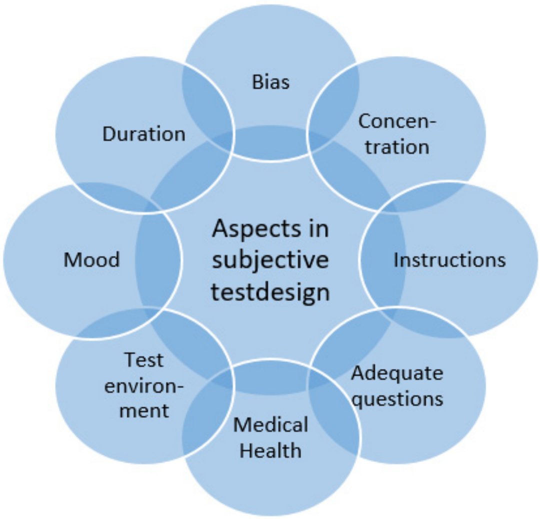

Figure 11. Aspects to be considered in the design of the listening test.

2.4.3. Performance of Listening Test

Twenty-nine people participated in the listening test. Fifteen of them were females. The test was made individually; thus, the test took place in the same room for every participant.

The training session contained the test and software instructions. The instructions were available for repetition during the entire listening test. The participants were instructed to make their choice based on their preferences if listening to information or instructions in a classroom environment. The participants were encouraged to make their choices and judgements based on their first impressions.

In the first part of the test participants answered questions about themselves:

- Age;
- Self-judgement of hearing capability;
- Their mood at the time;
- Previous experience of listening tests;
- Education or particular interest in the area of acoustics, as well as music.

The aim of collecting this data was to have background information if outlier results are identified.

To evaluate whether the listeners experienced differences, pairwise evaluation was made. Two different sound files were presented to the listeners, who considered whether they differed or not. This was repeated for the different combinations of listening positions in Conf 1–3, i.e., absorbent ceiling only, absorbent ceiling with absorbers on the walls, or vertically oriented diffusers on the walls. An equivalent type of judgement was made for the same listening positions but with varied configurations instead, in this case Conf 1–3.

The same procedure was performed for comparison between configurations with vertically and horizontally oriented diffusers, i.e., Conf 3 and 4, and for comparison of Conf 2 and 5, i.e., the two configurations with wall diffusers, vertically versus horizontally oriented. The set-up of evaluations can be found in Table 4.

Table 4. Set-up of evaluations, steps 1–3, is evaluation of different positions within one configuration. Steps 4–6 are evaluation of a specific position between different configurations.

Step	Object for Evaluation	Pairwise Sound Judgement	
1	Difference internally Conf 1	• R2/R5 • R2/R4 • R5/R4	
2	Difference internally Conf 2	• R2/R5 • R2/R4 • R5/R4	
3	Difference internally Conf 3	• R2/R5 • R2/R4 • R5/R4	
4	Differences for position R2	• Conf 1/Conf 2 • Conf 1/Conf 3 • Conf 2/Conf 3	• Conf 3/Conf 4 • Conf 2/Conf 5
5	Differences for position R4	• Conf 1/Conf 2 • Conf 1/Conf 3 • Conf 2/Conf 3	• Conf 3/Conf 4 • Conf 2/Conf 5
6	Differences for position R5	• Conf 1/Conf 2 • Conf 1/Conf 3 • Conf 2/Conf 3	• Conf 3/Conf 4 • Conf 2/Conf 5

An evaluation of the test itself was included in the test. The participants were able to give feedback on whether they had hard time to concentrate and whether the instructions had been clear. The participants judged their experience themselves. A scale 0–10 were used. Regarding concentration were 0 described as not difficult and 10 as very difficult. For instructions was 0 described as not clear and 10 as totally clear.

The jury test was performed using SQala, Artemi Suite 12.1, HEADacoustics.

3. Results

The following chapter presents the results for room acoustics and the listening test.

3.1. Room Acoustics

The room acoustics were investigated as average values, i.e., over the two source positions and seven receiver positions, as well as for the specific receiver positions R2, R4 and R5. In these cases, the source was placed in S2.

Evaluating the average values shows how adding absorptive wall panels (52CA_9WA_F) to the room with absorbent ceiling and furniture (52CA_F) decreases T_{20}, mainly at frequencies of 500 Hz and upwards; at octaves 1000 Hz, 2000 Hz and 4000 the difference was about 0.3 s. C_{50} changed in the same frequency range, as much as a 3–4 dB difference at octaves 1000, 2000 and 4000 Hz. For G, addition of wall panels gave a lower value of 0.5–1.0 dB as early as at octave of 250 Hz, where the furniture has absorption properties.

Replacing the absorptive tiles on the walls (52CA_9WA_F) with vertically oriented diffusers (52CA_9VWD_F) resulted in slightly higher T_{20} and lower C_{50}, 1–2 dB, in the higher frequency range. Opposite behavior is seen at the lower octaves 125–250 Hz. The diffusers are designed to operate as resonance absorbers in this frequency range, explaining this change. The effect of the resonance absorber is also seen in G. For the higher frequencies, it can be seen how the diffusers give higher G compared to configuration with absorbers.

In the next configuration, the wall diffusers were changed to a horizontal orientation. This change made no difference to G, meaning this value is independent of diffuser orientation; the absorption properties do not differ. However, for T_{20} and $C_{50,}$ changes were seen. Comparing configurations with different diffuser orientations gives a difference of approximately 1.5 dB in speech clarity, with lower values for horizontally oriented diffusers. T_{20} increases with horizontally oriented diffusers. The differences previously described are valid for the frequency range 1000–4000 Hz. In the lower frequency range, where the elements' main function is as resonance absorption, the room acoustic results are similar for the two configurations 3 and 4. It should be noted that the configuration with horizontally oriented diffusers still has an effect on the room acoustic parameters when compared to configuration with no acoustic treatment on the walls (Conf 1).

Replacing 12 absorptive ceiling tiles with diffusing elements, Conf 5 (48CA_4CD_9WA_F), in configuration with absorption panels on the walls, Conf 2 (52CA_9WA_F), gives on average a small decrease in T_{20}. C_{50} is on average similar for these two configurations. Slightly higher values are seen for G. Average results can be seen in Figure 12.

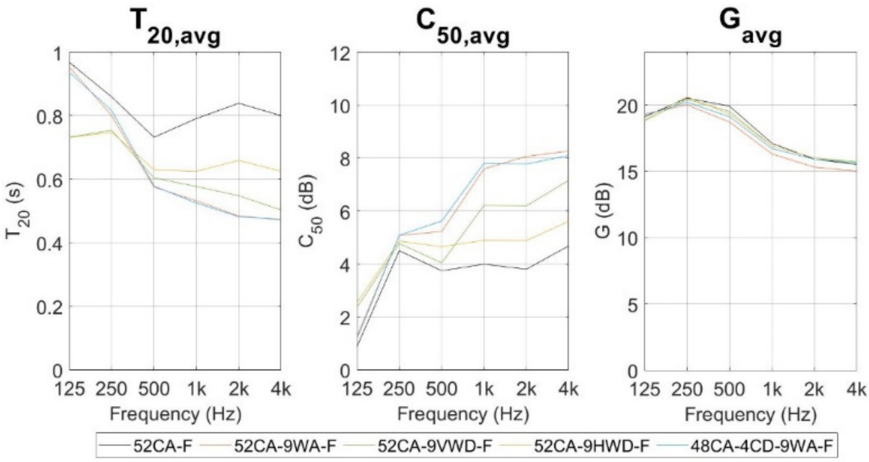

Figure 12. Room acoustic parameters for the five different configurations. Results presented in these graphs are average values from two source positions and seven receiver points, i.e., in total 14 measurements per configuration.

Focusing on internal differences for Conf 1–3 shows small variations in T_{20} values in each configuration. However, the smallest variation is in Conf 2, absorbing tiles on the walls.

As regards C_{50} for the same configurations and receiver positions, variations are apparent. The focus of the evaluation is within the higher frequency range. In terms of dB, the variations are smaller for Conf 2 and 3, i.e., configurations with acoustic treatment on the walls. It should also be noted that the variation between positions R4 and R5 is smallest for Conf 3, vertically oriented diffusers on the walls.

Looking into the G values, variations are slightly greater for the configuration with wall absorbers. Conf 1 and 3 behave similarly as regards variation. However, all three configurations have small variations between the two positions at the back of the room, R4 and R5. The results for internal differences in the Conf 1–3 are shown in Figure 13.

Comparisons between specific positions using vertically or horizontally oriented diffusers, Conf 3 and 4, show, in the higher frequency range, higher T_{20} values and lower C_{50} values in all positions for Conf 4. With regard to $C_{50,}$ the largest variant is seen in position R5, the difference being 3.2 dB. G is similar when comparing the same positions for the two configurations with diffusers on the walls.

In addition, the question has been investigated of whether the room acoustic parameters differ for configuration with ceiling diffusers replacing 12 absorptive tiles. The configuration for this comparison includes absorptive tiles on the walls, i.e., Conf 2 and 5. As regards T_{20} and G, slightly lower values are seen for Conf 2. Regarding $C_{50,}$ the configuration with ceiling diffusers gives an increase at 2000 Hz. This increase is around 1 dB in the positions further away from the source, R4 and R5. Room acoustic parameters for specific receiver positions (R2, R4 and R5), all configurations, are shown in Figure 14.

All room acoustic data can be found in Appendix A.

3.2. Listening Test

The average age of the 29 participants (15 females, 14 males) performing the listening test was 37 years. Regarding the question of whether it had been difficult to concentrate, the average value was 3 (scale 0–10 where 0 = not difficult, 10 = very difficult). On the question as to how clear the instructions were, the average answer was 10 (scale 0–10, 0 = not clear, 10 = totally clear). Three participants reported some type of hearing impairment. No one reported medical illness. Most participants described their mood with positive words such as enthusiastic, alert and curious. A couple of participants reported feelings of stress and tiredness. No significant differences in the answers could be found due to any of these aspects. In some cases, are deviating responses reported. These results have not affected the main outcome in the analysis of this study. The deviating responses were reported from different jury members and no specific outlier in the jury group could be identified. Deviating responses could not be related to the concertation ability or instruction clarity, neither to the responses on health. Thereby are all responses included in the results presented in coming paragraphs.

In the first part of the listening test, internal differences in configurations 1–3 were evaluated. On the question of whether the participants could identify a difference between different positions, differences between positions R2 and R5 as well as between R2 and R4 were clearly observed for all three configurations. Regarding a comparison of positions R4 and R5, 41% judged it to be the same within Conf 1. For Conf 3, this value was higher, with 48% considering it to be same. For Conf 2, the percentage judging the two positions to be the same was lower, 28%. These results can be found in Figure 15.

When asking participants whether they could observe a difference between different configurations, the positions are the same, with regard to configurations 1–3 the majority could observe a difference in all positions when comparing configurations 1 and 2. For position R4, however, 24% deemed the sounds to be similar. When comparing Conf 1 and 3, the percentage observing different values in R2 was 24%, in R4 28% and, in R5, the majority, 62% judged it to sound the same. Comparing Conf 2 and 3 showed that 90% thought it sounded the same in position R2, in R4 72% judged it to be the same and, in R5, this value was 55%. The results can be seen in Figure 16.

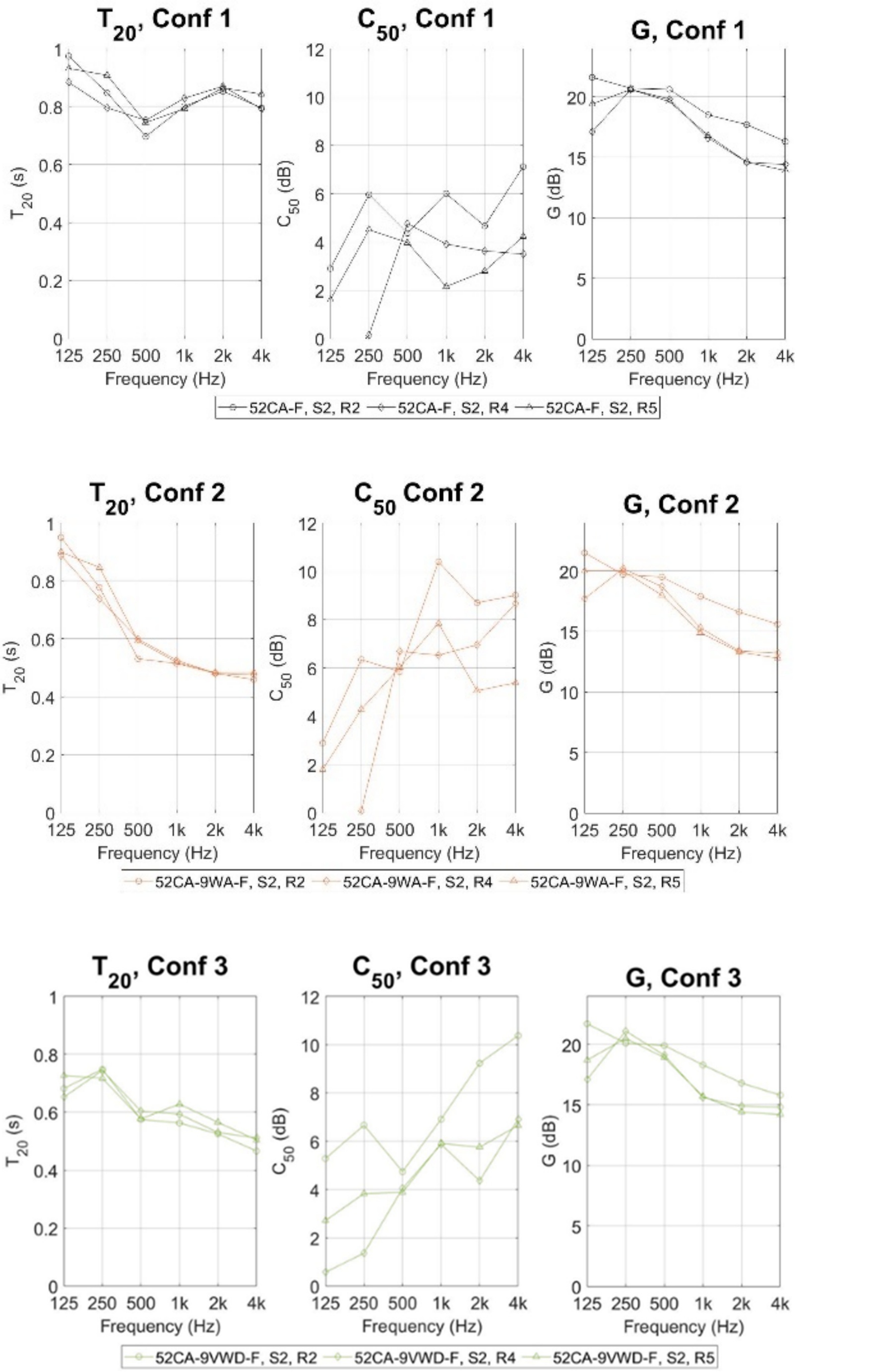

Figure 13. Results room acoustic parameters for three different positions R2, R4, R5 in Conf 1, Conf 2 and Conf 3.

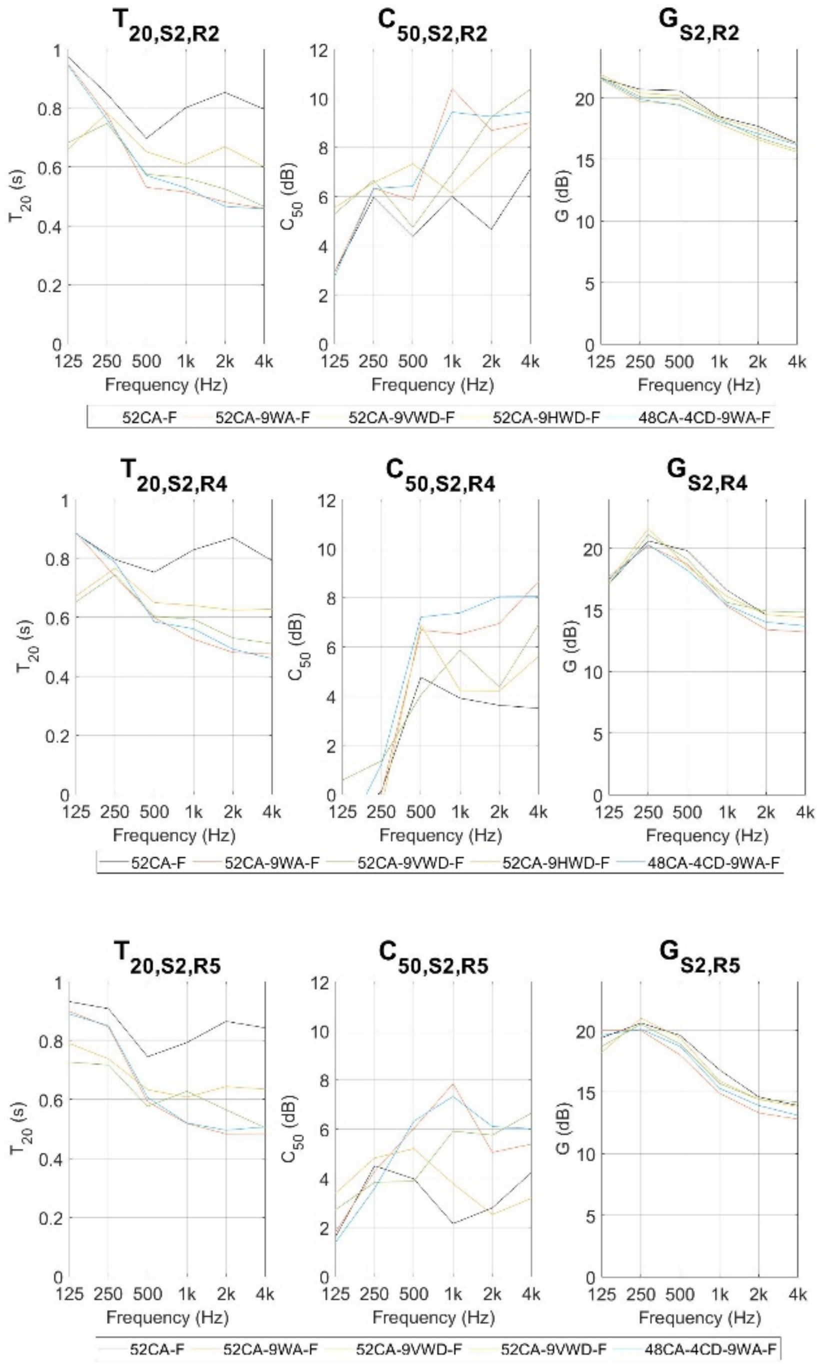

Figure 14. Room acoustic parameters in position R2, R4 and R5 for all configurations.

Comparing the two configurations were vertically and horizontally oriented diffusers was used showed that the majority did not observe a difference between the configurations. In position R4, only 6.9% observed a difference, in R4 21% observed a difference and in position R5 24% observed a difference. The results can be seen in Figure 17.

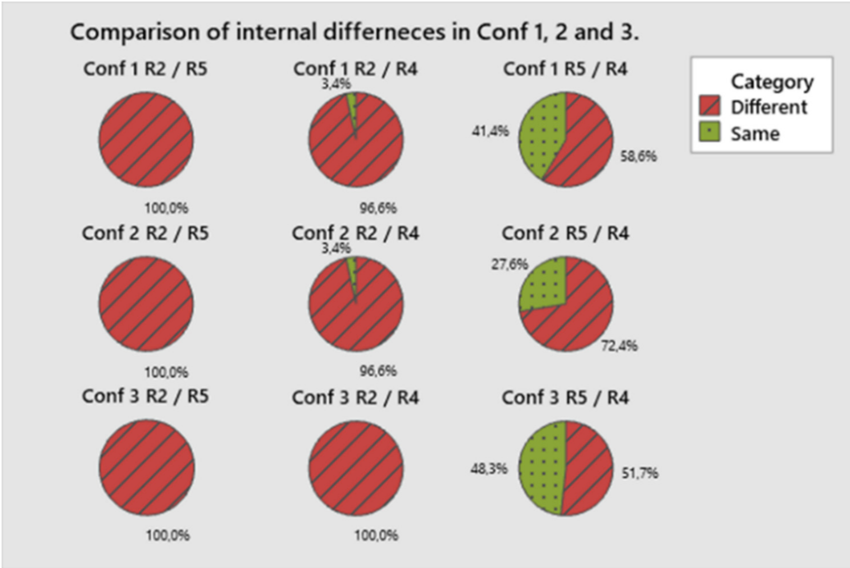

Figure 15. Result on perception of whether participants experienced the sound to be same or different for different positions within one configuration. Conf 1 in the first row, Conf 2 in second row and Conf 3 in third row.

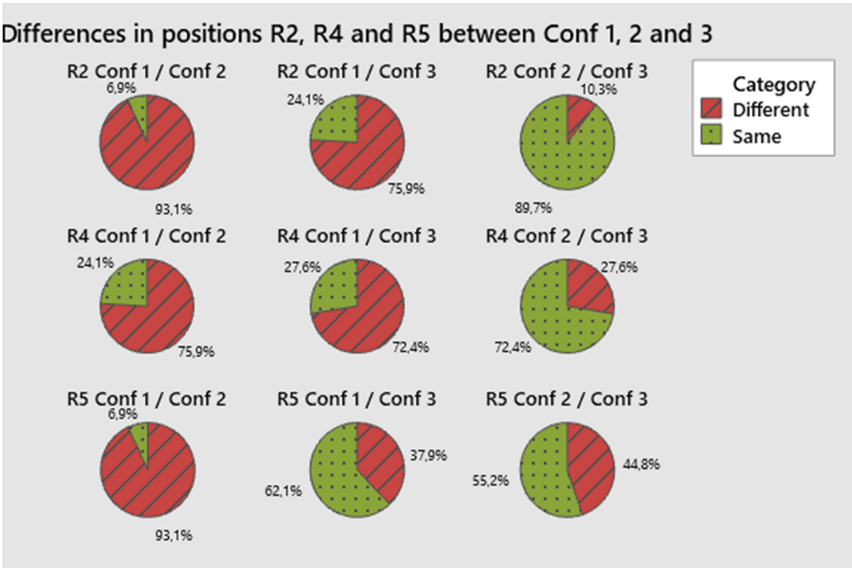

Figure 16. Differences between different configuration for certain positions. First row position R2, second row positions R4 and third row position R5.

Comparison of Conf 2 and 5, meaning the effect of ceiling diffusers, shows that the majority judged the sound to be the same; however, 38% thought it sounded different in position R5 and 24% thought it sounded different in position R4. Results can be seen in Figure 17.

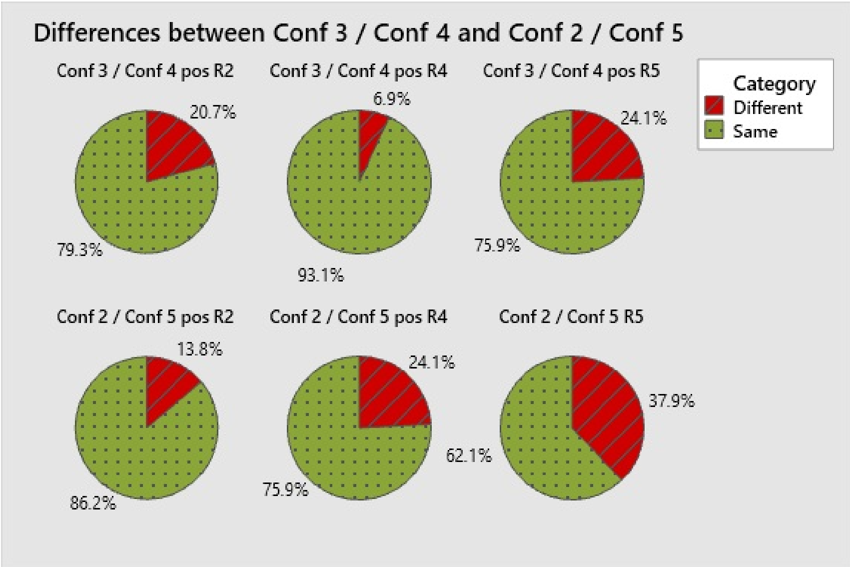

Figure 17. First row: the difference between configurations with vertically oriented diffusers, Conf 3, and horizontally oriented diffusers, Conf 4, for positions R2, R4 and R5. Second row: the difference between configurations with only absorbent ceiling, Conf 2, and with ceiling diffusers, Conf 5, for positions R2, R4 and R5.

4. Discussion

Looking at the internal differences in configurations 1, 2 and 3, participants perceived the sound to be different between R2 and R5 in all cases. Additionally, between R2 and R4, the majority perceived a difference. However, regarding a comparison between R4 and R5, the participants deemed to a greater extent the two positions to be the same for Conf 1 and 3, i.e., where walls where empty or covered with diffusers. Comparing the room acoustics in the positions R4 and R5 for Conf 2, i.e., when people experienced a difference, was C_{50} the parameter that differs. The difference was at octaves 2000 Hz and 4000 Hz, the difference was 2–3 dB. Looking at the same positions, R4 and R5, for Conf 1 and 3, for which more people experienced sound to be more similar was the difference in C_{50} smaller.

Comparing sounds in one position but for different configurations, 90% judged that the sounds for Conf 2 and 3 were the same in position R2. As regards room acoustic parameters we mainly see a difference in T_{20}, for the low frequencies. As people answered that they could not experience a difference, we can say that this difference in T_{20} is not enough to obtain a subjective difference. It should be noted that the sound source in this case was a female voice. A male voice may contain higher ratio of lower frequencies. For such situation can low frequency absorption give other results in perception.

Investigating the same configurations, 2 and 3, in position R4, differences are apparent in room acoustic parameters in the higher frequency range. Speech clarity differs by about 1 dB, reverberation time by 0.05 s and sound strength by 2 dB in octaves 2000 and 4000 Hz. As regards this position, still 72% deeming it to be the same. The differences just mentioned seems thereby not to be enough to significantly experience a difference in perception of speech. Continuing to study the same configurations, i.e., Conf 2 and 3 in the position R5, the majority of the participants, 55%, judged the two configurations to be the same. The reverberation time differs slightly more at the high frequencies. The C_{50} shows irregularities in its pattern for this position, but differences of about 1.5 dB between the two configurations are seen for this parameter in the higher frequency range. The sound strength differs slightly less at 2000–4000 Hz, but slightly more at 1000 Hz.

This evaluation indicates that the difference needed to subjectively experience a variation has in this study been higher than typical values for performance spaces in 3382-1 where JND for C_{50} and G is 1 dB. Furthermore, can we see an importance of looking separately into the different frequencies.

Evaluating the results for the previously discussed position R5 for Conf 1 and 3 gives an opposite indication. The subjective test showed that the majority considered the sounds to be the same; however, the room acoustic parameters T_{20} and C_{50} differ more in the same frequency range than for previously discussed configurations. For C_{50} the difference is 2.4–3.8 for the frequency range 1000–4000 Hz, with the difference in T_{20} being 0.2–0.3 s for the same frequency range. This implies that the subjective sound image goes beyond these parameters and additional descriptors are needed for a full and appropriate description of how people experience sounds.

Evaluation of the configuration using vertically, or horizontally oriented diffusers shows that the majority perceive the sounds to be the same. The greatest percentage of participants judging "different" was found in position R5, 24%. In this position, the largest differences in C_{50} and T_{20} are found. For $C_{50,}$ the difference at 2000 Hz and 4000 Hz is about 3 dB and T_{20} 0.08–0.10 s. G has similar values for these two configurations. This further reinforces the interpretation above, that the difference between these parameters must be greater than is recommended for performance spaces and that the subjective sound image must be considered.

Comparing the effect of ceiling diffusers showed that majority of the participants judged the two configurations, Conf 2 and 5, to be similar. The position where most participants found a difference was R5. The parameter differing in this position was mainly C_{50}, but the difference is lower than was required for the participants to observe a difference in the other evaluations in this study. A reason for this can be the different subjective sound image that the diffuser creates compared to absorptive panels.

Development of how to describe this sound image is needed. Such development can include further studies of the relation between perceived characteristics of sound to different room acoustic parameters. Additional room acoustic parameters may be considered, furthermore could the measurement technics be considered.

5. Conclusions

The evaluation in this study shows that it is important to not only consider average values but also specific positions in the room acoustic design of ordinary rooms. It also shows that greater differences in room acoustic parameters are needed for these types of environments than what is described as just noticeable differences for performance spaces in ISO 3382-1. Furthermore, the evaluation shows that greater differences are needed in the low frequency range compared to the high frequency range. This can be explained by people's lower hearing sensitivity at lower frequencies. Furthermore, a female voice was used in the study, which cannot produce as many low frequencies as a male voice can. The room acoustic parameters measured could not fully explain all the outcomes from the perception evaluation. An important interpretation arising from this study is that it is essential to take the subjective part of the sound image into consideration in the room acoustic design of ordinary rooms.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Data room acoustic measurements.

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An Energy Model for the Calculation of Room Acoustic Parameters in Rectangular Rooms with Absorbent Ceilings

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Abstract: The most common acoustical treatment of public rooms, such as schools, offices, and healthcare premises, is a suspended absorbent ceiling. The non-uniform distribution of the absorbent material, as well as the influence of sound-scattering objects such as furniture or other interior equipment, has to be taken into account when calculating room acoustic parameters. This requires additional information than what is already inherent in the statistical absorption coefficients and equivalent absorption areas provided by the reverberation chamber method ISO 354. Furthermore, the classical diffuse field assumption cannot be expected to be valid in these types of rooms. The non-isotropic sound field has to be considered. In this paper, a statistical energy analysis (SEA) model is derived. The sound field is subdivided into a grazing and non-grazing part where the grazing part refers to waves propagating almost parallel to the suspended ceiling. For estimation of all the inherent parameters in the model, the surface impedance of the suspended ceiling has to be known. A method for estimating the scattering and absorbing effects of furniture and objects is suggested in this paper. The room acoustical parameters reverberation time T_{20}, speech clarity C_{50}, and sound strength G were calculated with the model and compared with calculations according to the classical diffuse field model. Comparison with measurements were performed for a classroom configuration. With regard to all cases, the new model agrees better with measurements than the classical one.

Keywords: room acoustics; calculation models; absorption; scattering; airflow resistivity

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1. Introduction

Many people spend most of their working hours in rooms such as offices, and education and healthcare premises. For the wellbeing of the people in those work places, the acoustical conditions are an important factor. The most common acoustical treatment in these type of public rooms is a suspended absorbent ceiling. The acoustical design is often aimed at reducing noise levels, improving speech intelligibility or, as in open-plan offices, preventing sound propagation. Due to the fact that most of the sound absorption located at the ceiling and other surfaces can be quite sound reflecting, the decay of sound energy and its relation to absorption is not properly explained by the classical assumption of a linear decay under diffuse field condition. These room types comprise a group of rooms where the diffuse field assumption is not valid and the sole use of reverberation time for characterization of the acoustical conditions is not sufficient.

The aim of this paper is to present a model for calculation of reverberation time T_{20}, speech clarity C_{50}, and sound strength G, as defined in ISO 3382-1 [1] and ISO 3382-2 [2]. The model was particularly designed for rooms with suspended absorbent ceilings. For public rooms, such as classrooms, offices, health-care premises, dining rooms, sport arenas, retail premises and similar kind of spaces, the typical acoustical treatment is a suspended absorbent ceiling. The model presented is based on a statistical energy analysis (SEA) approach used to describe the conditions at steady state and during the sound decay.

Rooms, as mentioned above, are places where large numbers of people spend most of their time during the day. It is obvious that the environment where we spend so many of our working hours should contribute to well-being and the ability to perform working tasks in the best possible way. The acoustical conditions are important in this respect. The purpose of the model presented in this paper is to obtain an estimation of room acoustic parameters for a relevant characterization of the acoustical conditions.

Schools are one of our largest work places. For learning and for the well-being of students and staff in educational premises, acoustic conditions play a central part. It has been recognized in several studies [3–6] that learning and the ability to remember and concentrate are affected by acoustic conditions as well are general well-being and the onset of stress-related symptoms. The effect of different signal-to-noise ratios on the ability to recall words shows that noisy surroundings in classrooms impair learning [7–9].

The effect of room acoustic improvement on the work situation in schools has been investigated in [10,11]. It has been shown that, with improved room acoustic conditions, the students social behavior becomes calmer and the teachers experience less physiological load (heart rate) as well as less fatigue. Poor acoustics in classrooms can result in high vocal loading of teachers, which presents a risk factor for voice disorders [12]. Keeping speakers' acoustics conditions in mind, measurement methods for the prediction of voice support and room gain in classrooms have been developed [13,14].

The high activity-based noise levels in preschools have been thoroughly investigated [15,16]. However, the long-term effects on children and staff are still a topic for investigations [17].

The sound environment in hospitals is diverse due to different activities that take place, the sound of medical equipment, and alarms and background noise. This can contribute to stress symptoms among staff as well as being a hinderance to patient recovery [18].

The acoustically challenging environments that open-plan spaces involve have received a great deal of attention in recent years [19]. Standards have been developed that present new measurement methods relevant for the typical scenarios occurring in open-plan offices as well as guidelines for creating good acoustic quality in these environments [20,21].

The knowhow relating to characterization of the acoustical conditions in public rooms has increased in recent years. Several investigations [22–25] have pointed out the necessity of addressing several acoustic parameters to achieve a relevant characterization of the acoustic environment. As has been shown, parameters relating to noise levels and speech intelligibility are an important complement to reverberation time. In [26], the speech clarity parameter U_{50}, i.e., C_{50}, including the effect of background noise, is used for designing good speech conditions in classrooms.

In [27,28], Barron presents a model for calculating clarity index and sound strength in rooms assuming linear sound decay. In [29], special effort was focused on explaining the non-diffusivity effect of the sound fields in public rooms with ceiling treatment and how these circumstances influence these parameters.

Since Sabine's [30] discovery and his classical formula, reverberation time has been the key parameter in room acoustics. In many standards and regulations, it is still the main parameter defining target values for good acoustics [31]. However, today, there are some new standards that have included measures, such as C_{50} and speech transmission index STI [32], as complements to reverberation time [33].

The idea of two rooms with approximately the same reverberation times being perceived as different is not a new finding and is mentioned in textbooks on acoustics [34,35] as well. This is especially the case in public rooms with ceiling treatment.

Many suggestions for improvement of the reverberation time formulas have been made. Several examples of such refinements are given in [34,35].

The influence of different corrections to Sabine's formula has been investigated by Joyce [36,37]. In support of Sabine's formula, Joyce shows that understated conditions of weak absorption and irregular reflections provides the correct answer.

In [38] Fitzroy presents an empirically derived formula for the reverberation time in rooms with non-uniform distribution of absorption. A modified version of Fitzroy's formula is presented by Neubauer [39]. The non-uniform distribution of absorption is also dealt with by the formula of Arau-Puchades [40]. The effect of location of absorbent material in a mock-up of a classroom and in a reverberation chamber has recently been studied by Cuchrero et al. [41].

In [42], Sakuma uses an image source method where the image sources are grouped as axial, tangential, and oblique groups corresponding to normal modes in wave acoustics. Scattering is taken into account by introducing the scattering coefficient. The non-linear decay in rooms with non-uniform distribution of absorption as well as the importance of scattering are apparent in the results.

In [43], Bistafa and Bradley compared experimental results with analytical and computer predictions of reverberation time in a simulated classroom. Their paper emphasizes the need to quantify the amount of scattering due to furniture and other objects in a room. The influence of scattering is also experimentally investigated by Prodi et al. [44].

A general problem in many reverberation time formulas is the use of a random absorption coefficients as input data. This is of course natural, as most manufacturers of absorbent products provide this data measured according to ISO 354 [45]. However, the non-isotropic properties in rooms with ceiling treatment differ from the almost diffuse conditions in reverberation chambers. In fact, even in reverberation chambers, the concept of a diffuse sound field is hard to achieve [46]. In [47,48], Nilsson presented a model particularly developed for rooms with suspended absorbent ceilings. The non-diffuse conditions were dealt with by introducing two sound fields related to grazing and non-grazing sound waves. The idea of subdividing the sound field into a grazing and non-grazing group were also adopted in [49].

To deal with the non-diffuse conditions in the model presented in this paper, an estimation of the surface impedance of the ceiling is used. The reason is to take into account the angle-dependent properties of the ceiling absorber. This is a major difference to the other energy models referred to above. Another difference to the referred models is the handling of the scattering effect of interior objects such as furniture. In rooms with absorbent ceiling treatments, the directional scattering effect of objects is important. A method for estimation of the directional scattering effect is suggested as an outcome of the model formulation.

When evaluating the reverberation T_{20} or T_{30} according to ISO 3382-2 [2], the dynamical ranges -5 to -25 dB and -5 to -35 dB are used, respectively. This means that the early reflections of the impulse response are neglected. Therefore, T_{20} and T_{30} are often referred to as late reverberation times. In a room with absorbent ceiling treatment, the late reverberation times are often related to energy travelling in the horizontal plane, comprising grazing waves in relation to the absorbent ceiling.

The importance of early reflections for design of auditoria was already observed by Lochner and Burger [50]. Chiara et al. [51] has investigated the subjective influence of early diffuse reflections on speech intelligibility and spatial perception. In [52], Bradley et al. show the importance of early reflections for speech intelligibility both for normal- and hearing-impaired listeners. These investigations show the benefits of using parameters incorporating the early reflections such as speech clarity.

The examples in the text above show that public rooms with acoustic ceiling treatment comprise a large and important group of rooms that deserve closer examination. This involves investigation into how different acoustical treatment affects the sound field and how this impact can be predicted in a more accurate way than by the classical diffuse field assumption. Further, elucidate the limitations related to only using reverberation time as a descriptor characterising the acoustics.

This paper presents a model that considers the special features of rooms with ceiling treatment and gives an estimation of several room acoustic parameters that are important for the subjective perception of the acoustics. The model takes into account the mounting height of ceiling absorbers and absorbent wall panels, as well as the scattering effect of furnishing, diffusers, or other objects. The purpose is to serve the user with a model that gives an estimation of room acoustic parameters that are reasonably consistent with measurements in rooms with ceiling treatment and thus, also to emphasize phenomena that influence the subjective perception of the acoustics.

2. General Description of the Model

A general discussion of the model is presented in this chapter. The model is based on a statistical energy analysis (SEA) approach [53,54]. The model addresses rectangular rooms with absorbent ceilings, i.e., rooms where the main contribution to the total absorption is related to the ceiling. A more precise requirement for this condition is given further on.

Important considerations are, firstly, that the surface impedance of the absorbent ceiling, including the air cavity behind the absorber, has to be known, and secondly, that the absorbing and scattering effects of furniture and other interior fittings have to be estimated. A method for measuring the scattering effect is proposed in Section 3.2.5. This method takes into account the directional scattering of objects due to the orientation towards the ceiling.

With the exception of the ceiling, other surfaces in the room are characterized by the statistical absorption coefficient. Further, added wall panels are defined by their statistical absorption coefficient, as measured according to ISO 354 [45].

The room acoustic parameters calculated are reverberation time T_{20} according to ISO 3382-2, speech clarity C_{50} in dB, and sound strength G in dB according to ISO 3382-1.

Speech clarity is defined as

$$C_{50} = 10 \log \left(\frac{\int_0^{0.05} p^2(t)dt}{\int_0^{\infty} p^2(t)dt} \right) \tag{1}$$

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

Sound strength is defined as

$$G = 10 \log \left(\frac{\int_0^{\infty} p^2(t)dt}{\int_0^{\infty} p_{10}^2(t)dt} \right) \tag{2}$$

where $p(t)$ is the impulse response at the measurement point and $p_{10}(t)$ is the impulse response measured at 10 m in a free field.

An omni-directional sound source is required for measurement of the acoustical parameters.

The model comprises the following steps:

Basic formulas are derived in Section 3.1 comprising

- Establish a general expression for the energy sound decay in a two-system SEA model.
- Express the total sound energy decay in the parameter sound strength G as defined in ISO 3382-1.
- From the expression for the total sound energy decay, derive an expression for the speech clarity C_{50} and the reverberation time T_{20}.

Estimation of the inherent parameters in the basic formulas are presented in Section 3.2 comprising

- Subdivide the total sound field into a grazing and non-grazing part where grazing refers to sound waves propagating almost parallel to the absorbent ceiling.
- Calculate the angle-dependent absorption coefficient, Section 3.2.1.
- Estimate the number of modes in the grazing subsystem as well as a representative absorption coefficient, Section 3.2.2.
- Estimate the number of modes in the non-grazing subsystem as well as a representative absorption coefficient, Section 3.2.3. Two approaches for estimation of the number of non-grazing waves were used: one empirical and one theoretical.

- Based on a 2-dim and 3-dim reverberation formula, estimate the reverberation times T_g and T_{ng} corresponding to the grazing and non-grazing subsystem, respectively. See Section 3.2.4.
- By knowing T_g and T_{ng} and the number of modes in each subsystem, the energy ratio C for the grazing and non-grazing sound fields in the formula for sound strength G can be calculated.

As an effect of the subdivision of the total sound field into a grazing and non-grazing part, the scattered and absorbed sound, due to objects such as furniture in the room, can be interpreted as a coupling loss factor between the two subsystems, see Figure 1. The coupling loss factor is reformulated as an equivalent scattering absorption area, denoted as A_{sc}. A corresponding measurement method of A_{sc} is suggested. See further Section 3.2.5.

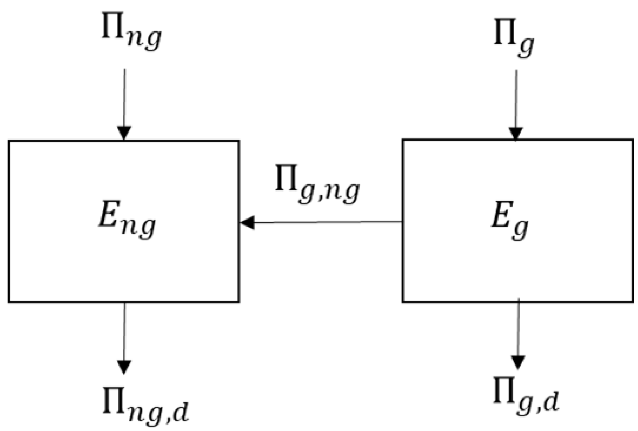

Figure 1. The SEA model.

As the distance r is included in the model, the room acoustic parameters as a function of distance can be calculated. However, in the calculations performed, a representative value of r is used. See Equation (41).

The theoretical background for the model is presented in the next chapter and verifying measurements in Section 5. The new model will hereinafter be referred to as "non-diffuse" and the classical diffuse field model (Sabine) as "diffuse".

3. Theory

3.1. The SEA Model

The sound field in a room with absorbent ceiling treatment is modelled as an SEA system consisting of two subsystems. One subsystem comprises non-grazing waves and the other comprises grazing waves. The term grazing refers to the angle of incidence towards the ceiling absorber. Thus, grazing comprises waves travelling almost parallel to the absorbent ceiling. The coupling loss factor between the two subsystems is related to the energy transfer from the grazing subsystem to the non-grazing subsystem. This energy transfer is most often due to the interior fittings in the room such as furniture, but could also be due to a tilting wall, for example. The back-transfer from the non-grazing to the grazing subsystem is neglected. The SEA model is illustrated in Figure 1.

The power flow into the grazing (g) and non-grazing (ng) subsystem (Π_{ng}, Π_g), as well as the dissipated power $\left(\Pi_{ng,d}, \Pi_{g,d}\right)$, are shown in Figure 1. The total energy in the subsystems are denoted as E_{ng} and E_g, respectively. The power lost by the grazing subsystem to the non-grazing is represented by $\Pi_{g,ng}$. Generally, a weak coupling is assumed, i.e., that the losses related to the coupling between the two system is less than the internal losses in the grazing and non-grazing subsystems [54].

In a room with non-uniform distribution of absorption, such as the rectangular room with a highly absorbent ceiling and the other surfaces almost reflecting, the energy decay is estimated by

$$E(t) = E_{ng}(0)e^{-\omega\eta_{ng}t} + E_g(0)e^{-\omega\eta_g t} \tag{3}$$

$E_{ng}(0)$ and $E_g(0)$ are the initial energies for the non-grazing and grazing subsystems, respectively. The loss factor in the non-grazing and the grazing subsystems are denoted as η_{ng} and η_g, respectively.

Using $\Pi = \omega\eta E$ and, assuming that the coupling loss factor is negligibly small compared to the internal losses in the two subsystems, the energy ratio is given by

$$E(t) = E_{ng}(0)(e^{-\omega\eta_{ng}t} + \frac{E_g(0)}{E_{ng}(0)}e^{-\omega\eta_g t}) = E_{ng}(0)(e^{-\omega\eta_{ng}t} + \frac{\eta_{ng}\Pi_g}{\eta_g\Pi_{ng}}e^{-\omega\eta_g t}) \tag{4}$$

The condition in Equation (4) above is valid for a rectangular room with absorbent ceiling, but without furniture. Including furniture will lead to the introduction of a coupling loss factor related to the energy transfer from the grazing to the non-grazing sound field, see Figure 1. Replacing η_g in Equation (4) by $\eta_g + \eta_{g,ng}$ where $\eta_{g,ng}$ is the coupling loss factor, the absorbing and scattering effect of furniture can be accounted for. The coupling loss factor is further discussed in Section 3.2.5.

As shown in [55], the ratio Π_g/Π_{ng} is approximately given by N_g/N_{ng}, where N_g and N_{ng} are the number of modes in the grazing and the non-grazing subsystems, respectively.

In geometrical acoustics, sound waves are often represented as rays with a certain sound intensity. Further, in room acoustical calculations, the reverberation time is a well-established parameter and normally the frequency depending on reverberation times are studied in frequency bands, usually octave bands.

By converting Equation (4) into sound intensity, assuming octave band values and using the relation $\Delta\Pi_g/\Delta\Pi_{ng} \approx \Delta N_g/\Delta N_{ng}$, and further introducing the reverberation time T using the relation $\omega\eta = 6\ln(10)/T$, we get

$$I(t) = I_{ng}(0)(e^{-13.8t/T_{ng}} + \frac{T_g\Delta N_g}{T_{ng}\Delta N_{ng}}e^{-13.8t/T_g}) \tag{5}$$

The procedure presented for a linear decay by Barron and Lee [27] is applied for the double sloped decay, as given by Equation (5).

The steady-state condition at $t = 0$ gives the power balance

$$W = \omega\eta\frac{I}{c}V \tag{6}$$

where W is the input power and V is the room volume.

Assuming a point source and a distance r_0 between the source and receiver and further, that the sound field at steady-state is diffusewith a reverberation time T_{ng}, the intensity at steady-state is given by [56]

$$I(0) = I_0 r_0^2 \frac{T_{ng}}{V}\frac{4\pi c}{6ln(10)} = 312 I_0 r_0^2 \frac{T_{ng}}{V} \tag{7}$$

where I_0 is the intensity of the direct sound at the distance r_0 from the sound source.

The total (energy) decay, as given by Equation (5), adjusted towards the steady-state intensity in Equation (7) will be given by

$$I(t) = 312 I_0 r_0^2 \frac{T_{ng}}{V(1+C)}(e^{-13.8t/T_{ng}} + Ce^{-13.8t/T_g}) \tag{8}$$

where

$$C = \frac{T_g\Delta N_g}{T_{ng}\Delta N_{ng}} \tag{9}$$

Including the direct sound gives

$$I(t) = I_d + I_{rev} \tag{10}$$

I_{rev} is given by Equation (8) and I_d is the direct sound at distance r given by

$$I_d = \frac{W}{4\pi r^2} \tag{11}$$

where W is the input power.

Following Barron et al. [27], the sound strength G is calculated. The sound strength G is defined as

$$G = L_p - L_{p,10} \tag{12}$$

where L_p is the sound pressure level at the measurement point and $L_{p,10}$ is the sound pressure level at a distance of 10 m in a free field given by

$$L_{p,10} = 10\log\left(\frac{\rho c}{p_{ref}^2}\frac{W}{4\pi 10^2}\right) \tag{13}$$

where p_{ref} is 2×10^{-5} Pa.

Combining Equations (8), (10) and (12) gives

$$G = 10\ \log\left(\frac{100}{r^2} + 31,200\ \frac{T_{ng}}{V(1+C)}(e^{-\frac{13.8t}{T_{ng}}} + Ce^{-\frac{13.8t}{T_g}}\right)) \tag{14}$$

Setting $t = r/c$ [27] i.e., the time for the sound wave to propagate r metres, gives the final expression. This implies that the decay starts after the direct sound arrived at the receiver position.

$$G = 10\ \log\left(\frac{100}{r^2} + 31,200\ \frac{T_{ng}}{V(1+C)}(e^{-\frac{0.04r}{T_{ng}}} + Ce^{-\frac{0.04r}{T_g}}\right)) \tag{15}$$

The received sound energy is divided into three components, the direct sound (d), the early reflected sound i.e., a delay <50 ms (e_{50}), and the late reflected sound i.e., a delay >50 ms (l_{50}). Using Equation (8) normalized to $I_0 = W/\left(4\pi 10^2\right)$ gives

$$d = 100/r^2 \tag{16}$$

$$e_{50} = I_n(t) - I_n(t+50) = 31,200\frac{T_{ng}}{V(1+C)}\left[e^{-\frac{0.04r}{T_{ng}}}\left(1 - e^{-\frac{0.691}{T_{ng}}}\right) + Ce^{-\frac{0.04r}{T_g}}\left(1 - e^{-\frac{0.691}{T_g}}\right)\right] \tag{17}$$

$$l_{50} = I_n(t+0.05) = 31,200\frac{T_{ng}}{V(1+C)}\left(e^{-\frac{0.04r+0.691}{T_{ng}}} + Ce^{-(\frac{0.04r+0.691}{T_g}}\right) \tag{18}$$

The sound strength G is given by

$$G = 10\ \log(d + e_{50} + l_{50}) \tag{19}$$

The speech clarity C_{50} is given by

$$C_{50} = 10\log\left(\frac{d + e_{50}}{l_{50}}\right) \tag{20}$$

T_{20} is calculated using the logarithmic version of Equations (8) and the -5 to -25 dB dynamical range according to ISO 3382-2.

To calculate T_{20}, C_{50}, and G, the inherent parameters T_{ng}, T_g, and C in Equations (8), (17), and (18) have to be estimated. This is described in the next paragraph.

3.2. Estimation of the Inherent Parameters T_{ng}, T_g and C

This chapter concerns the approach of estimating the inherent parameters in Equations (8), (17), and (18). Estimation of these parameters is of central importance in the model and some detailed explanations are presented in this paragraph. These estimations involve considerations regarding how to define absorption and the number of modes for the grazing and non-grazing sound fields and how to take into account the effect of sound-scattering objects in the room. The method involves defining a grazing and non-grazing region, according to Figure 2. The grazing sector is defined by the grazing angles θ_g. For the non-grazing sector, two approaches were used: a theoretical one and an empirical one. Before we go into the derivation of θ_g and the limits for the non-grazing sector, the calculation of the angle-dependent absorption coefficient will be discussed.

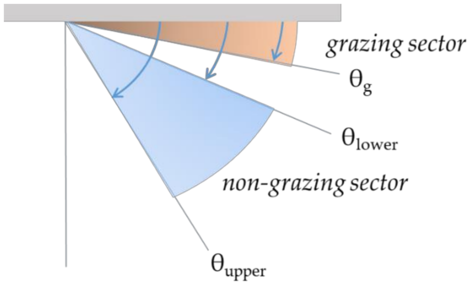

Figure 2. Illustration of the grazing and non-grazing sectors.

3.2.1. The Angle-Dependent Absorption Coefficient

For each sector, representative absorption coefficients (α_{ng}, α_g) and a representative number of modes (ΔN_{ng}, ΔN_g) have to be determined. It is assumed that the surface impedance of the ceiling absorber is known or can be estimated. Several types of commercial software' are available today for calculating the angle-dependent surface impedances [57,58] for different types of absorbers. In this study, only suspended ceilings of porous material were investigated. For porous absorbers, the surface impedance $Z(f,\theta)$ can be calculated by applying empirical models if the air flow resistivity is known. In this case Miki's model was used [59]. An extended reaction is assumed when calculating α_{ng} and α_g. The angle-dependent absorption coefficient for a plane sound wave impinging on a plane infinite surface is given by

$$\alpha(f,\theta) = 1 - \left| \frac{Z(f,\theta)\cos(\theta) - \rho_0 c_0}{Z(f,\theta)\cos(\theta) + \rho_0 c_0} \right|^2 \tag{21}$$

where $Z(f,\theta)$ is the surface impedance at incidence angle θ, ρ_0 is the density of air, and c_0 is the speed of sound. The surface impedance for an extended reaction is calculated as [60]

$$Z(f,\theta) = \frac{Z_c k}{k_x} \left[\frac{-jZ_0 \cot(k_x d) + Z_c \frac{k}{k_x}}{Z_0 - jZ_c \frac{k}{k_x} cot(k_x d)} \right] \tag{22}$$

where k is the wave number in the absorber, $k_x = \sqrt{k^2 - k_0^2 \sin^2(\theta)}$ is the normal component of k, k_0 is the wave number in air, d is the thickness of the absorber, and Z_c is the characteristic impedance of the absorber. The backing impedance Z_0 is given by

$$Z_0(f,\theta) = -j\left(\rho_0 c_0 \frac{k_0}{k_x}\right) \cot(k_0 d_0 \cos\theta) \tag{23}$$

where d_0 is the depth of the air cavity behind the absorber.

The characteristic impedance for the absorber Z_c is calculated by Miki's model according to

$$Z_c = \rho_0 c_0 \left[1 + 0.070 \left(\frac{f}{\sigma} \right)^{-0.632} - j0.107 \left(\frac{f}{\sigma} \right)^{-0.632} \right] \quad (24)$$

and wave number

$$k = \frac{\omega}{c} \left[1 + 0.109 \left(\frac{f}{\sigma} \right)^{-0.618} - j0.160 \left(\frac{f}{\sigma} \right)^{-0.618} \right] \quad (25)$$

The only material parameter needed for Miki's formula is the air flow resistivity σ of the porous material. Miki's formula is an improvement of the Delany and Bazley model [61]. Another modification of the Delany and Bazley model has been developed by Komatsu [62].

The extended reaction (the angle-dependent impedances) is of particular importance for accurate estimation at low frequencies. This is illustrated in Figure 3 where local and extended reactions are compared for the reverberation time T_{20} measured in a sparsely furnished room with dimensions 7.56 m $\times$ 7.30 m $\times$ 3.50 m and with a 15 mm thick absorbent ceiling at a mounting height of 200 mm (case 4 in Section 4). The figure shows the results using extended vs. local reaction in the model. Considerable deviation at low frequencies (125 Hz and 250 Hz) appears.

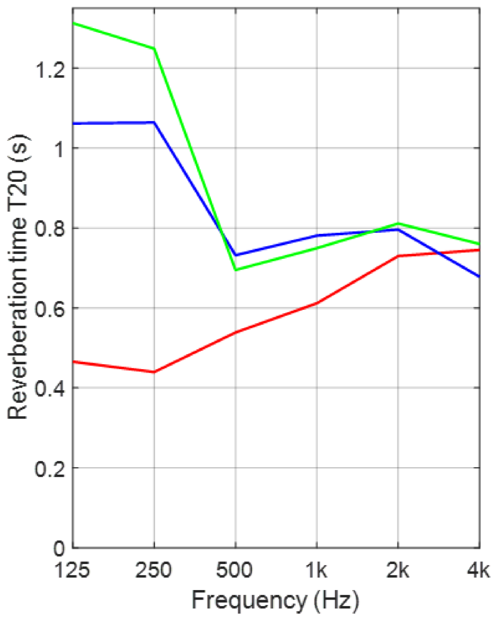

Figure 3. Local vs. extended reaction. Calculations according to the SEA model in a classroom with a 15 mm thick porous ceiling absorber with a mounting height of 200 mm (case 4 in the Section 5). Calculated local reaction (red), measured (blue), calculated and extended reaction (green).

3.2.2. Estimation of α_g and ΔN_g

To calculate the total energy decay, Equation (8) in Section 3.1, the number of modes in each sector and the corresponding reverberation times must be known. In this paragraph and the following paragraph, we will firstly estimate the representative absorption coefficients α_g and α_{ng} for the grazing and non-grazing sectors in Figure 2, as well as the number of modes ΔN_g and ΔN_{ng} in each sector.

The grazing sector is defined by an angle θ_g given by

$$\theta_g = \arccos\left(\frac{c}{4fL_x}\right) \tag{26}$$

The derivation of θ_g is given in Appendix A. The grazing sector in the wavenumber space is illustrated in Figure 4.

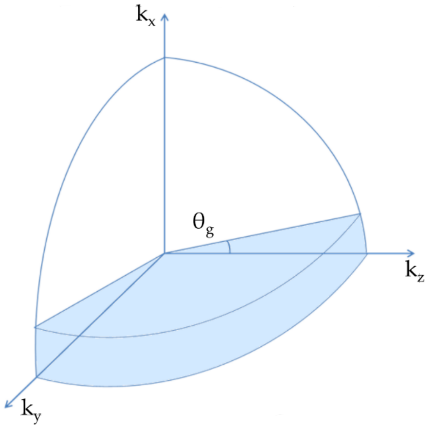

Figure 4. Grazing sector in the wavenumber space.

By knowing the surface impedance of the ceiling, the angle-dependent absorption coefficient can be calculated. The grazing absorption coefficient α_g is then calculated as the average absorption coefficient in the grazing region, i.e., between $\pi/2 - \theta_g$ and $\pi/2$. This absorption is often quite small but not negligible when compared to the total absorption for the grazing field. Equation (26) is a high-frequency estimation. At low frequencies, i.e., at 125 Hz and 250 Hz, the grazing absorption is estimated by

$$\alpha_{g,ceiling} = \pi \rho c A'_{xl} \tag{27}$$

where A'_{xl} is the real part of the admittance for the ceiling absorber. A'_{xl} is given by the real part of $1/Z$, where Z is given by Equation (22), assuming an extended reaction. The derivation of Equation (27) is given in Appendix B.

The number of grazing modes in the frequency band Δf is given by [55]

$$\Delta N_g(\theta_g) = \left[\left(\frac{4\pi f^2 V}{c^3}\right)\cos\left(\frac{\pi}{2} - \theta_g\right) + \left(\frac{2f}{c^2}\right)\left(\pi L_y L_z + \theta_g\left(L_x L_z + L_x L_y\right)\right) + \left(\frac{1}{c}\right)\left(L_y + L_z\right)\right]\Delta f \tag{28}$$

where V is the volume and L_x, L_y, and L_z are height, length, and width of the room, respectively. As $\theta_g \to 0$, the number of grazing modes corresponds to the tangential and axial modes in the yz plan.

3.2.3. Estimation of α_{ng} and ΔN_{ng}

To estimate α_{ng}, an intermediate step was used. This step includes the introduction of a weighted normalised absorption coefficient given by

$$\alpha_n(f,\theta) = \frac{\alpha(f,\theta)\Delta N(f,\theta)}{\max(\alpha(f,\theta)\Delta N(f,\theta))} \tag{29}$$

In this expression, $\Delta N(f,\theta)$ is the number of modes as a function of frequency and angle, as given by Equation (28) replacing θ_g with θ. The absorption coefficient $\alpha(f,\theta)$ is the angle-dependent absorption coefficient given by Equation (21), assuming an extended reaction. The non-grazing absorption coefficient α_{ng} is given by Equation (21) for an angle (θ_{ng}) corresponding to the maximum value in the distribution given by Equation (29).

Examples of this distribution are given for case 1 in Section 4 and for the frequencies 250 Hz and 4000 Hz, see Figure 5. In the classical diffuse field assumption, the angle-dependent absorption coefficient is weighted by the factor $\sin(2\theta)$, according to the Paris formula [63]. For comparison, the diffuse field weighting $\sin(2\theta)$ is also shown. As can be seen in the figure, there is a bias between the classical approach and the distribution, according to Equation (29). The representative angle for the non-grazing absorption coefficient is somewhat higher compared to the $\sin(2\theta)$. For the higher frequency, we see that the classical weighting corresponds to almost 45 degrees, as expected. The irregular shape at 250 Hz is due to the assumption of an extended reaction.

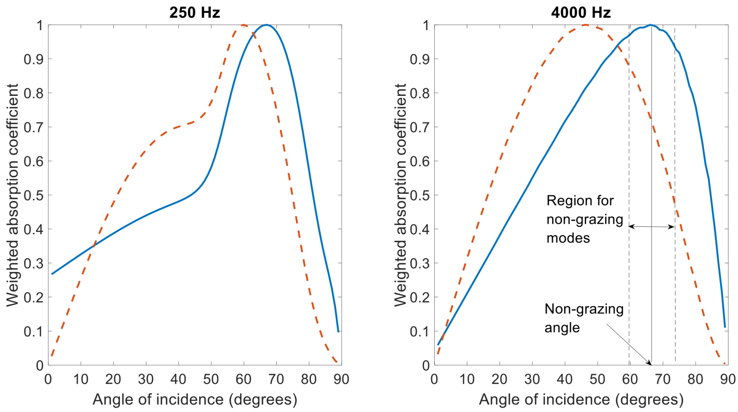

Figure 5. Distribution curves for the normalised weighted absorption coefficient according to Equation (29) for case 1 in Section 4.1. (Red) diffuse model, (blue) non-diffuse model.

Two approaches for determination of ΔN_{ng} were used: a theoretical one and an empirical one. For the empirical approach, the number of non-grazing modes was determined by adjustment towards experimental results for several configurations where room dimensions and acoustical treatment and furnishing were varied. An approach using minimization of a cost function to perform a curve fitting is presented in [64]. In the empirical method, the upper and lower angles defining the non-grazing sector, see Figure 2, are given by $\theta_{ng,\ lower} = \theta_{ng}(1 - \Delta\theta)$ and $\theta_{ng,\ higher} = \theta_{ng}(1 + \Delta\theta)$, where $\Delta\theta$ was estimated by comparison with measurements. Note that the angle of incidence $= \pi/2 - \theta$. Further, θ_{higher} is restricted to be less than $\pi/2$. The values for $\Delta\theta$ is given in Table 1 for the octave bands 125 Hz to 4000 Hz.

Table 1. Empirical determined limit parameter $\Delta\theta$ for defining the non-grazing region.

Frequency Hz	125	250	500	1000	2000	4000
$\Delta\theta$	0.63	0.31	0.14	0.17	0.07	0.08

The number of modes in the non-grazing sector ΔN_{ng} in Figure 2 is given by the repeated use of Equation (28) and is given by

$$\Delta N_{ng} = \Delta N_g\left(\theta_{ng,upper}\right) - \Delta N_g\left(\theta_{ng,lower}\right) \tag{30}$$

The theoretical approach involves calculating the number of modes for the non-grazing sector ΔN_{ng} as

$$\Delta N_{ng} = \frac{1}{\alpha_{ng}} \int_{0}^{\pi/2} \alpha(f,\theta)N(f,\theta)d\theta \tag{31}$$

where α_{ng} is the absorption coefficient corresponding to the angle defined by the maximum in the weighted normalized absorption coefficient given by Equation (29). By knowing this non-grazing angle, see Figure 5 right, the non-grazing absorption coefficient α_{ng} can be given by Equation (21).

For a room with dimensions 7.56 m × 7.30 m × 3.50 m and with an absorbent ceiling corresponding to case 1 in Table 2, the number of included modes in the non-grazing group given by the empirical and the theoretical approaches are compared in Figure 6. At lower frequencies (125 Hz and 250 Hz), the correspondence is good. At higher frequencies, the theoretical estimation gives significantly higher values compared to the empirical one. The consequence of this discrepancy will be further discussed in Section 5.

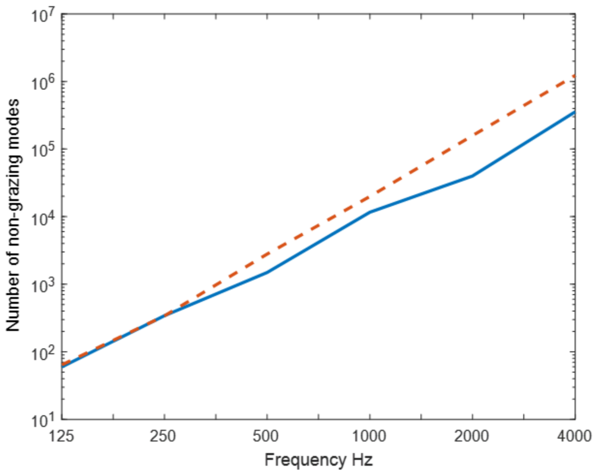

Figure 6. The number of modes in the non-grazing sector estimated by the empirical (solid) and theoretical (dashed) approaches.

The empirical and theoretical approaches described above are used for frequencies of 500 Hz and above. At 125 Hz and 250 Hz, the non-grazing absorption coefficient is estimated in the same way as the grazing one at low frequencies, i.e.,

$$\alpha_{ng,ceiling} = \pi\rho c A'_{xl} \tag{32}$$

where A'_{xl} is the real part of the admittance for the ceiling absorber, see Equation (27).

By knowing the number of modes in each sector, i.e., ΔN_g and ΔN_{ng}, and the representative absorption coefficients α_g and α_{ng}, we can go on and estimate the corresponding reverberation times T_g and T_{ng}.

3.2.4. Estimation of T_g and T_{ng}

The non-grazing reverberation time T_{ng} is given by

$$T_{ng} = \frac{0.161V}{A_{ng,ceiling} + A_{furniture} + A_{surface} + 4mV} \tag{33}$$

where $A_{ng,ceiling} = \alpha_{ng} S_{ceiling}$ and α_{ng} is the absorption coefficient corresponding to the angle given by the maximum in the weighted normalized absorption coefficient, as described in Section 3.2.3. $A_{furniture}$ is the Sabine equivalent absorption area for the furniture. An estimation of $A_{furniture}$ is given in [49] as $A_{furniture} = V_{furniture}^{2/3}$. $A_{surface}$ is the equivalent absorption area for the walls and floor. Normally, the absorption coefficients for those surfaces are rather small and can be found in tables, e.g., in [49]. The air absorption is taken into account by the term $4mV$ where m is the energy attenuation constant in air and V is the room volume.

Equation (33) is similar to the Sabine formula, but the skewness in the energy distribution is taken into account by using α_{ng}, as described in the paragraph above.

The grazing reverberation time T_g is given by a 2-dim version of Sabine formula [55]

$$T_g = \frac{0.127V}{A_{g,ceiling} + A_{sc} + A_{surface} + \pi mV} \tag{34}$$

where $A_{g,ceiling} = \alpha_g S_{ceiling}$ and α_g represents the absorption coefficient for the grazing sector, as derived in Section 3.2.2. In this formula, we also introduce the parameter equivalent scattering absorption area A_{sc}. This parameter quantifies the absorption and scattering effects of furniture and other objects in rooms with absorbent ceiling treatment. Thus, it also accounts for the directional scattering effects that can appear in these types of rooms, depending on the objects' orientation relative to the absorbent ceiling. The estimation of A_{sc} will be further discussed in the next paragraph. $A_{surface}$ is similar, as in Equation (33). It could be stated that a 2-dimensional statistical absorption coefficient should be used instead of a 3-dimensional one, but as the difference is small [55], $A_{surface}$ is calculated in the same way, as in Equation (33). It is assumed that the contribution of the floor is small and that it can be represented by the statistical absorption coefficient. However, for the air absorption, the distinction between the 2- and 3-dimensional sound fields is accounted for by using πmV instead of $4mV$.

3.2.5. Estimation of A_{sc}

The sound-scattering effects of furniture and other objects in rooms will greatly influence the room acoustic parameters in rooms where the absorbent material is concentrated to the ceiling. Reverberation time T_{20} and speech clarity C_{50} will be particularly affected. Sound strength G will normally be less affected as it is related to the steady-state conditions and thus will not be sensitive to the distribution of the absorbent material. To quantify the scattering effect, the following procedure was used.

In the terminology of SEA, the transfer of energy from the grazing to the non-grazing sound field is expressed in a coupling loss factor $\eta_{g,ng}$. The power flow $\Pi_{g,ng}$ from the grazing to the non-grazing subsystem is given by

$$\Pi_{g,ng} = \omega \eta_{g,ng} E_g \tag{35}$$

where $\eta_{g,ng}$ is the coupling loss factor from the grazing to the non-grazing subsystem and E_g is the energy in the grazing subsystem.

The coupling loss factor $\eta_{g,ng}$ can be estimated in a rectangular room with a highly absorptive ceiling. It is assumed that the two-system SEA model is valid for the sound field in the room, both with and without scattering objects (furniture) present. This is very often the case in rooms with absorbent ceiling treatment, as it is really difficult to create isotropic conditions in these types of rooms.

The coupling loss factor is then given by

$$\eta_{g,ng} = \eta_{g,with\ obj} - \eta_{g,without\ obj} \tag{36}$$

where $\eta_{g,with\ obj}$ is the grazing loss factor with objects in the room and $\eta_{g,\ without\ obj}$ is the grazing loss factor without objects in the room. These loss factors are determined from the reverberation time T_{20}, i.e., the late part of the decay curves in the room with and without objects. The relation between the reverberation time T and the loss factor is given by

$$\eta = \frac{6ln10}{\omega T} \tag{37}$$

In a two-dimensional sound field, an equivalent scattering absorption area can be defined as [55]

$$A_{sc} = \frac{\pi \omega V}{c} \eta_{g,ng} \tag{38}$$

where c is the speed of sound and V is the room volume.

Combining Equations (36)–(38) gives the equivalent scattering absorption area for objects as

$$A_{sc} = 0.127V\left(\frac{1}{T_{20,with}} - \frac{1}{T_{20,without}}\right) \tag{39}$$

where $T_{20,\ with}$ and $T_{20,without}$ are the reverberation times in the room with ceiling absorber, with and without objects, respectively. Equation (39) assumes that the late reverberation time T_{20} in a room with a highly absorptive ceiling is determined by a two-dimensional sound field. The measure A_{sc} is affected by the sound scattered into the ceiling and by the absorption of the objects. This measure is similar to the equivalent absorption area used in Sabine formula. It is used in the same way in Equation (34).

Of course, the A_{sc} will depend on the ceiling absorption properties. However, if the mean absorption coefficient of the ceiling absorber, for the mid and high frequencies, is larger than about 0.7, we will obtain a reasonable estimation of A_{sc} that can be used in most common situations of rooms with absorbent ceilings [65].

The A_{sc} for the investigated furniture configurations were measured according Equation (39) and are further discussed in the Section 5.

3.3. Summary

By knowing T_g, T_{ng}, ΔN_g, and ΔN_{ng}, the coefficient C in the basic formulas in Section 3.1 can be calculated. It is given by

$$C = \frac{T_g \Delta N_g}{T_{ng} \Delta N_{ng}} \tag{40}$$

It is possible to calculate the distance r between the sound source and the receiver for the actual positions, but in our calculations a representative distance was used given by

$$r = \frac{1}{2}\sqrt{L_y^2 + L_z^2} \tag{41}$$

where L_y and L_z are the width and length of the rectangular room, respectively.

Thus, all parameters are given and can be inserted into Equations (16)–(18) for further calculation of C_{50}, and G. T_{20} is calculated using the logarithmic version of Equation (8).

It should also be mentioned that, as the number of grazing and non-grazing modes are mainly related to the floor area and the volume of the room, it is of interest to investigate the model's applicability for other room shapes than rectangular, as long as the ceiling absorber is parallel to the floor.

4. Measurements and Methods

4.1. Measurement Configurations

The measurements were performed in a mock-up of a classroom with dimension length × width × height = 7.56 m × 7.30 m × 3.50 m, where 3.50 m refers to the height to the soffit. The classroom was sparsely furnished with 10 tables, 19 chairs, and 3 shelves, see Figure 7.

Figure 7. Sparsely furnished classroom mock-up. To the right with wall panels on two adjacent walls.

Two types of suspended ceilings were tested at two mounting heights. One of the suspended ceilings was tested in combination with wall panels on two adjacent walls, see Figure 7 right. The different configurations and specification of the material used are presented in Table 2.

Table 2. Measurement configurations.

Case	Ceiling and Wall Panels	Mounting Height (Depth of Air Cavity) of Suspended Ceiling (mm)	Air Flow Resistivity of Ceiling Absorber (kPas/m^2)
1	50 mm glasswool ceiling absorber * no wall panels	750	11.8
2	15 mm glasswool ceiling absorber **, no wall panels	785	77.8
3	15 mm glasswool ceiling absorber **, 6.48 m^2 40 mm glasswool wall absorber *** distributed on two adjacent walls and directly mounted on the walls, see Figure 7.	785	NA
4	15 mm glasswool ceiling absorber **	185	77.8
5	50 mm glasswool ceiling absorber *	150	11.8

* Ecophon Industry Modus, ** Ecophon Gedina A, *** Ecophon Wall Panel A. Note: the air flow resistivity is only used as input data for the ceiling absorbers and not for the wall panels. For the wall panels the practical absorption coefficients are used, see Figure 8.

The absorption data for the products used are presented in Figure 8. The absorption coefficients were measured according to ISO 354 [45] and evaluated by ISO 11654 [66]. This presentation of absorption data as a practical absorption coefficient is common practice by manufactures of absorbent ceilings.

4.2. Measurement Method

The room impulse responses were measured using the Dirac system (Dirac type 7841, v.6.0). An exponential sweep signal was fed to an omnidirectional loudspeaker and recorded by an omnidirectional microphone. Two loudspeaker positions at the front of the classroom were used and, for each loudspeaker position, six microphone positions were used throughout the room. No microphone positions were closer than 2 m to the loudspeaker and none were closer than 1 m to any of the room surfaces.

The room acoustic parameters measured were reverberation time T_{20} (s), speech clarity C_{50} (dB), and sound strength G (dB). C_{50} and G are defined in ISO 3382-1. T_{20} was evaluated according to ISO 3382-2 using the interval −5 to −25 dB of the decay curve. The sound strength G was measured using a constant sound power source (Nor278, Norsonic). The sound power source was located in the same positions as the loudspeaker.

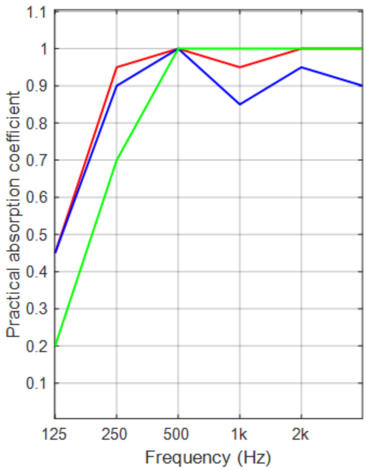

Figure 8. The practical absorption coefficients for the ceiling absorbers and wall panels used in the experiments. (Red) Ecophon Industry Modus 50 mm, (blue) Ecophon Gedina A 15 mm, (green) Wall Panel A 40 mm.

4.3. Repeatability

A repeatability test was performed for the measurement procedure described above. The measurements were repeated five times. Between each measurement, the loudspeaker and the microphone were taken out of the room and reinstalled at different positions. For details see [67].

In Table 3, the uncertainty is given for the measurement procedure.

Table 3. Uncertainty interval related to repeatability, corresponding to a 95% confidence interval, for the measurement procedure used in the experiments.

	G_{avg} (dB)	$C_{50,avg}$ (dB)	$T_{20,avg}$ (s)
125 Hz	±0.61	±0.56	±0.077
250 Hz	±0.30	±0.29	±0.018
500 Hz	±0.40	±0.29	±0.010
1000 Hz	±0.25	±0.27	±0.006
2000 Hz	±0.37	±0.38	±0.010
4000 Hz	±0.36	±0.36	±0.008

The variations in repeated measurements are less noticeable (JND), according to ISO 3382-1 [1]. This supports the discussion of significant differences in the measurements.

4.4. Estimation of the Equivalent Scattering Absorption Area A_{sc}

The A_{sc} for the furniture configurations is estimated by Equation (39). The A_{sc} for the furniture in combination with the two ceiling treatments and for the two mounting heights, given in Table 2, were measured. No wall panels were present during these measurements. The results are presented in Section 5.1. The same number of microphone and loudspeaker positions were used, as for the measurements of the room acoustic parameters.

4.5. Comparison between Measurements and Calculations

The measurements and calculations were compared for the octave band frequencies 125 Hz to 4000 Hz. Calculations of C_{50} and G were performed with the formulas presented in Section 3, according to Equations (19) and (20). T_{20} was calculated by the logarithmic version of Equation (8) using the -5 to -25 dB dynamical range according to ISO 3382-2.

For comparison, calculations according to the Sabine formula were included. The reverberation time T was calculated as

$$T = \frac{0.161V}{A_{ceiling} + A_{furniture} + A_{surface} + 4mV} \tag{42}$$

where $A_{ceiling} = \alpha_p S_{ceiling}$ and α_p is the practical absorption coefficient given in Figure 8. $A_{furniture} = V_{furniture}^{2/3}$, according to the EN 12354-6. For a sparsely furnished room, $V_{furniture}$ is approximately 1–2% of the room volume [29]. $A_{surface}$ and the air absorption were calculated in the same way as in Equation (33).

The absorption coefficients for the floor and walls were estimated from the reverberation time measurements in the empty room, i.e., without an absorbent ceiling. Those values were used both in the diffuse and non-diffuse calculations for calculating $A_{surface}$.

Assuming a linear decay under diffuse field conditions and a reverberation time, given by Equation (42), C_{50} and G are calculated as

$$C_{50} = 10\log\left(10^{(6/T)0.05} - 1\right) \tag{43}$$

And

$$G = 10\log\left(\frac{4}{A}\right) + 31 \tag{44}$$

where $A = 0.16\frac{V}{T}$ is the equivalent absorption area in m^2 sabin and V is the room volume.

5. Results

5.1. Estimation of A_{sc}

The equivalent scattering absorption area A_{sc} for the furniture was measured for configurations 1, 2, 4, and 5 given in Table 2. The A_{sc} is estimated according to Equation (39). In Figure 9, the results are presented together with the averaged values.

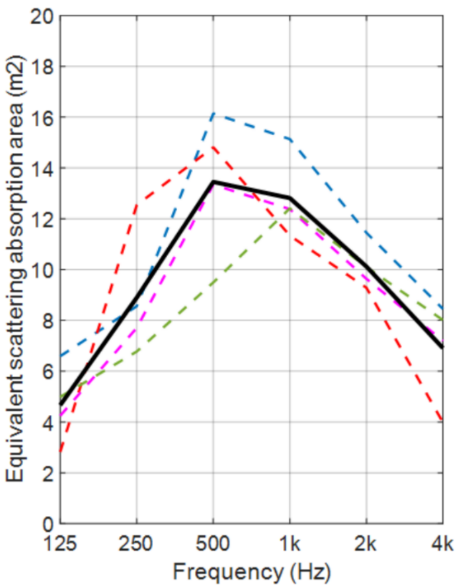

Figure 9. A_{sc} for the furniture estimated from cases 1, 2, 4 and 5 in Table 2, (black) average, (blue) case 4, (red) case 5, (purple) case 1 and (green) case 2.

A_{sc} depends on the absorption of furniture as well as the scattered sound energy transmitted to the non-grazing sound field and mainly absorbed by the ceiling absorber. As can be seen in Figure 9, the frequency behavior is quite similar for the different cases despite the fact that there is a variation of the ceiling absorber concerning airflow resistivity, thickness, and mounting height. This supports the idea that, for ceiling absorbers with a reasonably high absorption, see comment in Section 3.2.5, the correction for furniture absorption and scattering by A_{sc} is justified. For furnishing with tables, chairs, and shelves, the highest values of A_{sc} appears for the mid frequencies, as apparent from Figure 9. In practice, it is also possible to define A_{sc} per m^2 floor area to obtain a value that can be used for different sizes of rooms. In [29], values of A_{sc} per m2 floor area are suggested for what can be considered as sparse, normal, and dense furnishing. It is noteworthy that, in EN 12354-6, the correction for furniture and other objects in the room is independent of frequency.

5.2. Measurement Results

The measurements results are presented in Figures 10–14, corresponding to the cases 1 to 5 in Table 2. In the figures (a) is the reverberation time $\boldsymbol{T}_{20}$ in seconds, (b) is the speech clarity $\boldsymbol{C}_{50}$ in dB and (c) is the sound strength $\boldsymbol{G}$ in dB. Comparisons are made between measurements, Sabine calculation and the non-diffuse calculation. For the non-diffuse calculation, both the empirical and the theoretical approaches, discussed in Section 3.2.3, are shown.

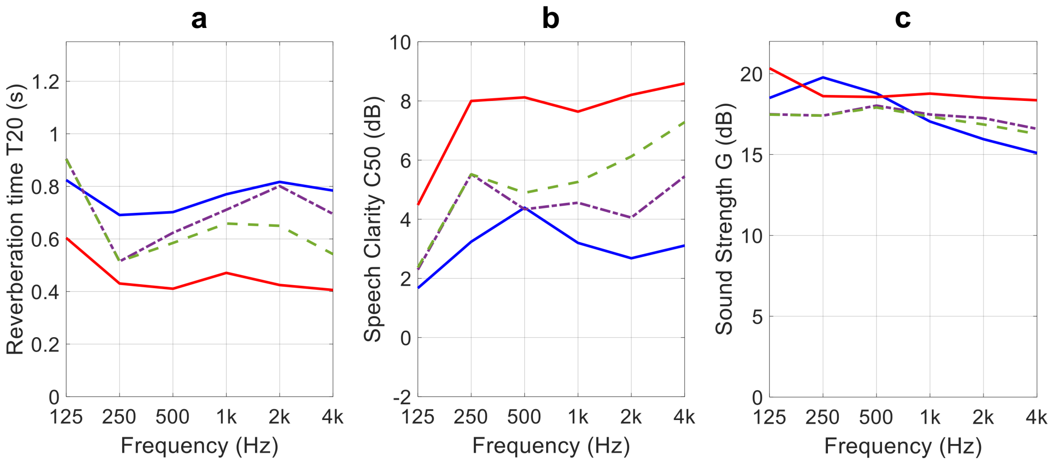

Figure 10. Sparsely furnished room with dimensions 7.35 × 7.50 × 3.50 m. Ceiling treatment: 50-mm glass wool absorber at a mounting height (air cavity behind the absorber) of 750 mm. (**a**) Reverberation time $\boldsymbol{T}_{20}$ in seconds, (**b**) speech clarity $\boldsymbol{C}_{50}$ in dB, (**c**) sound strength $\boldsymbol{G}$ in dB. Curves shown are (red) diffuse calculation (Sabine), (blue) measurement, (dashed) non-diffuse calculation, where the number of non-grazing modes is estimated by Equation (31), and (dash-dotted) non-diffuse calculation, where the number of non-grazing modes is empirically estimated, see Table 1.

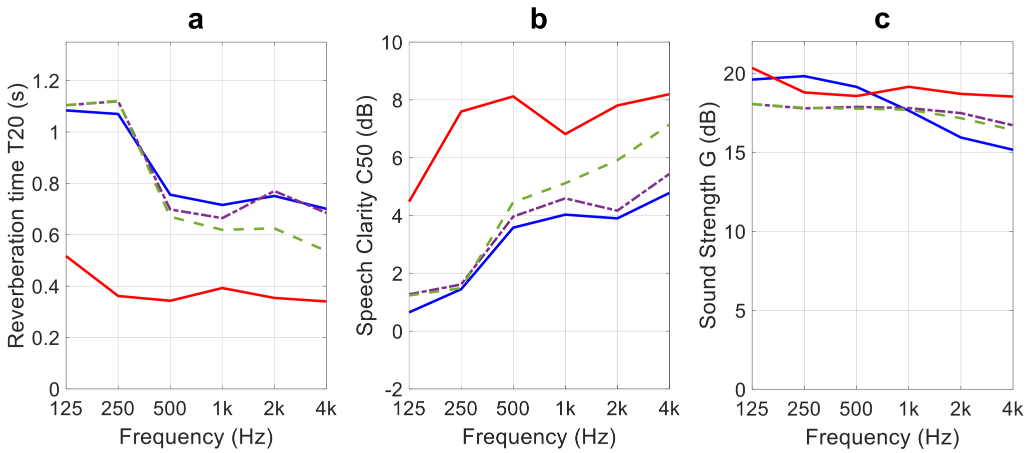

Figure 11. Sparsely furnished room with dimensions 7.35 × 7.50 × 3.50 m. Ceiling treatment: 15-mm glass wool absorber at a mounting height (air cavity behind the absorber) of 785 mm. (**a**) Reverberation time T_{20} in seconds, (**b**) speech clarity C_{50} in dB, (**c**) sound strength G in dB. Curves shown are (red) diffuse calculation (Sabine), (blue) measurement, (dashed) non-diffuse calculation, where the number of non-grazing modes is estimated by Equation (31), and (dash-dotted) non-diffuse calculation, where the number of non-grazing modes is empirically estimated, see Table 1.

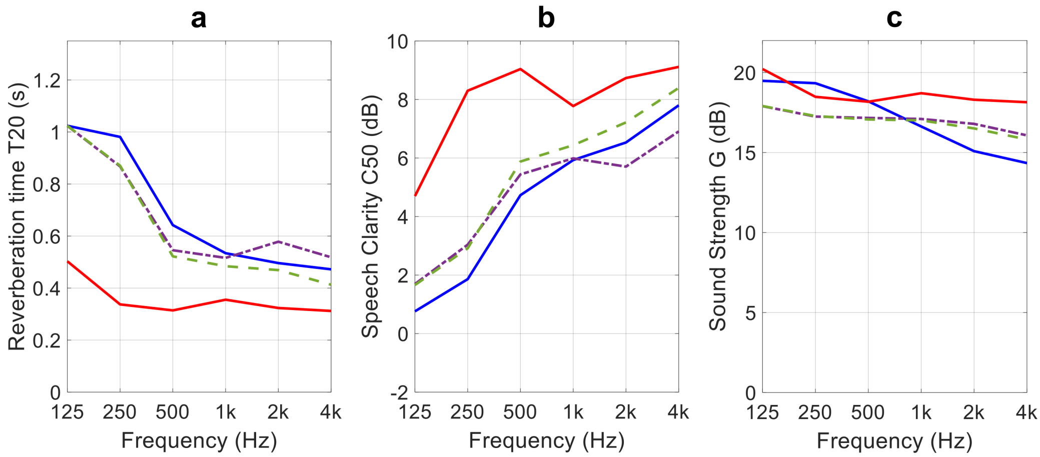

Figure 12. Sparsely furnished room with dimensions 7.35 × 7.50 × 3.50 m. Ceiling treatment: 15 mm glass wool absorber at a mounting height (air cavity behind the absorber) of 785 mm. 6.48 m^2 40 mm glass wool wall absorber equally distributed on two adjacent walls and directly mounted on the walls, see Figure 7. (**a**) Reverberation time T_{20} in seconds, (**b**) speech clarity C_{50} in dB, (**c**) sound strength G in dB. Curves shown are (red) diffuse calculation (Sabine), (blue) measurement, (dashed) non-diffuse calculation, where the number of non-grazing modes is estimated by Equation (31), (dash-dotted) non-diffuse calculation, where the number of non-grazing modes is empirically estimated, see Table 1.

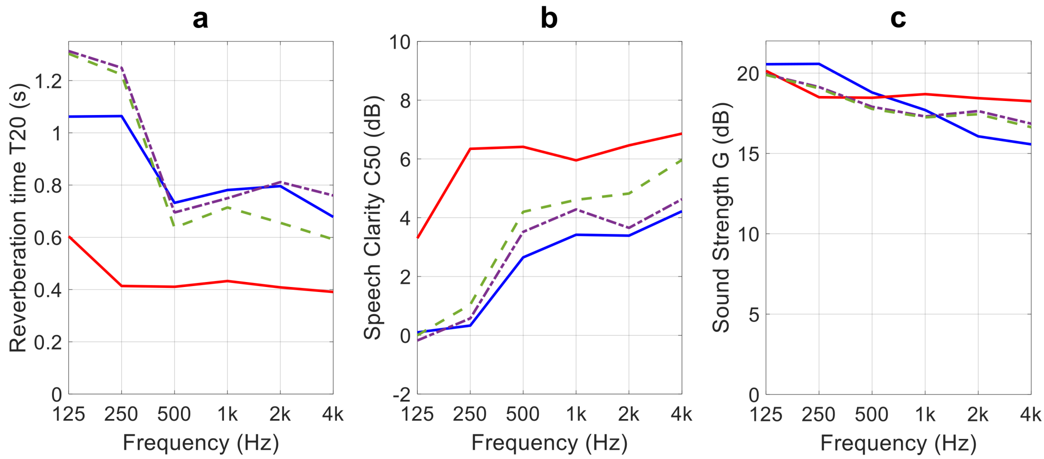

Figure 13. Sparsely furnished room with dimensions 7.35 × 7.50 × 3.50 m. Ceiling treatment: 15 mm glass wool absorber at a mounting height (air cavity behind the absorber) of 185 mm. (**a**) Reverberation time T_{20} in seconds, (**b**) speech clarity C_{50} in dB, (**c**) sound strength G in dB. Curves shown are (red) diffuse calculation (Sabine), (blue) measurement, (dashed) non-diffuse calculation, where the number of non-grazing modes is estimated by Equation (31), (dash-dotted) and non-diffuse calculation, where the number of non-grazing modes is empirically estimated, see Table 1.

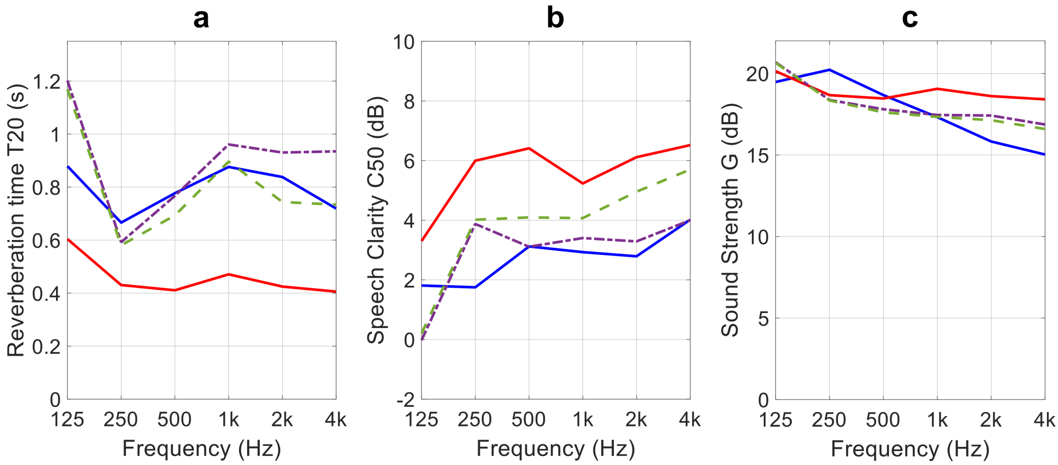

Figure 14. Sparsely furnished room with dimensions 7.35 × 7.50 × 3.50 m. Ceiling treatment: 50 mm glass wool absorber at a mounting height (air cavity behind the absorber) of 150 mm. (**a**) Reverberation time T_{20} in seconds, (**b**) speech clarity C_{50} in dB, (**c**) sound strength G in dB. Curves shown are (red) diffuse calculation (Sabine), (blue) measurement, (dashed) non-diffuse calculation, where the number of non-grazing modes is estimated by Equation (31), and (dash-dotted) non-diffuse calculation, where the number of non-grazing modes is empirically estimated, see Table 1.

Overall, the non-diffuse model fits better with the measurement results than the diffuse model. In particular, the overestimation of the absorption in the diffuse model is reduced in the non-diffuse model. The large differences between the diffuse calculations and the measurement results are typical for sparsely furnished rooms with an absorbent ceiling treatment. The cause of this is the lack of diffusion and the influence of the grazing sound field. Naturally, the empirical estimation given in Table 1 agrees better with measurements than the theoretical approach, according to Equation (31). This is more apparent at the higher frequencies. It is noticeable that the non-diffuse model captures the frequency behavior better than the diffuse one.

An important feature of the non-diffuse model is the reaction to wall panels. The effect of wall panels is the reduction in the energy in the grazing sound field. In sparsely furnished rooms, this largely influences the late reverberation time and the speech clarity. This is clearly shown in Figure 15. The correspondence between the non-diffuse calculation and measurement is good. For the diffuse model, a much smaller effect is noticed. The effect of wall panels on sound strength G is small. As G is a steady-state measurement, it is mainly related to the total absorption in the room, assuming that the sound field is fairly diffuse before the onset of the decay. During the decay, the degeneration of the sound field towards a grazing sound field will affect reverberation times and speech clarity to a great extent, as shown in the experimental results.

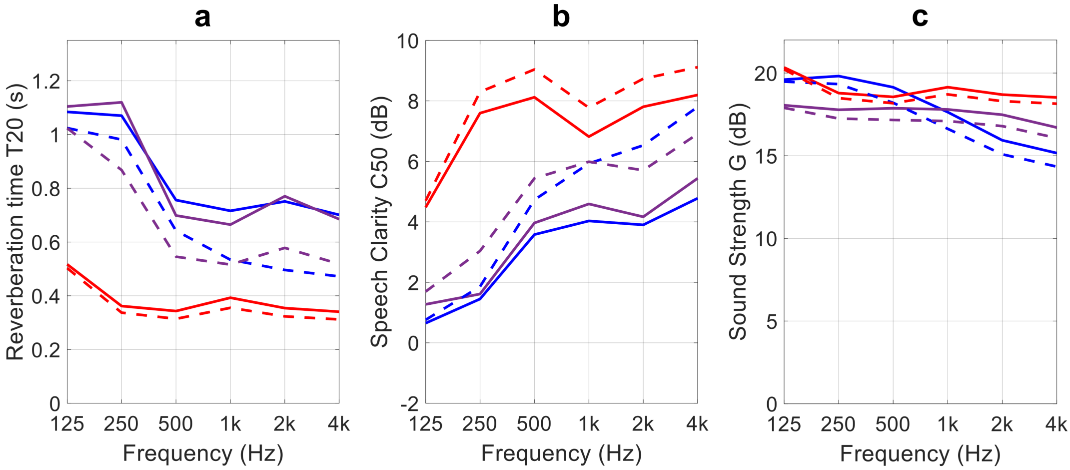

Figure 15. Comparison of case 2 and 3 in Table 2, i.e., the cases with and without wall panels. (**a**) Reverberation time T_{20} in seconds, (**b**) speech clarity C_{50} in dB, (**c**) sound strength G in dB. (Blue solid) measured without wall panels, (blue dashed) measured with wall panels, (purple solid) non-diffuse calculation without wall panels, (purple dashed) non-diffuse calculations with wall panels, (red solid) diffuse calculations without wall panels, and (red dashed) diffuse calculations with wall panels. The empirical approach is used for the non-diffuse calculations, see Section 3.2.3.

Note that the results presented above refer to a sparsely furnished room which is very sensitive to the accuracy of the input data. It is notable that the case with the wall panels decrease the discrepancy between the theoretical and empirical model and also fits better with measurements.

In Figure 16, a comparison of the two ceilings absorbers corresponding to case 1 and 2 in Table 2 is shown. The practical absorption coefficients for these absorbers, as given by the manufactures, is shown in Figure 8. Besides the large difference between the diffuse calculations on the one hand (red curves) and the measurements and non-diffuse calculations on the other (blue and green curves) some other remarks can be made. The practical absorption coefficients, based on ISO 354 measurements, show similar values at 125 Hz for the two absorbers. Accordingly, the diffuse calculations show the same reverberation time at this frequency. However, the non-diffuse calculations give a large difference at 125 Hz which also corresponds to the measurements. It is also noteworthy that, at high frequencies, the non-diffuse calculations and the measurements show contradictory behavior in comparison with the diffuse calculations. The diffuse calculations follow the difference in the practical absorption coefficients which is not the case for the measurements and the non-diffuse calculations. This emphasizes the fact that the absorption coefficients measured under reverberant conditions, as in ISO 354, do not comprise sufficient information for the acoustic design of rooms with ceiling treatment. Other information is needed and, in the model presented, the surface impedance of the ceiling absorber is necessary input data.

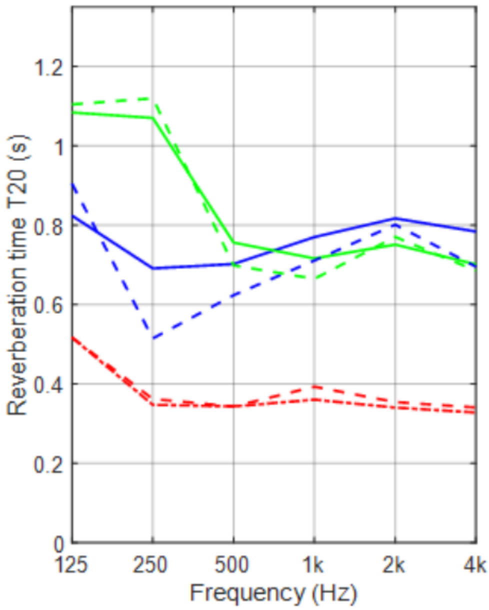

Figure 16. Measured and calculated reverberation times for case 1 and 2 in Table 2. Fifty mm and fifteen mm thick porous ceiling absorbers at a mounting height of 760 mm and 785 mm, respectively, were investigated. (Dashed green) 15 mm absorber, non-diffuse calculation; (solid green) 15 mm absorber, measurement; (dashed blue) 50 mm absorber, non-diffuse calculation; (solid blue) 50 mm absorber, measurement; (dashed red) 50 mm absorber, diffuse calculation; and (dash-dot red) 15 mm absorber, diffuse calculation.

6. Discussion

A model is presented based on a subdivision of the sound field into a grazing and non-grazing subsystem, where grazing refers to sound waves propagating almost parallel to the absorbent ceiling. An advantage of this approach is its interpretation of sound scattering due to interior equipment such as furniture, diffusors, or similar. The scattering effect is quantified in a parameter related to the energy transfer from the grazing to the non-grazing group. The parameter is denoted as the equivalent scattering absorption area A_{sc} and comprises the scattering and absorbent effect of interior objects in a room with a highly absorptive ceiling. Due to the presumption of an absorbent ceiling, the directional scattering effects of objects will appear. It is assumed that the ceiling absorption is much larger than the average absorption for walls and floors. An average absorption coefficient for the ceiling absorber greater than 0.7 for the octave bands ranging from 250 to 4000 Hz seems to be sufficient for most practical situations, but this has to be further investigated [65]. There is an assumption concerning sufficiently great ceiling absorption to ensure that the energy reflected back to the non-grazing field can be neglected. It might also be of future interest to specify the conditions for a laboratory configuration as to how to estimate A_{sc}. The methodology could be used to give input data for typical furnishing scenarios in different segments such as schools, offices, and healthcare premises. The directional effects of diffusors were studied in a classroom configuration by Arvidsson et al. [67].

In the presented model, it is assumed that the surface impedance is known or can be calculated for the suspended ceiling. Other surfaces are dealt with in a normal way using the practical or statistical absorption coefficients. Data for this can be found in handbooks in acoustics or manufactures' websites. The surface impedance is not a parameter normally provided by the manufacturers of absorbent ceilings. However, several examples of commercial software exist today that calculates the surface impedances for different types of absorbers.

The need to include more complex boundary conditions for improved accuracy has also been noted in the development of simulation models [68]. Furthermore, the assumption of local reaction was investigated and the benefits of an extended reaction were shown to improve in accuracy, especially at lower frequencies [69].

In the model, the distance from the sound source to the receiver is a parameter. In this investigation, a representative value, see Equation (41), was used. For open-plan offices, it is of interest to calculate the sound propagation over distances corresponding, e.g., to different workplaces. As the model accounts for the distance and takes into account the angle-dependent absorption of the ceiling absorber, it would also be of interest to investigate this application.

Another application where the non-diffuse sound fields appear are sport halls. A common treatment in such rooms is an absorbent ceiling. The present model clarifies the considerable deviation between diffuse field calculations and measurements that often appear in these rooms. It also shows the importance of a more uniform distribution of absorbent material.

The general assumption of the SEA approach and the method for a subdivision into a grazing and non-grazing sound field can be further improved. It is assumed that the ceiling is the most absorptive area in the type of rooms investigated. However, a more precise description of the non-uniform absorption conditions would be valuable. Comparison with field measurements of different room types would clarify the models applicability and point out opportunities for improvements. Similarly, the limits in the method of estimating the equivalent scattering absorption area must be further investigated. The statistical approach requires a certain minimum room volume for the application of the model. This needs further investigation, but experiences so far indicate a room volume larger than 50 m^3.

In any event, the purpose of the model is to give a direct and reasonably accurate estimation of room acoustic parameters in rooms with absorbent ceiling treatments. The model accounts for the actual mounting height of the ceiling absorber, including both the scattering and absorbing effects of furniture, and reveals the typical characteristic behavior of sound fields in rooms with ceiling treatment, such as the effects of adding wall absorbers.

7. Conclusions

A statistical energy analysis (SEA) model was developed for rooms with absorbent ceiling treatments. The model is based on a subdivision of the sound field into a grazing and non-grazing subsystem where grazing refers to sound waves propagating almost parallel to the absorbent ceiling. The scattering and absorbing effects of furniture and other interior objects is quantified in a measure denoted as the equivalent scattering absorption area A_{sc}. This parameter is related to the energy transfer between the grazing and non-grazing subsystem. The back-transfer from the non-grazing to the grazing subsystem is assumed to be negligible. As a consequence, it is assumed that the ceiling absorption is much greater than the average absorption for walls and floors. An average absorption coefficient for the ceiling absorber greater than 0.7 for the octave bands ranging from 250 to 4000 Hz seems to be sufficient for most practical situations, but this has to be further investigated. In the model, it is assumed that the surface impedance for the suspended ceiling is known or can be calculated. Other surfaces are dealt with in the usual way, using the practical or statistical absorption coefficients. Based on the airflow resistance of the ceiling absorbers investigated, the surface impedances are estimated by the Miki's model, assuming an extended reaction. Thus, the actual mounting height of the ceiling absorber can be accounted for.

The new model was compared with the classical diffuse field model. Experiments were carried out in a classroom mock-up. Two different ceiling absorbers for two different mounting heights were each investigated. One of these cases was also tested in combination with wall panels on two adjacent walls. For all the experiments carried out, the new model shows better agreement with measurements than the classical diffuse field model. The new model reproduces the frequency behaviour of the room acoustic parameters as well as accounting for wall panels in closer agreement with measurements than the diffuse field model.

Further comparison with well-documented field measurements is necessary for the fine-tuning of the model, as well as investigation of the methodology used for estimating the equivalent scattering absorption area.

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Appendix A

Derivation of the grazing angle at high frequencies.

A more profound argumentation for the theory outlined in this appendix is given in [55,70].

We consider the rectangular room in Figure A1.

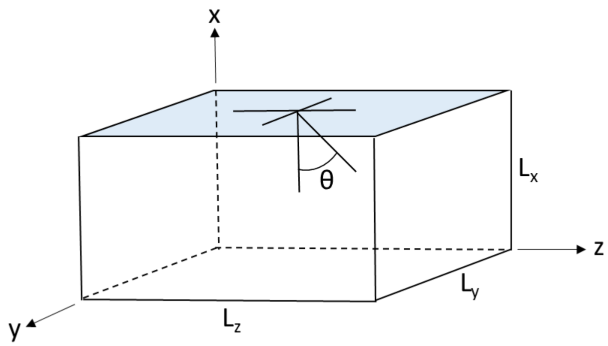

Figure A1. Room with absorbent ceiling.

From the wave equation, the complex wave number is given by

$$\underline{k}^2 = \underline{k}_x^2 + \underline{k}_y^2 + \underline{k}_z^2 \quad \text{(A1)}$$

and

$$\cos(\theta) = \frac{k_x}{k} \quad \text{(A2)}$$

where k_x and k is the real part of $\underline{k}_x$ and $\underline{k}$, respectively.

Near the absorbing ceiling we expect a phase step of nearly π for grazing incidence. This means that the real component of $\underline{k}_x$ is approximately [55]

$$k_x = \frac{\pi}{L_x}\left(n_x + \frac{1}{2}\right) \quad \text{(A3)}$$

where n_x is an integer $0, 1, 2 \ldots$

Equations (A2) and (A3) gives

$$\cos(\theta) = \frac{c\pi}{\omega L_x}\left(n_x + \frac{1}{2}\right) \tag{A4}$$

θ_g is defined by Equation (A4) for $n_x = 0$. Thus we get

$$\theta_g = \arccos\left(\frac{c}{4fL_x}\right) \tag{A5}$$

By knowing the impedance Z of the ceiling absorber, the grazing absorption coefficient α_g is then calculated as the average absorption coefficient in the grazing region defined by θ_g.

Appendix B

Grazing absorption at low frequencies.

If we consider sound propagation mainly in the yz-plan in Figure A1, the surfaces at $x = 0$ and $x = L_x$ are exposed for the grazing sound field. An expression for a grazing decay constant at low frequencies was derived by Morse and Bolt [71]. An expression of the decay constant at low frequencies is given by

$$\delta = \rho c^2\left(\frac{A'_{x0} + A'_{xl}}{2l_x} + \frac{A'_{y0} + A'_{yl}}{l_y} + \frac{A'_{zo} + A'_{zl}}{l_z}\right) \tag{A6}$$

where A' is the real part of the admittance. Assuming all the walls and floor in Figure A1 rigid, except for the ceiling, we get

$$\delta = \rho c^2 \frac{A'_{xl}}{2l_x} \tag{A7}$$

For the almost two-dimensional grazing sound field, the contribution from the ceiling to the grazing absorption is given by [55].

$$\eta_{g,ceiling} = \frac{c}{\pi V\omega} S_{ceiling}\alpha_{g,\ ceiling} \tag{A8}$$

The relation between the loss factor η and the decay constant δ is

$$\eta = \frac{2\delta}{\omega} \tag{A9}$$

The grazing ceiling absorption is given by combining Equations (A7)–(A9). We get

$$\alpha_{g,ceiling} = \pi\rho c A'_{xl} \tag{A10}$$

where A'_{xl} is the real part of the admittance for the ceiling absorber. A'_{xl} is given by real part of $1/Z$ where Z is given by Equation (22), assuming an extended reaction.

Equation (A10) is used as an approximation for $\alpha_{g,ceiling}$ for the frequencies 125 Hz and 250 Hz.

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Subjective Experience of Speech Depending on the Acoustic Treatment in an Ordinary Room

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Abstract: In environments such as classrooms and offices, complex tasks are performed. A satisfactory acoustic environment is critical for the performance of such tasks. To ensure a good acoustic environment, the right acoustic treatment must be used. The relation between different room acoustic treatments and how they affect speech perception in these types of rooms is not yet fully understood. In this study, speech perception was evaluated for three different configurations using absorbers and diffusers. Twenty-nine participants reported on their subjective experience of speech in respect of different configurations in different positions in a room. They judged sound quality and attributes related to speech perception. In addition, the jury members ranked the different acoustic environments. The subjective experience was related to the different room acoustic treatments and the room acoustic parameters of speech clarity, reverberation time and sound strength. It was found that people, on average, rated treatments with a high degree of absorption as best. This configuration had the highest speech clarity value and lowest values for reverberation time and sound strength. The perceived sound quality could be correlated to speech clarity, while attributes related to speech perception had the strongest association with reverberation time.

Keywords: acoustic comfort; acoustic design; room acoustics; sound quality; sound strength; speech clarity; speech perception; reverberation time

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1. Introduction

This study deals with the acoustic environment of ordinary public rooms such as classrooms and offices. Typically, complex tasks are performed in these types of environments—tasks that require chains of thought and the processing of information. To accomplish such tasks, appropriate room acoustics are necessary. It is well known that noise can cause stress and disturb concentration [1]. Studies by Kjellberg et al. and Ljung et al. show how the sound environment can also affect cognitive performance [2–4]. Those studies show how greater effort is needed to perform tasks if the sound environment is unsatisfactory. Furthermore, the effort required to remember single words is less than that required in order to process information [5]. For non-native listeners, the room acoustic environment is even more critical. Lam [6] could see that greater effort is needed for such listeners to achieve equivalent scores in tests. Furthermore, well-being can also be associated with the acoustic environment [7].

Traditionally, reverberation time, T_{20}, is the room acoustic parameter that is controlled in ordinary rooms. This parameter is the time it takes for the sound level to decrease 60 dB from the moment the sound source is turned off. However, it has been found that complementary parameters are needed in order to properly describe the acoustics required to achieve a satisfactory sound environment. One such parameter is speech clarity, C_{50}, accounting for the ratio of early reflections. The early reflections will contribute to the direct sound [8]. Bradley et al. [9] recommend focusing on increasing the ratio of early reflections rather than on lowering the reverberation time in rooms used for speech. It has also been shown in another study by Bradley and Reich that C_{50} can, to some extent, complement a low signal-to-noise (S/N) ratio [10]. Yang and Bradley investigated speech intelligibility for different room acoustic conditions, finding high scores in intelligibility along with an increase in early reflections; S/N also affected speech intelligibility, with a lower effect being seen for varied reverberation time [11]. It has also been seen in a study by Sato et al. that higher energy in early reflections can compensate for a lower sound level with regard to speech intelligibility and listening difficulty [12]. In a study investigating the reading ability of Italian second graders, C_{50} was the best correlating acoustic parameter [13]. C_{50} is included in the standard ISO 3382-1 Acoustics—Measurement of room acoustic parameters—Part 1: Performance spaces [14], where performance spaces are environments such as theatres and concert halls. Another parameter included in this standard and that is normally controlled in performance spaces is sound strength [15–17], G, providing information as to how a room responds to the sound source. As mentioned above, T_{20} is normally the focus parameter in ordinary rooms, where the target is often to lower T_{20} by adding absorbing material. The addition of absorbing material will also result in a lower sound level. A risk to be considered in relation to a high degree of absorption is too low a speech level, resulting in not everyone in the audience receiving information [18].

Lately, the need for additional parameters has also been observed in standards, such as the Italian standard UNI 11532 [19], where speech clarity, C_{50}, is included for classrooms. In regard to offices, parameters such as the speech transmission index, STI, are included in the standard EN-ISO 3382-3 for acoustic measurements in open offices [20]. Furthermore, a new standard with recommendations for the design of this type of environment has been published: ISO 22955:2021 Acoustics—Acoustic quality of open office spaces [21].

The acoustic properties needed depend on the activity being performed in a room; a classroom with one person speaking places different demands to an open office that could have several sound sources. Typically, several different activities run at the same time in open plan environments. These different environments demand different acoustic properties and, thus, different acoustic treatments.

In studies by Choi [22–24], diffusers and absorbers were combined in a small-scale set-up. Using simulations, Labia et al. investigated the placement of absorbers and diffusers in a meeting room environment [25]. In a previous study, a combination of these types of materials was examined in a full-scale mock-up [26]. The results show how an acoustic ceiling is a good baseline, affecting several room acoustic parameters, and also how additional treatment, such as absorbers or diffusers, can be used to fine-tune room acoustics; this means that a combination of these types of solutions can be appropriate.

The placement of the absorbing material is important [27,28]. Azad et al. also investigated the combination of absorbers and diffusers, specifically how a diffuser directing the sound to an absorbent area in a non-diffuse room shows significant effects on the room acoustic parameters evaluated [29]. Shtrepi et al. investigated how the location of diffusers and the distance from them can affect room acoustics, and showed that the perception of room acoustic parameters did not vary significantly with the location of the diffusers, nor were listeners sensitive to the location of the diffusers [30].

The need to consider diffusion and scattering in these types of rooms is also considered in the Italian standard UNI 11532-2 [19] and the German standard 18041 [31].

How diffusers can affect speech intelligibility was investigated by Visentin et al. [32], who identified improvements relating to diffuse reflections as compared to specular. The listening effort related to acoustic design has also been investigated by Visentin et al. [33]. Sanavi et al. studied whether treatment with absorption or diffusing material affects the subjective experience of the acoustics, showing that the jury could recognize both types of treatments, but that the absorber was rated better [34]. In a previous study, evaluation was made of whether people could perceive a difference between various types of acoustic treatments as well as in different positions in the room. It was found that configurations including diffusers were, to a greater extent, perceived as similar in different positions in the room. It was also found that room acoustic parameters such as T_{20}, C_{50} and G could not fully explain the subjective experience; other descriptors or the development of measurement techniques could be an alternative. However, C_{50} was the parameter that best explained the subjective experience of the acoustics. A difference of at least 2 dB was needed for the jury to perceive a difference [35]. In a study by Bradley and Reich, it was concluded that 3 dB is a relevant value as a just noticeable difference (JND) in rooms for speech [36]. In ISO 3382-1 [14], in performance spaces, the typical value for JND is 1 dB for C_{50}. However, it has been recognized in different studies that the JND can differ for different frequencies and for different types of music [37].

Study Objective

In ordinary public rooms such as classrooms, complex tasks are performed. From the abovementioned references, it is clear that a room's acoustics affect cognitive performance. Further, the type of acoustic treatment used will affect the acoustics differently, both objectively and subjectively. The relation between these two aspects, the objective parameters and subjective experience, in ordinary public rooms for speech, is not yet fully understood. The study of this relation has been the objective of the work presented in this article.

The study is part of a research programme aiming at improving the acoustics in ordinary public rooms. In previous studies included in that programme, the effect on room acoustic parameters depending on the type of acoustic treatment was investigated [26]. This was followed up by a study of whether people could subjectively experience a difference between the configurations using different treatments [35]. The subjective experience of sound is further investigated in the study presented in this article by relating the different configurations and the room acoustic parameters to aspects such as sound quality, attributes and ratings of the different environments. This aims at achieving a better understanding of what people prefer when it comes to the acoustics in ordinary public rooms for speech and, in so doing, at increasing the chances of creating satisfactory acoustic environments. The long-term goal is that the outcome from this research can be used in room acoustic design in order to improve people's acoustic comfort.

2. Materials and Methods

In this study, a mock-up area in a laboratory environment was used. The area of the room was approximately 52 m^2 and the ceiling was installed 2.70 m from the floor. The furnishings were comparable with those of a typical classroom. The room acoustic parameters were measured and sound samples for listening tests were recorded. The following section describes the materials and configurations used in the study, as well as the methods for the measurements and listening tests.

2.1. Acoustic Materials

Two different types of acoustic material were used: a sound absorber and a sound reflecting element (a diffuser).

The sound absorber was made of porous material, with a thickness of 40 mm and an air flow resistivity of 40 kPas/m^2, measured according to ISO 9053-2 [38]. The porous absorber was mounted on the ceiling for all configurations evaluated, and, for one configuration, on the walls. The absorption properties of the material were measured according to ISO 354 [39] for the overall depth of system (ODS) 200 mm and on ODS 50 mm. The ODS value is the distance from the soffit to the top side of the product. 200 mm is the standardised ODS for this type of product. ODS 50 mm can be applied for products mounted directly on the walls. The measured absorption values were evaluated according to ISO 11654 [40], giving a_w = 1, which is the highest possible value.

The diffusing elements had directional diffusing properties in the higher frequency range, but also absorption properties in the lower frequency range, in terms of resonance absorption. The diffusers were mounted in order to direct most of the reflections vertically, i.e., the z-direction. The diffusing characteristics of the diffuser in relation to a flat panel are shown in Figure 1.

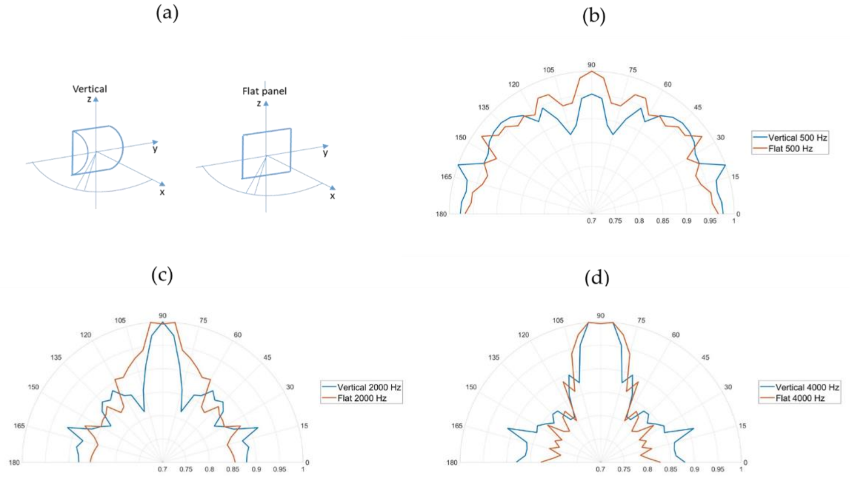

Figure 1. Diffusion characteristics at (**b**) 500 Hz, (**c**) 2000 Hz and (**d**) 4000 Hz. Upper left figure (**a**) shows the orientation of the diffusers' relative room coordinates.

2.2. Mock-Up and Configurations

Room acoustic measurements and recordings for the listening tests were made in a mock-up with dimensions 7.32 m × 7.57 m × 3.50 m. The room was furnished as a classroom. Eleven tables and eighteen slightly upholstered chairs were used. Two of the tables were used to simulate a teacher's desk.

Three different room configurations were investigated. In all configurations, an absorbent ceiling was used, installed at a height of 2.70 m from the floor. In configuration 1, no other treatment than the ceiling was used. In configuration 2, porous absorbers were mounted on two perpendicular walls. In configuration 3, diffusers replaced the absorbers on the walls. The diffusers redirected the majority of sound waves in vertical direction. The three configurations are presented in Figure 2.

2.3. Room Acoustic Measurements

The room acoustic parameters evaluated were reverberation time (T_{20}), speech clarity (C_{50}) (Equation (1)) and sound strength (G) (Equation (2)). Two source positions and seven receiver positions were used—see Figure 3, where 'R' indicates receiver and 'S' indicates source. Details of the measurement procedure of these measurements can be found in our previously published article [35].

Speech clarity, C_{50}, is defined as:

$$C_{50} = 10lg\frac{\int_0^{50\text{ms}} h^2(t)dt}{\int_{50\text{ms}}^{\infty} h^2(t)dt}\ [\text{dB}] \tag{1}$$

Sound strength, G, is defined as:

$$G = 10lg\frac{\int_0^{\infty} h^2(t)dt}{\int_{0\text{ms}}^{t_{dir}} h^2_{10\text{m}}(t)dt}\ [\text{dB}] \tag{2}$$

where

h(t) is the impulse response.

$h_{10\text{m}}$ is the impulse response at 10 m in a free field.

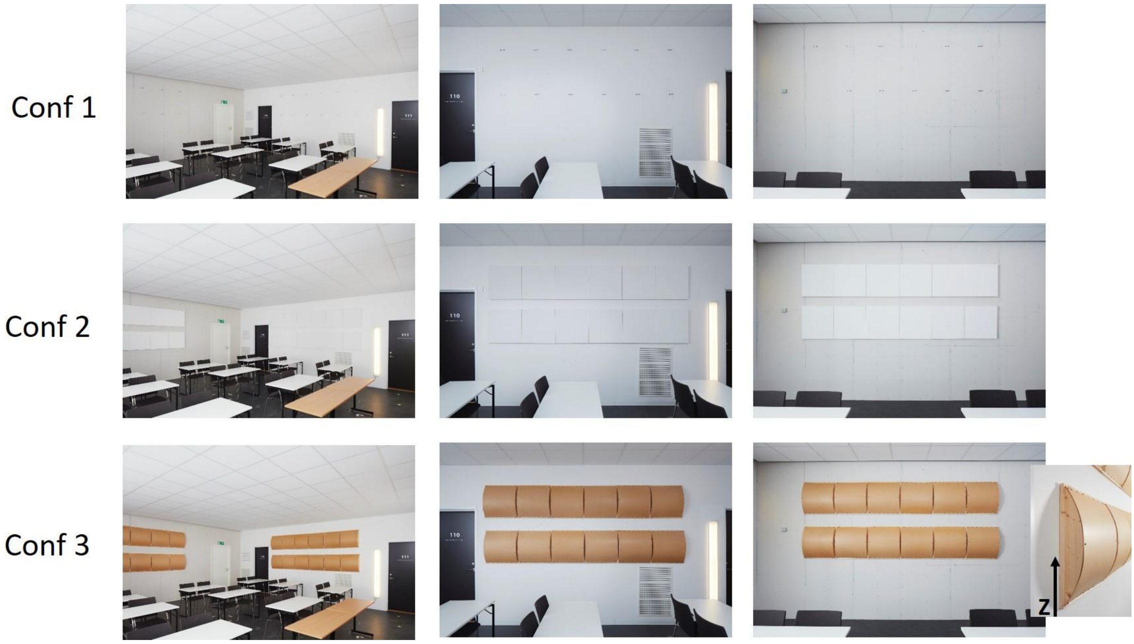

Figure 2. Configurations used in the experiments. Upper row: Conf. 1. 52 m^2 absorbent ceiling. The room was furnished. Second row: Conf. 2. 52 m^2 absorbent ceiling; 9 m^2 absorbing tiles distributed on two walls. The room was furnished. Third row: Conf. 3. 52 m^2 absorbent ceiling; 9 m^2 diffusers distributed on two walls. The room was furnished.

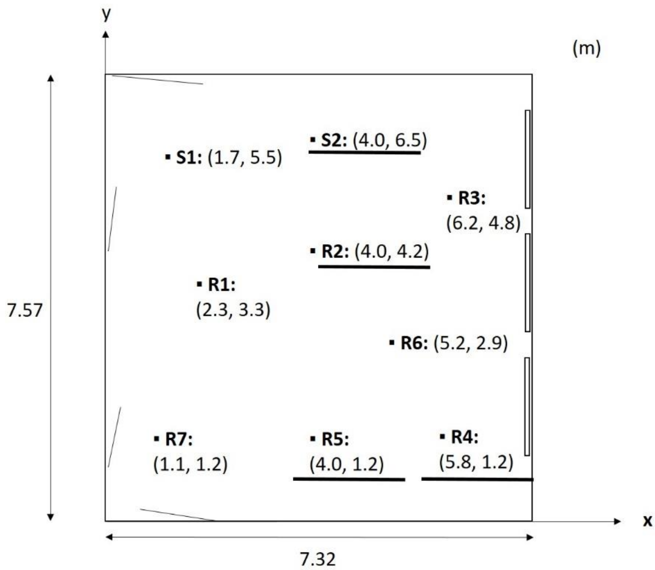

Figure 3. Source and receiver positions. Two source positions: S1 and S2. Seven receiver positions: R1–R7. All positions were used in room acoustic measurements. In sound sampling for listening tests, source S2 and receiver positions R2, R4 and R5 were used, underlined in the figure.

For both speech clarity and sound strength, the early reflections are included. When evaluating T_{20}, according to ISO 3382-2 [41], the evaluation interval is −5 dB to −25 dB, given that the early reflections are excluded.

The measurements were performed during the course of one day with stable temperature and humidity conditions. The background noise was <30 dBA.

2.4. Sound Sampling and Listening Test Design

Sounds for the listening tests were sampled by recording sounds in the same environment on the same day as the room acoustic measurements were performed. Female speech, sampled in an anechoic chamber, was played from a loudspeaker, type Genelec 8030B placed in S2, with the acoustic centre at a height of 1.55 m from the floor. The emitted sound power level was the same for all samplings.

Recordings were made with binaural headphones, type B2U, HEAD acoustics. Each sample was 4–6 s long and was recorded at height of 1.20 m from the floor. Recordings were made with binaural headphones, BHS II (3322) HEAD Acoustics (HEAD acoustics GmbH: Herzogenrath, Germany), with calibrated microphones. A B2U (3323) HEAD Acoustics adapter (HEAD acoustics GmbH: Herzogenrath, Germany), was used for recording and playback equalisation and the same headphones were used for recordings and playback during listening tests. Recordings were made in positions R2, R4 and R5. The different positions were the same as described in the previous section on room acoustic measurements; however, the chosen positions for the listening test can be seen in Figure 4. The set-up for sound samplings is shown in Figure 5.

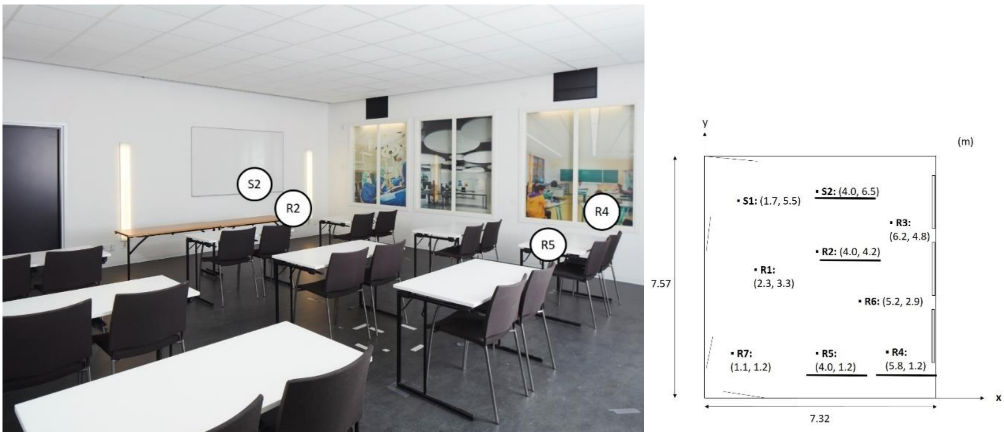

Figure 4. The positions used for sound sampling. The speech was emitted from S2 and sampled in R2, R4 and R5. In the sketch to the right, the positions used in sound sampling are underlined. All positions shown in the sketch were used for the averaged values of room acoustic measurements.

Figure 5. Set-up for sound sampling. Loudspeaker, Genelec 8030B, used as sound source placed in position S2. The right picture shows headphones BHS II and adapter B2U for recording the sounds and equalisation for listening test. Sampling was conducted in R2, R4 and R5.

Due to the challenge of creating a test including people's subjective experience, a number of aspects had to be considered in the test design. One such aspect was the duration of the test in relation to the ability of the jury members to maintain concentration during the test session. The test was designed to last a maximum of 20 min. To avoid bias for any of the participants, the test was conducted in a neutral room. In addition, none of the jury members had any involvement in the study, and the sounds were encoded. This meant that no information about the different sounds could be connected to a specific position or configuration for any of the participants. Another aspect that may affect the outcome of a perception test is personal status, such as medical health and mood. Self-reporting on these aspects was included in the test session. The participants rated their mood at the specific time of the performance of the listening test. The scale for this rating was 0–5, with 0 meaning not good at all and 5 meaning excellent. Furthermore, the question of ability to concentrate was reported after the test. A scale was also used here, from 0–10. With regard to concentration, 10 was deemed to be not difficult to concentrate. Concerning instructions, 10 indicated that the instructions were totally clear. The responses to these questions, i.e., regarding mood, health, ability to concentrate, etc., could be considered if any outlier results were found.

Before the test was conducted, a pilot study was performed. Five people did the test, which was followed up with a discussion of the test itself. The outcome from the pilot study led to clarifications in the instructions and shorter sound samples. Consequently, the results from the pilot study are excluded from the analysis and results presented in the coming sections.

The jury consisted of a randomised sample of 29 people. Fifteen of the participants were female. In the first part of the test, a training session was performed. This training gave instructions on how to use the software, the different types of tests were demonstrated and necessary definitions were explained. Additionally, participants were asked to consider themselves to be in a classroom where they were listening to information and were encouraged to make their choices based on their first impressions.

The perception test included three different types of judgements: judgement of sound quality, choosing pre-defined attributes and ranking. The judgements were applied for each of the three configurations in the three different receiver positions, i.e., nine points were considered in total.

Regarding sound quality, a scale with 10 grades was used. Number 1 corresponded to intolerable and 10 to excellent. People were asked to consider themselves sitting in a room where they listen to information when rating on the 10-point scale.

Mean and median values were evaluated and related to the different configurations. The 10-point scale for sound quality was also subdivided into three groups in order to obtain an understanding of the overall impression of quality for the different configurations and the room acoustics. The following sound quality groups were used:

A: Satisfactory, corresponding to points 8–10

B: Acceptable, corresponding to points 5–7

C: Unsatisfactory, corresponding to points 1–4.

Predefined attributes were related to speech perception. The jury participants were not acousticians, and the attributes were described for the participants in general terms, as follows:

Echoic- Echo/tendencies of echo.

Unclear- No echo, but indistinct; you need to concentrate extra hard to hear.

Clear- The sound is clear but not comfortable to listen to.

Pleasant- The sound is clear and comfortable to listen to.

With regard to the results on sound quality as well as the attributes, correlation and regression were investigated. The sound quality or attributes were, in these cases, set as the response variable, and room acoustic parameters were the exploratory variable.

Regarding correlation, it was investigated whether a linear association existed and, in addition, the strength and statistical significance of any such correlation. The value 'r' indicates the quality of the correlation, in the range $-1 \leq r \geq 1$. r = 0 means no correlation, while r = 1 and r = −1 mean total correlation. In the evaluation of statistical significance, the confidence interval was set to 95%. Using the Null Hypothesis (H_0) set to ρ = 0, no linear relationship existed between the variables. The Alternative Hypothesis (H_1) was set to $\rho \neq 0$; a linear relationship did exist. The significance level α = 0.05. The hypothesis was tested using the *p*-value associated with the correlation coefficient. If $p \leq \alpha$, we reject H_0; if $p > \alpha$, we fail to reject H_0.

Minitab® 19.1.1 was used for the statistical analysis.

For the regression, one explanatory variable was used, meaning simple regression was applied. The degree of explanation (R^2) was evaluated.

In the ranking session, the participant was asked to rank which sound out of three they preferred if they were listening to information in a classroom. Sounds from the three different configurations in the same position were used in this session, i.e., the rating was relative to the different configurations.

3. Results

This section presents the results on room acoustic parameters in Section 3.1, followed by the results on subjective experience in Section 3.2.

3.1. Room Acoustic Parameters

The three different room acoustic parameters of reverberation time (T_{20}), speech clarity (C_{50}) and sound strength (G) were evaluated in octaves from 125–4000 Hz. The average values over the two source positions and seven receiver positions (see Figure 3) were evaluated. Furthermore, the specific positions R2, R4 and R5, i.e., the positions for which listing tests were performed, were evaluated. For these specific positions, sound source position S2 was used, i.e., the same source position used for emitting speech in the listening tests.

Starting with the average values, the configuration without wall treatment (conf. 1) gave the highest T_{20} values throughout the full frequency range evaluated. With regard to the configurations with wall treatment, the values of T_{20} were slightly lower at frequencies 500–4000 Hz for the configuration with porous absorbers on the wall (conf. 2). However, in the lowest frequency range evaluated, 125–250 Hz, the T_{20} was lowest for the configuration with diffusing elements (conf. 3). These lower values are due to resonance absorption in the diffusing elements.

The previously discussed results concerning T_{20} are valid both for the average values and for the specific positions.

With regard to C_{50}, configuration 1 gave the lowest values, i.e., the highest number of late reflections considered to disturb the speech clarity, throughout the full frequency range evaluated. This is valid in relation to both the average and specific position values.

Configuration 2 had, on average, the highest values in C_{50}, i.e., the highest number of early reflections contributing to improved speech clarity, at frequencies 500–4000 Hz. A slightly higher value in C_{50} was seen for configuration 3 in the low frequency range of 125–250 Hz. This means that the same trends regarding frequency range were seen for T_{20} and C_{50}.

The evaluation of sound strength showed the lowest values for the configuration with the highest amount of absorption, configure 2. Configurations one and three had similar values in G. It should be noted that, when considering the average values, only small variations were noted for this parameter, as all configurations had an absorptive ceiling that significantly regulated this parameter.

The specific receiver positions R2, R4 and R5 were evaluated, with S2 as source position. The results in these positions were the ones used in comparison with the responses in the listening test. Regarding the reverberation time, T_{20}, the trends for the different positions were similar to the average values. At frequencies from 500 Hz and upwards, the lowest value in T_{20} was seen for configuration 2, containing the most absorption. The resonance absorption properties of the diffusers were also seen in the different positions, with configuration 3 giving the lowest T_{20} values at low frequencies.

There was considerable variation in the parameter C_{50}, depending on position. Differences of 3 dB or more were seen for all configurations when the three specific positions were compared. The difference, depending on treatment, in the positions in the rear part of the room should be noted. In the higher frequency range, C_{50} was lower for configuration 2 than for configuration 3 in position R5. This is the opposite compared to the average values, indicating the importance of also considering the specific position in a room. The lowest values in C_{50} were obtained for configuration 1, in all specific positions, compared to the average values.

Sound energy was reduced by the distance from the source and, in positions further away from the speaker, positions R4 and R5, the values of G were more than 1 dB lower at frequencies 2000–4000 Hz for configuration 2. Smaller differences were seen for configurations 2 and 3.

The mechanism causing the changes in room acoustic parameters for configurations 2 and 3 differ. With regard to configuration 2, the sound energy is absorbed and thus the acoustic parameters are adjusted. For configuration 3, the sound waves are broken up by the diffusing elements in different directions. The soundwaves are thus prevented from travelling back and forth between the walls. The fact that sound waves can travel back and forth between the walls is the reason for the highest T_{20} and lowest C_{50} for configuration 1. The adjustments of the reflection pattern with diffusers alter T_{20} and C_{50}, while the sound energy in the room remains. Thus, the sound strength, G, did not change for configuration 3 in relation to configuration 1 in the high frequency range. With the use of absorbers, G is also affected. Slightly lower G at low frequencies for configuration 3 is due to the resonance absorption by the diffusers.

Graphs with the results on room acoustic parameters, average and specific positions can be found in Supplementary S1.

3.2. Listening Test

In the following sections, the results from the listening test are presented. It should be noted that the participants in the listening test had no insight into the study, the tests were performed in a neutral room and all sounds were decoded. This means that the jury members did not have any information about the different sounds they were listening to.

3.2.1. Jury Members

In order to identify any potential differences in the responses, an ANOVA was used for the evaluation of sound quality and attributes.

Regarding sound quality, no specific outlier was found. Seven jury members responded with slightly lower values. In the group of seven who answered with lower values, all found the instructions to be totally clear. Their ages varied from 26 to 48 years. Two members found it more difficult to concentrate during the full test, one reported a bad mood and one reported having a hearing aid. This means that no common attribute for the seven members could be found. Consequently, none of these seven responses were removed in the evaluation of sound quality.

One jury member answered more often with high quality values for the configuration with no additional wall treatment and with diffusers. However, this person still followed the same trend as the mean values. Mean and median values did not change on removal of this person's responses. These responses were thus also used in the evaluation of the sound quality.

With regard to outliers, no outlier could be identified in the ANOVA made for the attributes on speech perception. However, there was a trend of three jury members giving higher ratings, i.e., more often choosing clear or pleasant. These three members reported that they could maintain concentration, that the instructions were clear and that they were in a good mood. No hearing aids were reported for these three members. However, one of them was the same person who reported high sound quality values. As no significant outlier results were found, and as individual preferences are natural, all responses were used in the evaluation of the attributes.

3.2.2. Sound Quality

The sound quality was rated on a 10-point scale, where 1 was described as intolerable and 10 as excellent. The jury members were asked to consider that they were in a situation listening to information. All 29 jury members judged the sound quality for the three positions R2, R4 and R5 for three configurations (see Figure 4).

For all configurations, position R2, i.e., the position closest to the speaker, was judged to have the highest sound quality when considering each configuration.

Configurations 2 and 3 were judged to have the same value for this position, a quality of 9, in both mean and median values. No jury member rated this position lower than 7, which was considered to be good sound quality. Regarding position R4, configurations 1 and 3 were judged to be the same when mean and median values were considered, with a result of 6 in sound quality, which was still considered good. For configuration 2, the same position, R4, was judged as a 7 in mean and median. This configuration was judged to have the same quality in position R5, i.e., a sound quality of 7, while configuration 3 got 6 and configuration 1 got 5 when the mean values were considered.

Overall, configuration 2 was judged to be the best when this quality scale was used. Moreover, Q1 had the lowest value of 5 for position R5, which was still considered acceptable. However, for configurations 1 and 3, Q1 had a value of 4, which was not satisfactory. It should also be mentioned that the variations between the 29 jury members were lowest for configuration 2. The descriptive statistics concerning the sound quality are shown in Table 1.

Table 1. Descriptive statistics of sound quality judgements.

Variable	N	Mean	St. Dev	Variance	Minimum	Q1	Median	Q3
Conf. 1_R2	29	7	2.0	3.8	3	7	8	9
Conf. 1_R4	29	6	1.9	3.8	2	4	6	7
Conf. 1_R5	29	5	1.6	2.5	2	4	4	6
Conf. 2_R2	29	9	0.8	0.7	7	9	9	10
Conf. 2_R4	29	7	1.7	2.7	3	7	7	8
Conf. 2_R5	29	7	1.6	2.5	4	5	7	8
Conf. 3_R2	29	9	0.9	0.8	7	8	9	9
Conf. 3_R4	29	6	1.9	3.7	2	4	6	7
Conf. 3_R5	29	6	1.7	2.8	3	4	6	7

The sound quality reported by the jury members was divided into different groups in order to obtain an understanding of which configurations could be deemed satisfactory or not. Three different groups were created:

A. Satisfactory: sound quality level 8–10.
B. Acceptable: sound quality level 5–7.
C. Unsatisfactory: sound quality level 1–4.

When the data from all the individual judgements were evaluated, it was found that 10% of the jury members judged configuration 1, position R2, to be unsatisfactory. Concerning the same position for configurations 2 and 3, the majority were in group A: satisfactory. For position R4, in the corner of the room, some jury members judged the sound quality at levels corresponding to group C: unsatisfactory; this was obtained for all configurations, but in different positions. For configuration 1, as many as 35% judged it unsatisfactory. For configurations 2 and 3, 17% and 31% judged it unsatisfactory, respectively. For position R5 in configuration 1, the majority, 59%, judged the quality at levels corresponding to unsatisfactory. The same position, R5, for configuration 3 was also judged to be unsatisfactory by 31% of the jury members. Only 13% of the responses were in the unsatisfactory range for configuration 2 in position R5. The results for the grouping are shown in Figure 6.

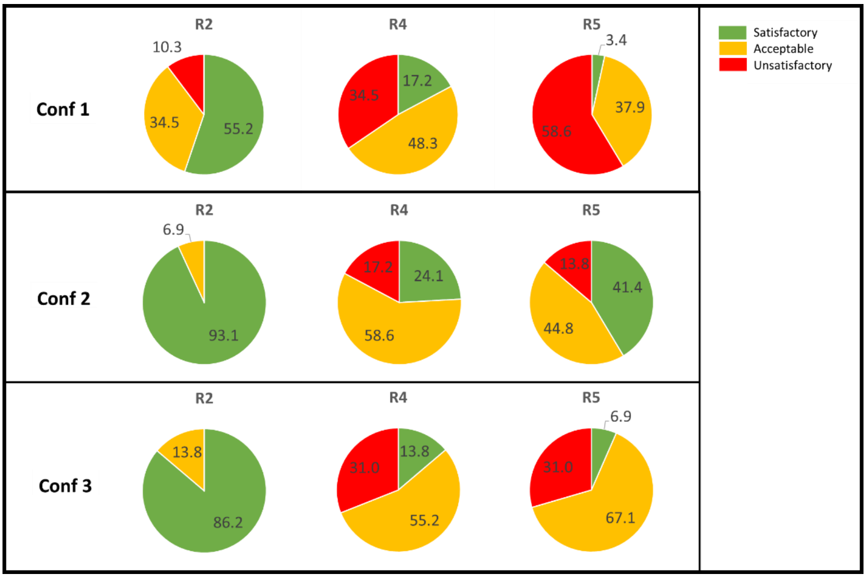

Figure 6. Sound quality grouped into three levels, A: satisfactory (green), B: acceptable (yellow), and C: unsatisfactory (red). The results for the position closest to the speaker, R2, are seen in the first column; the results for the position in the corner, R4, are seen in the middle column; and the results for the position in the back, R5, at the same distance in x as the speaker position, are seen in the right column.

It was investigated whether any association between the responses in sound quality and the room acoustic parameters exists. The mean values of the responses from the jury members for each listening position, R2, R4 and R5, for the three configurations were used. This means that a total of nine points were evaluated. In respect of the room acoustic parameters, the values of T_{20}, C_{50} and G for octaves 125–4000 Hz for the same positions and configurations were used.

The Pearson correlation gave responses on correlation (r) and p-values. Regarding the association between sound quality and T_{20}, the response in correlation quality was low. The highest value was seen for a frequency of 500 Hz, with $r = -0.664$. The p-value was 0.051, meaning statistical significance was just on the borderline.

For C_{50}, a higher correlation was obtained, especially for the higher frequency range of 1000 Hz–4000 Hz. The correlation coefficient for C_{50} at 1000 Hz was 0.824, for 2000 Hz 0.921 and for 4000 Hz 0.817. These r-values can be interpreted as a good correlation for a subjective test like this listening test. In addition, the p-values showed a statistical significance ($p < 0.05$) for these frequencies. In the regression investigation, C_{50} was used as the explanatory value. For the frequency range with high correlation quality, i.e., 1000–4000 Hz, a linear regression with good R^2 was found. For 1000 Hz, the R^2 was 68%, for 2000 Hz 85% and for 4000 Hz 67%. At the lower frequencies, low correlation quality was obtained. A regression analysis was also made, but resulted in a low R^2. With regard to G, no association with sound quality could be found. It should be observed that low variations in G were obtained between the positions and configurations investigated. The correlations for the sound quality and room acoustic parameters are presented in Table 2. Equations for the linear regression, together with its degree of explanation, can be found in Supplementary S2.

Table 2. Results from correlation and regression analysis for perceived sound quality and room acoustic parameters. A good correlation between C_{50}, in the higher frequency range, can be noted. Results with $p < 0.05$ are marked in bold.

Room Acoustic Parameter	Frequency (Hz)	Pearson Correlation Sound Quality—Room Acoustic Parameter 95% CI	
		Quality (r)	***p***
T_{20}	125	−0.015	0.969
T_{20}	250	−0.334	0.380
T_{20}	500	−0.664	0.051
T_{20}	1000	−0.588	0.096
T_{20}	2000	−0.543	0.131
T_{20}	4000	−0.583	0.099
C_{50}	125	0.527	0.145
C_{50}	250	0.546	0.129
C_{50}	500	0.492	0.179
C_{50}	**1000**	**0.824**	**0.006**
C_{50}	**2000**	**0.921**	**0.000**
C_{50}	**4000**	**0.817**	**0.007**
G	125	0.258	0.503
G	250	−0.524	0.148
G	500	−0.072	0.853
G	1000	0.158	0.685
G	2000	0.299	0.434
G	4000	0.336	0.377

3.2.3. Attributes

The responses from all 29 members of the jury are presented below.

Evaluation of the attributes for all 29 participants shows high scores of echo in the configuration where no acoustic material was used on the walls (conf. 1). In the position close to the speaker, 66% deemed it echoic, and the position on the line from the source but at the back of the room, R5, was deemed to be echoic by 80% of the jury members. Sixty-nine per cent judged the position at the back corner, R4, to be echoic.

With regard to the configurations with absorption on the walls, the majority found the sound to be clear or pleasant in all positions. However, 17% found the position in the back corner, R4, to be unclear.

For the configurations with diffusers on the walls, the majority judged the acoustic environment to be clear or pleasant. For the position close to the speaker, position R2, >90% deemed it to be clear or pleasant. However, for the positions at the back, a considerable number of jury members judged the environment to be unclear or even echoic. Twenty-eight per cent found the position on the line from the speaker at the back, R5, to be echoic. For the position in the back corner, R4, 17% found it echoic. A pie chart presents the results of jury members' perception of the attributes (Figure 7).

A correlation analysis was performed using the Pearson correlation. The association between the attributes and room acoustic parameters T_{20}, C_{50} and G over the octaves 125–4000 Hz was investigated. The attributes are explained by number, where 1 corresponds to echoic, 2 corresponds to unclear, 3 corresponds to clear and 4 corresponds to pleasant. The mean value of the 29 participants' judgements was used in the analysis.

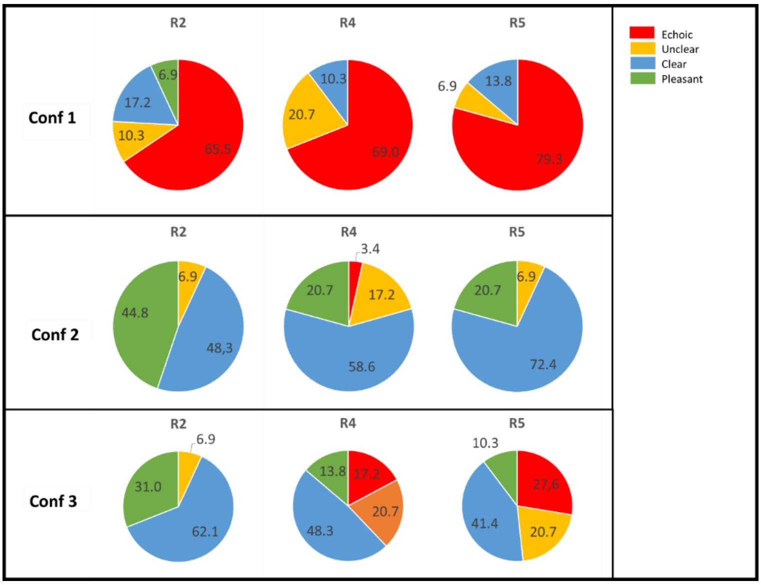

Figure 7. Pie chart for the 29 participants' judgement of attributes. 1/red = echoic, 2/orange = unclear, 3/yellow = clear, 4/green = pleasant. The results for the position closest to the speaker, R2, are seen in the first column; the results for the position in the corner, R4, are seen in the middle column; and the results for the position in the back, R5, at the same distance in x as the speaker position, are seen in the right column.

The highest strength of correlation to the attributes was found for T_{20} at frequencies 500–4000 Hz. The correlation quality for T_{20} at 500 Hz was $r = -0.877$, for 1000 Hz $r = -0.915$, for 2000 Hz $r = -0.90$ and for 4000 Hz $r = -0.889$. For these frequencies, the p-value was <0.05, meaning the correlation was statistically significant. Linear regression for T_{20} at these frequencies was found to get an R^2 range from 77 to 84%, with the highest value being obtained for 1000 Hz.

Regarding C_{50}, a fairly high correlation strength was found in the higher frequency range, 1000–4000 Hz, but not as high as for T_{20}. For C_{50} at 1000 Hz, $r = 0.810$, at 2000 Hz $r = 0.708$ and at 4000 Hz $r = 0.708$. At these frequencies, the p-value was <0.05, meaning statistical significance was obtained. Linear regression analysis showed R^2 ranging from 50% to 66%.

Regarding G, a low correlation of quality with attributes was obtained. As mentioned earlier, the variations for this parameter were low between the positions and configurations investigated. The correlation data are presented in Table 3. The equations for linear regression, together with the degree of explanation, can be found in Supplementary S2.

3.2.4. Ranking

In the ranking part of the listening test, the participants answered in respect of which configuration they would prefer if sitting in an environment listening to information. The ranking was made for comparison between the configurations, for each position, i.e., positions R2, R4 and R5.

The results show the same ranking for all positions. Configuration 2 was rated as number one, configuration 3 as number two and configuration 1 as number three. However, the responses were differently distributed for the different positions. In position R5, configuration 2 was rated most frequently as the preferred option, with the lowest deviation for the three different positions. In position R4, configuration 2 was just slightly better than configuration 3. Configuration 1 was clearly rated as number three for all positions. The results are found in Table 4.

Table 3. Results from analysis on correlation and regression for attributes and room acoustic parameters. The best correlation was found for T_{20}. However, C_{50} also gave fairly good correlation in the higher frequency range, meaning that T_{20} cannot fully explain the attributes. Results with $p < 0.05$ are marked in bold.

Room Acoustic Parameter	Frequency (Hz)	Pearson Correlation Attributes—Room Acoustic Parameter 95% CI	
		Quality (r)	*p*
T_{20}	125	−0.325	0.393
T_{20}	250	−0.509	0.162
T_{20}	**500**	**−0.877**	**0.002**
T_{20}	**1000**	**−0.915**	**0.001**
T_{20}	**2000**	**−0.907**	**0.001**
T_{20}	**4000**	**−0.889**	**0.001**
C_{50}	125	0.247	0.522
C_{50}	250	0.169	0.663
C_{50}	500	0.543	0.131
C_{50}	**1000**	**0.810**	**0.008**
C_{50}	**2000**	**0.708**	**0.033**
C_{50}	**4000**	**0.767**	**0.016**
G	125	0.373	0.322
G	250	0.659	0.054
G	500	−0.394	0.295
G	1000	0.040	0.918
G	2000	0.088	0.823
G	4000	0.074	0.850

Table 4. Results on rating for sound in different positions for the different configurations.

	Conf. 1_R2	Conf. 2_R2	Conf. 3_R2	Conf. 1_R4	Conf. 2_R4	Conf. 3_R4	Conf. 1_R5	Conf. 2_R5	Conf. 3_R5
Average	2.86	1.17	1.97	2.72	1.45	1.83	2.86	1.10	2.03
Standard deviation	0.34	0.46	0.49	0.52	0.72	0.59	0.51	0.40	0.18
Confidence (0.95)	0.13	0.17	0.18	0.19	0.26	0.22	0.18	0.15	0.07
Lower Quartile	3.00	1.00	2.00	3.00	1.00	1.00	3.00	1.00	2.00
Median	3.00	1.00	2.00	3.00	1.00	2.00	3.00	1.00	2.00
Upper Quartile	3.00	1.00	2.00	3.00	2.00	2.00	3.00	1.00	2.00

4. Discussion

Three different configurations were investigated from objective and subjective perspectives. From an objective perspective, the three room acoustic parameters of reverberation time (T_{20}), speech clarity (C_{50}) and sound strength (G) were measured. The average values as well as specific receiver positions were considered. With regard to the different receiver positions, a large difference was observed between some positions. This stresses the importance of considering the acoustic properties in different locations of the room, even for ordinary rooms. In the acoustic design of performance spaces, such as theatres and concert halls, the typical procedure is to make sure everyone in the audience enjoys a good acoustic experience. Ensuring good listening conditions for everyone in the audience in ordinary rooms, such as classrooms, should be just as natural.

With regard to the listening test, all participant responses were used in the evaluation, as no outliers could be identified. The fact that differences in the jury members' mood or ability to concentrate did not affect the results may be due to the results found being independent of these types of aspects.

With regard to the correlation and regression analysis, a strong correlation to the room acoustic parameters could be found, mainly in the higher frequency range. This can be explained by the fact that the acoustic treatment used operated mainly in that frequency range. Additionally, due to the greater sensitivity of our hearing at the higher frequencies and because speech normally contains mainly high frequency sounds, the sounds that the jury judged were in this higher frequency range.

The diffusers contributed low frequency absorption at 125–250 Hz. This difference seems not to have affected people's judgement for any of the perception evaluations. However, it should be kept in mind that female speech was used in the study. If male speech had been used, more low frequency sound could have been emitted, resulting in the low frequency absorption playing a more significant role and thus leading to other responses in the perception tests.

The study included a rating of the different configurations. In addition, the sound quality judgements can be used in analysing preferred solutions. These two evaluations show the same results: the preferred configuration in ranking and the configuration with the best sound quality was the configuration with an absorbent ceiling and absorbers on the walls (conf. 2). This solution has the lowest reverberation time (T_{20}), the highest speech clarity (C_{50}) and the lowest sound strength (G).

Whether it was the type of treatment or the values of the room acoustic parameters that people prefer was also considered by studying the correlation between people's subjective experience and the different room acoustic parameters investigated, resulting in some indications.

The correlation found between sound quality and C_{50} for the frequency range 1000–4000 Hz can be regarded as strong, with a correlation quality of 0.817–0.921. The *p*-values showed statistical significance and, in addition, a high degree of explanation could be seen for the regression using C_{50} for these frequencies as explanatory variables. The other room acoustic parameters measured (T_{20} and G) did not show any correlation, giving strength to a cause and effect relation existing between speech clarity and perceived quality for frequencies 1000–4000 Hz. We could thereby assume that C_{50} does explain the cause and effect for perceived sound quality.

Regarding the correlation between the attributes, the strongest correlation was found to reverberation time (T_{20}). The r-value showed a strong correlation, with r-values from -0.877 to -0.915, and *p*-values showing statistical significance for this correlation. However, for C_{50} as well, a correlation to the attributes in the higher frequency range was seen. This correlation was not as strong as for T_{20}, indicating that T_{20} does not fully explain the effect of perception on the attributes used in this study.

No correlation to G was observed. This may depend on the fact that the acoustic configurations used resulted in small variations in G, and this parameter had already been adjusted by an acoustic ceiling. However, other types of questions to the jury could be better associated to this parameter, such as regarding loudness.

From the results on the correlation between room acoustic parameters and people's subjective experience, it seems that C_{50} is a good descriptor for people's perception of speech. Sound quality evaluation indicates that a $C_{50} > 8$ dB was needed to obtain satisfactory sound quality. C_{50} can be adjusted either by adding diffusers or absorbers, with higher values being obtained with the absorbers.

In a previous study [40] in this research programme, it was found that the configuration with diffusers on the walls, configuration 3, gave a more similar subjective experience than the one with absorbers. The fact that people have the same possibilities to hear speech independent of the position in the room is, of course, of great importance. The combination of these findings can be useful in the future acoustic design of ordinary rooms.

5. Conclusions

This study investigated how people experience speech in three different acoustic environments. Twenty-nine people judged speech that was recorded with binaural headphones in different positions in the different environments. The observations from people were related to different types of acoustic treatments as well as to different room acoustic parameters. From this evaluation, it can be concluded that it is important to consider C_{50} in rooms for speech, as C_{50} effectively describes people's perception of speech and is, in addition, related to their experience of sound quality. To obtain satisfactory sound quality, $C_{50} > 8$ dB is required. The achievement of this value should be controlled in several positions in the room and not only on an average basis. In order to achieve a C_{50} of 8 dB, an absorbent ceiling is a good baseline, but additional treatment, either absorbing or diffusing, is needed. However, from previous studies, it has been found that diffusers contributed to a more uniform experience of sound.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/ijerph182312274/s1, Figure S1. Average values over two sources and seven receiver positions for room acoustic parameters reverberation time, T20, speech clarity, C50, and sound strength, G; Figure S2. The three room acoustic parameters evaluated, reverberation time, T20, speech clarity, C50, and sound strength, G, for specific receiver positions using source position S2 and receiver position R2, i.e., close to the speaker; Figure S3. The three room acoustic parameters evaluated, reverberation time, T20, speech clarity, C50, and sound strength, G, for specific receiver positions using source position S2 and receiver position R4, i.e., in the corner.; Figure S4. The three room acoustic parameters evaluated, reverberation time, T20, speech clarity, C50, and sound strength, G, for specific receiver positions using source position S2 and receiver position R5, i.e., same x-position as the speaker in the rear part of the room. Table S1. Configuration Description; Table S2. Equations for linear regression with degree of explanation, R2, for sound quality using room acoustic pa-rameters as explanatory parameter; Table S3. Equations for linear regression with degree of explanation, R2, for attributes using room acoustic parameters as explanatory variable.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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Article

Quantification of the Absorption and Scattering Effects of Diffusers in a Room with Absorbent Ceiling

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Abstract: In ordinary public rooms, such as classrooms and offices, an absorbent ceiling is the typical first acoustic action. This treatment provides a good acoustic baseline. However, an improvement of specific room acoustic parameters, operating for specific frequencies, can be needed. It has been seen that diffusing elements can be effective additional treatment. In order to choose the right design, placement, and quantity of diffusers, a model to estimate the effect on the acoustics is necessary. This study evaluated whether an SEA model could be used for that purpose, particularly for the cases where diffusers are used in combination with an absorbent ceiling. It was investigated whether the model could handle different quantities of diffusing elements, varied diffusion characteristics, and varied installation patterns. It was found that the model was sensitive to these changes, given that the output from the model in terms of acoustic properties will be reflected by the change of diffuser configuration design. It was also seen that the absorption and scattering of the diffusers could be quantified in a laboratory environment: a reverberation chamber. Through the SEA model, these quantities could be transformed to a full-scale room for estimation of the room acoustic parameters.

Keywords: absorbers; diffusers; room acoustic design; room acoustic parameters; scattering

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1. Introduction

In ordinary public rooms such as classrooms and offices, a satisfactory room acoustic environment is critical. It will affect the performance of cognitive tasks and have an impact on hearing and speech in that both listeners and speakers will be affected and, in addition, it also relates to people's well-being. In previous articles [1,2] from this research group, the effect of different room acoustic treatments in ordinary rooms has been studied. Both the effect on room acoustic parameters [1] and the effect on subjective experience [2] have been investigated. In these studies, it was found that diffusers can be a convenient treatment in addition to a sound-absorbing ceiling. An absorbent ceiling is a typical acoustic treatment in this type of room. However, due to the non-uniform distribution of the absorption, the effects of sound spreading interior fittings such as furniture or other diffusing objects are significant and have to be accounted for in the acoustical design. The directional characteristics of sound diffusing elements is a property that is hard to incorporate in today's simulation software. As has been shown in previous papers [1], this is an effect that can be used to fine tune the acoustical conditions. The aim of this paper is to present and evaluate a method of quantifying the sound-spreading effect of objects in rooms with absorbent ceilings. The method is emanating from the SEA model presented in [3]. Basically, a measure is introduced that quantifies the sound energy transfer between the two subsystems used in the SEA model and referred to as the grazing and non-grazing group. The sensitivity of the quantification parameter, denoted equivalent scattering absorption area A_{sc}, for different sound spreading configurations is analyzed. A novel method for measuring this parameter in a laboratory set-up is also suggested and exemplified.

The acoustic environment of a room is highly dependent on the sound reflections in the room. As far back as 1964, Lochner and Burger [4] showed the importance of early reflections in rooms used for speech and how the ratio of early reflections will affect the subjective experience. The early reflections will contribute to the direct sound. In a study by Bradley et al. [5], the authors recommended focusing on increasing the early reflections rather than lowering the reverberation time in rooms used for speech. The importance of early reflections and their relation to subjective impression has been further investigated in several studies [6–10]. Puglisi et al. examined the effect of early reflections on cognitive skills by studying the reading speed of Italian second graders, finding a correlation to C_{50} but not, however, to reverberation time [11]. It has also been shown by Bradley and Reich [12] that C_{50} to some extent can complement a low S/N ratio. In several of the above-mentioned references, the importance of considering several room acoustical parameters in acoustic design is raised. Sound strength, G, a parameter describing how the room responds to the sound energy emitted from a sound source, is normally used in the acoustic design of performance spaces [13–15].

In terms of cognitive skills, the acoustic environment is critical. It is well known that noise disturbs concentration, but room acoustic properties will also affect the ability to perform complex tasks. In [16–18], different acoustic conditions were evaluated in relation to cognitive skills, showing for example how the ability to recall words is affected when the reverberation time is longer or the background noise higher. An unsatisfactory sound environment can cause a more demanding interpretation and processing of words, even if the words are correctly recalled. Thereby, it is of great importance to ensure good acoustics in these room, and to do so, appropriate acoustic treatment is necessary.

To adjust the above-mentioned acoustic parameters and create a satisfactory sound environment for the performance of cognitive skills, different types of acoustic treatments can be used. At present, it is typical for ordinary rooms to use porous absorbers. The placement of such treatment is important as regards the effect on different room acoustical parameters [19,20]. Furthermore, the absorption coefficients are also angle dependent, and methods have been developed to take this into account on a laboratory scale [21]. Nolan et al. worked on a measurement method for in situ measurement of angle-dependent absorption [22,23].

Environments where high effort is dedicated to the acoustics include performance spaces, such as concert halls and theatres. A typical acoustic treatment in these environments is the use of diffusers. This is based on the need to avoid flutter echoes, support the artist, and ensure everyone in the audience has a favorable acoustic experience [24]. The same types of acoustic challenges can be found in ordinary public rooms such as classrooms and offices, but instead of voice support for a performing artist, it can be a teacher that needs voice support. Furthermore, it is critical that the students can hear information properly. Choi has investigated the combination of absorbers and diffusers in a small-scale model, studying the effect on different acoustic properties [25–28]. The placement of absorbers and diffusers on walls was investigated in [29].

The effect on different room acoustic measurements was evaluated in full scale in the first step of this study, showing how different treatments can be used depending on different acoustic requirements [1]. It was shown how diffusers can be used to effectively improve speech clarity and reverberation time while maintaining the sound energy, G, in the room. Using the diffusers in the ceiling gave significant results in terms of C_{50} at the back of the room, with a difference of 3 dB for octave 1000 Hz. According to ISO 3382-1 [30], the just-noticeable difference, JND, for this parameter is 1 dB, with the first part of this standard being dedicated to performance spaces. However, the just-noticeable difference for speech was investigated by Bradley and Reich, showing that larger differences, such as up to 3 dB, are needed for a sustainable improvement in the room [31]. Visentin et al. investigated the perception of a diffuse versus a specular reflection, showing that diffuse reflections were preferable and made speech clearer [32]. Shtrepi et al. [33] investigated the effect of the location of diffusers as well as the distance from those from both objective and subjective aspects [34,35].

It has been shown that rooms with an acoustic ceiling will not have a diffuse sound field, and the decay will not be linear. As a consequence of this, calculation in accordance with diffuse sound field theory will not be appropriate for these types of rooms. With the aim of accounting for the circumstances of the sound field in a room with an absorbent ceiling, a calculation model has been developed [3]. The model is based on statistical energy analysis, SEA, and the theory of SEA is explained in [36]. SEA models are convenient for use as prediction models on a system level [37]. The SEA model referred to above has been shown to provide better predictions than models that assume diffuse conditions [38].

Study Objective and Principal Conclusion

Previous studies have shown how diffusers can contribute to the fine tuning of the acoustics in ordinary rooms and, further, how diffusers could provide a more uniform subjective experience of the acoustic environment [1,2]. For the use of diffusers in such rooms, it is necessary to have a model to estimate the acoustic effect that the treatment will provide. Such a model has been investigated in this study.

The model used is an SEA (statistical energy analysis) model, which been developed particularly for rooms with absorbent ceilings [3]. It was investigated whether this model is sensitive enough to be applicable to a variation of diffuser set-ups. From a number of configurations involving different quantities of diffusers, different diffuser characteristics, and different installation patterns, the model's sensitivity was evaluated. These experiments were performed in a full-scale room. The evaluation showed that a parameter denoted A_{sc}, equivalent absorption scattering area, could be related to the different set-ups of diffusers. This parameter, A_{sc}, is used as input parameter in the SEA model to calculate the acoustic properties.

Accordingly, in order to use the SEA model for estimation of the acoustic properties, the A_{sc} for an element must be known. It was investigated whether quantification in terms of A_{sc} could be made at a smaller scale. Comparison of the A_{sc} obtained in the full-scale room and the smaller scale showed similar values. Thus, this way of quantifying diffusers is suggested as a method to quantify diffusers for ordinary rooms.

2. Materials and Methods

In ordinary rooms such as classrooms and offices, the typical acoustic treatment is an absorbent ceiling. This treatment will affect the sound field in the room by diminishing the diffuse field and enhancing a grazing field with sound waves traveling almost parallel to the ceiling. To consider this sound, wave propagation is critical for accurate room acoustic estimations for these rooms.

Another important aspect to be considered in these rooms is the effect of objects, such as furniture and other interiors. These objects can contribute both absorption and scattering, which will affect the room acoustics. Furthermore, the effect will differ for different frequencies. In the standard EN 12354-6 concerning sound absorption in enclosed spaces, the equivalent absorption area (A_{obj}) is accounted for by using the formula $A_{obj} = V_{obj}^{2/3}$ [39]. This formula is to be used in the Sabine formula, which assumes a diffuse sound field.

Since the absorbent ceiling and objects will have a considerable effect on the room acoustic properties in a room, a model developed to account for these two aspects has been applied in this study. The prerequisites and equations for this model are described in the following paragraphs. The complete derivation of the energy model can be found in [3]. Information about experiments and materials used in the study is found below in this chapter.

2.1. A Statistical Energy Analysis Model for Ordinary Rooms

The energy model applied in this study has been developed for rooms with an absorbent ceiling. It is assumed that the sound field in these rooms will be a build-up of grazing and non-grazing sound waves. In practice, this applies when the mean absorption coefficient for the ceiling is larger than 0.7 for the octave bands 250–4000 Hz [3]. The grazing sound field accounts for the sound waves propagating almost parallel to the ceiling. The SEA model accounts for these two sound fields by introducing two sub-systems, a grazing and a non-grazing sub-system. Energy can be transferred from the grazing to the non-grazing sub-system. This energy transfer is due to different scattering objects such as furniture [3]. The setup of sub-systems and energy flow is depicted in Figure 1.

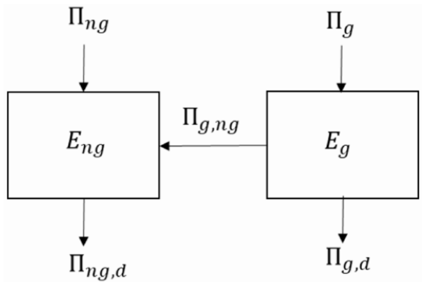

Figure 1. The total energy of each system is denoted E_{ng} and E_g, where the index "*ng*" refers to non-grazing and "*g*" refers to grazing. Energy flowing into the system is denoted $\prod_{ng}$ and $\prod_g$ and dissipating from the system $\prod_{ng,d}$ and $\prod_{g,d}$. Energy transmitted from the grazing to the non-grazing sub-system is denoted $\prod_{g,ng}$.

The total decay in a room with an absorbent ceiling is built up of grazing and non-grazing modes. In the early part of the decay, the non-grazing modes are dominant. The latter part is dominated by the grazing modes and will mainly determine the reverberation time. The decay is depicted in Figure 2.

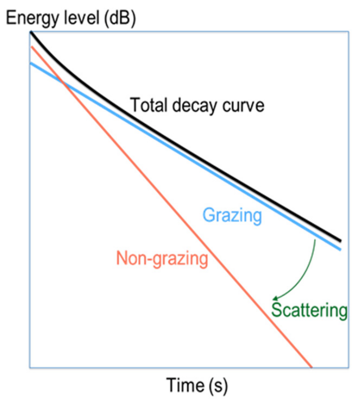

Figure 2. The total decay in a room is the sum of the energy in the grazing and the non-grazing sound fields [40].

The total decay in intensity is given by [3]

$$I(t) = I_{ng}(0)(e^{-13.8t/T_{ng}} + \frac{T_g \Delta N_g}{T_{ng} \Delta N_{ng}} e^{-13.8t/T_g}) \tag{1}$$

where
I_{ng} is the intensity in the non-grazing sub-system
T_{ng} is the reverberation time in the non-grazing sub-system, given by Equation (2) below
T_g is the reverberation time in the grazing sub-system, given by Equation (3) below
N_g is the number of modes in the grazing sub-system
N_{ng} is the number of modes in the non-grazing sub-system

The formula for the reverberation time in the non-grazing sub-system is given by [3]

$$T_{ng} = \frac{0.161V}{A_{ceiling} + A_{furniture} + A_{surface} + 4mV} \tag{2}$$

where
V is the volume of the room
$A_{ceiling}$ is the absorption area of the ceiling in the non-grazing sub-system
$A_{furniture}$ is the Sabine equivalent absorption area of the furniture
$A_{surface}$ is the equivalent absorption area of the walls and floor
$4mV$ is the air absorption, m is the energy attenuation constant in air, and V is the volume of the room.

The formula for the reverberation time in the grazing sub-system has been adapted for a two-dimensional sound field. Furthermore, the equivalent scattering absorption area, A_{sc}, has been introduced in this equation. A_{sc} quantifies the effect in terms of absorption and scattering from different objects. The grazing reverberation time is given by [3]

$$T_g = \frac{0.127V}{A_{g,ceiling} + A_{sc} + A_{surface} + \pi mV} \tag{3}$$

where
$A_{g,ceiling}$ is the absorption area of the ceiling in the grazing sub-system
A_{sc} is the equivalent scattered absorption area (see Equation (4))
πmV is the air absorption in the two-dimensional field, the grazing sub-system, m is the energy attenuation constant in air, and V is the volume of the room.

The energy transmitted from the grazing to the non-grazing sub-system is described as the coupling loss factor, which is denoted $\prod_{g,ng}$ in Figure 1 and depicted as scattering in Figure 2. The coupling loss factor can be expressed as an equivalent scattering absorption area A_{sc} [3]. An estimation of A_{sc} for scattering objects is obtained by measuring the reverberation times in rooms with absorbent ceiling treatment with and without objects according to Equation (4) [3].

$$A_{sc} = 0.127V(\frac{1}{T_{20,with}} - \frac{1}{T_{20,without}}) \tag{4}$$

where
V is the volume of the room
$T_{20,with}$ is the reverberation time with objects
$T_{20,without}$ is the reverberation time without objects

In the study presented in this paper, Equation (4) has been used to calculate the scattering and absorption properties, A_{sc}, for diffusers. $T_{20,with}$ is the reverberation time measured with diffusers (for different configurations, see below).

A prototype of a diffuser was used. The orientation of this diffuser was used in different quantities and patterns in order to evaluate whether A_{sc} would be a measure sensitive enough to reflect how the diffusers affect the room acoustics. The relation between

A_{sc} and the room acoustic properties was evaluated and is presented in the Results paragraph below. It was also evaluated whether A_{sc} measured in a full-size classroom and measured on a smaller scale can be related. This was done since it is important that elements such as diffusers can be quantified in a laboratory scale. All the configurations tested, the test environment, and the material properties are presented below in this chapter.

2.2. Test Environment

Measurements were conducted in a mock-up of a rectangular classroom with the dimensions 7.32 × 7.57 × 3.50 m, see Figure 3, and in a reverberation chamber with the dimensions 3.57 × 3.99 × 4.00 m, see Figure 4. In both cases, the ceiling was installed at a height of 2.70 m from the floor.

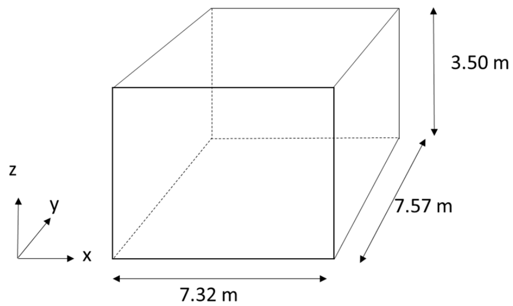

Figure 3. Dimensions of the classroom.

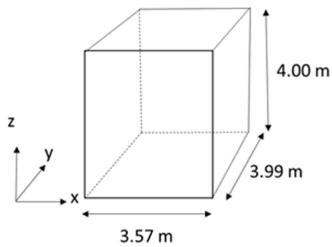

Figure 4. Dimensions of the reverberation chamber.

All measurements were performed over a two-day period. The mock-up was located in a laboratory environment where the humidity and temperature were controlled and kept constant. The background noise level was <30 dB (A).

In cases that included furniture (classroom mock-up), eleven tables and eighteen slightly upholstered chairs were used. The furnished room is depicted in Figures 1 and 5.

Figure 5. The mock-up classroom with furniture.

These furnishings contributed to a small amount of absorption at the higher frequencies and scattering at mid-frequencies. Absorption properties were evaluated according to diffuse sound field theory, Sabine, from measurements when only furniture was placed in the classroom, with no absorbent ceiling. Without a ceiling, it has been assumed that the sound field is diffuse, and therefore, the Sabine formula is used in this case. The absorption properties and equivalent scattering absorption area, i.e., both absorption and scattering from the furniture, were calculated using Equation (4). The absorption and scattering from the furniture can be found in Figure 6.

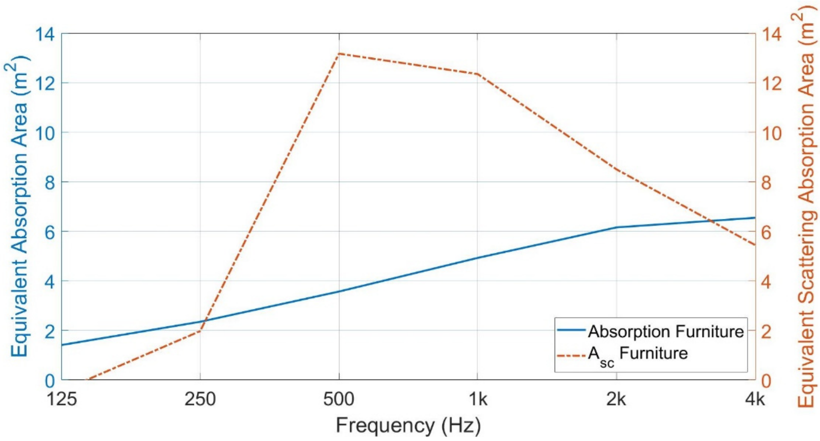

Figure 6. Absorption and equivalent scattering absorption area, A_{sc}, from the furniture. The furniture contributes to absorption in the higher frequency range and scattering at the mid-frequencies.

2.3. Acoustic Treatment

Porous absorbers and diffusers were used in the study. Their material properties are described in the following paragraphs.

2.3.1. Porous Absorbers

The porous absorbers used were a commercial product made of glass wool. The thickness of the product was 40 mm, and its air flow resistivity was 40 kPas/m^2, which was measured in accordance with ISO 9053-2 [41]. The measurement of the absorption properties for this product was performed according to ISO 354 [42] with the measurement made at an overall depth of the system (ODS) of 200 mm and was further evaluated according to ISO 11654 [43]. The weighted absorption coefficient α_w is equal to 1. The sketch up ODS set up for a 40 mm product can be seen in Figure 7.

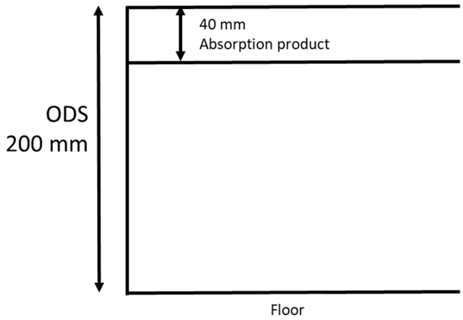

Figure 7. Sketch of mounting system for overall depth (ODS) of the system of 200 mm.

The sound absorbing tiles were in modules measuring 600 mm × 600 mm. When installed in the ceiling, they covered an area of approximately 52 m^2.

2.3.2. Diffusers

The term diffuser is not clearly defined in the literature. The elements used in this case contribute to the dispersion of reflections in different ways, such as spatial dispersion and scattering as well as diffraction. Altogether, the elements contribute to a more diffuse sound field and are thus called diffusers in this study.

The diffusers used were prototypes made of wood, with a timber frame and a surface covered with hardboard material. The module size was 600 mm × 600 mm, maximum depth 100 mm. See the sketch in Figure 8.

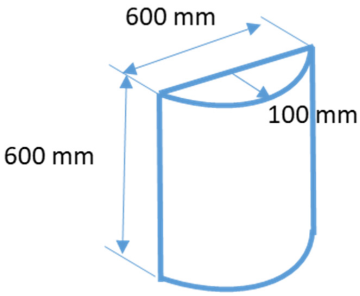

Figure 8. Sketch with dimensions of the diffusers used in the study.

The diffusers were mounted in two different orientations, vertical and horizontal. With vertically oriented diffusers, most of the sound waves reflected in a vertical, z-direction, while with horizontally oriented diffusers, most of the sound waves reflected in a horizontal, x-direction. A description of prototypes mounted vertically can be found in Figure 9, and those mounted horizontally can be found in Figure 10.

Figure 9. Diffuser vertically oriented; most sound waves are reflected in the vertical direction.

Figure 10. Diffuser horizontally oriented; most sound waves are reflected in the horizontal direction.

The diffusion characteristics for the frequencies were measured in a semi-anechoic chamber. An impulse response was used, the energy was measured in the reflections, and direct sound was removed. The reflections for every 10 degrees from 0 to 90 degrees were measured. The characteristics for the vertically oriented and for the horizontally oriented diffusers and for a flat panel were evaluated. The results for 500 Hz, 2000 Hz, and 4000 Hz are presented in Figure 11.

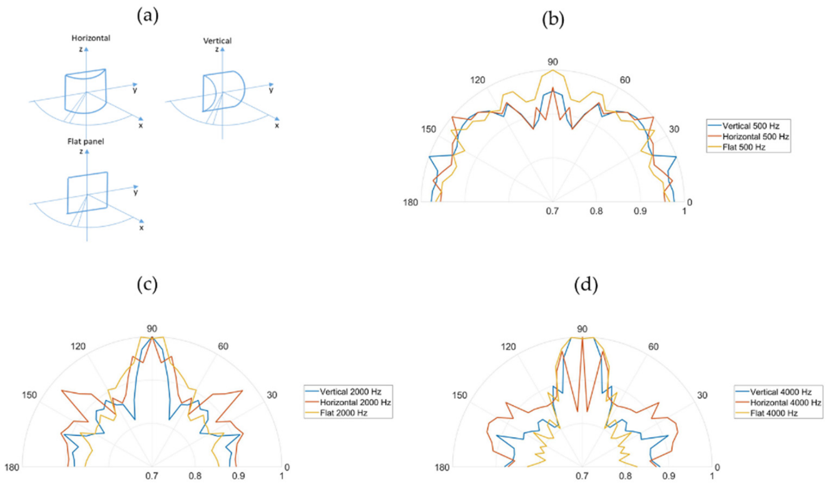

Figure 11. Diffusion characteristics for one diffuser related to the coordinate system defined in (**a**) for the diffusers mounted vertically and horizontally, as well as for a flat panel, for the frequencies 500 Hz (**b**), 2000 Hz (**c**), and 4000 Hz (**d**).

The diffusers have resonance absorption properties at the lower frequencies [1]. The absorption properties of the diffusers were evaluated from measurements when only diffusers were mounted in the classroom. The diffuse sound field was assumed as the room was empty apart from the diffusers. The absorption properties were calculated using Sabine's formula. The evaluation shows that the diffusers contribute with absorption in frequencies 125–500 Hz with the highest contribution at 125 Hz. These properties are independent of the diffuser orientation. The effect of this absorption in a room will be related to the amount of diffusers used.

The diffusers do not have specific directional scattering properties at these low frequencies. At the higher frequencies, the diffusers do have directional scattering effects, which are dependent on the orientation of the diffusers. This can be shown in terms of A_{sc} calculated by using Equation (4). The A_{sc} includes both absorption and scattering effects. The absorption together with the total equivalent scattering absorption area, A_{sc}, exemplified for 12 diffusers, vertically and horizontally oriented, can be seen in Figure 12. The graph shows the same value for the two different orientations in terms of absorption. The different scattering properties, in terms of A_{sc}, show the orientation dependency for the higher frequency range. In the case of vertical diffusers, sound waves directed toward the ceiling have a larger effect on the A_{sc} compared to the horizontally oriented diffusers. For the latter, sound waves are still dispersed but are mainly redirected in the horizontal plane and consequently not directed to an absorbent surface. Since A_{sc} accounts for both absorption and scattering, the A_{sc} value is lower for the horizontally oriented diffusers in the higher frequency area, which is where the diffuser affects the sound field the most.

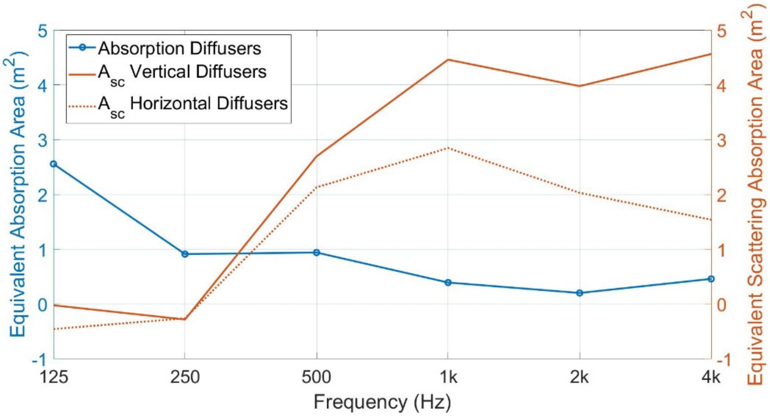

Figure 12. The graph shows the results for the cases of 12 diffusers mounted in rows; in each row, the diffusers are connected to each other. **Left axis:** Equivalent absorption area for the diffusors. Note: this absorption is independent of the diffusor orientation. **Right axis:** Equivalent scattering absorption area, A_{sc}, for vertically, VD, and horizontally, HD, oriented diffusers.

2.4. Configurations

Starting from the absorbent ceiling only, diffusers were added in steps of 2 diffusers per wall, with up to 12 diffusers per wall being used. For example, see Figure 13. The addition of diffusers was performed for both vertically oriented and horizontally oriented diffusers.

In the cases of 8 and 12 diffusers, two different patterns were used, which were connected or separated. In the connected pattern, the diffusers were mounted in rows but connected to each other in each row, i.e., connected on two sides. In the separated pattern, denoted SEP, each diffusing element was free on all sides. For example, see Figure 14.

In a second step, furniture was added to all the configurations to evaluate whether the effect per diffusing element differed due to furnishings.

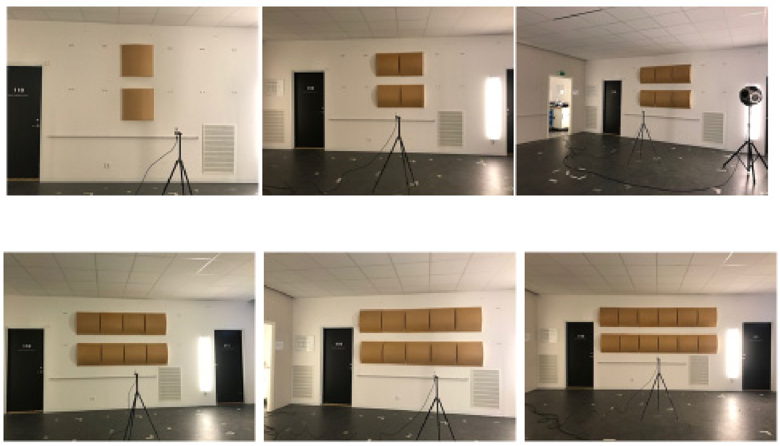

Figure 13. Example of configurations from two diffusers/wall, four diffusers in total. Two diffusers per wall were added up to the maximum number of 12 diffusers per wall, 24 diffusers in total. In this example, the case of vertically oriented diffusers is depicted.

(a)

(b)

Figure 14. The mounting patterns connected (**a**) and separated (**b**) and, in this case, for configuration with vertically oriented diffusers (six diffusers per wall, i.e., 12 diffusers in total. (**a**) corresponds to configuration with description CA_F_12VD, and (**b**) corresponds to CA_F_12VD_SEP.

The same set-up of diffusers was always used for two adjacent walls; see Figure 15. All configurations are described in Table 1. The left part of the table shows configurations without furniture and the right part of the table shows corresponding configurations with furniture.

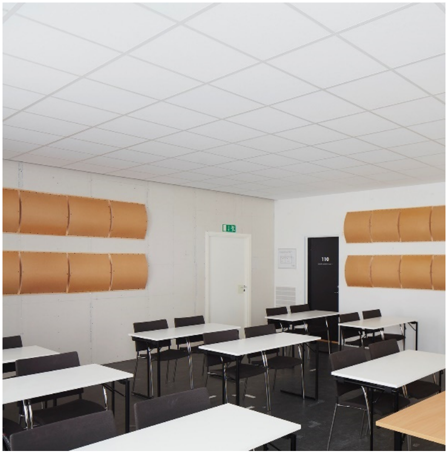

Figure 15. Diffusers, in all configurations, were mounted on two adjacent walls, as shown in this image. In each configuration, the same set-up was always used for the two walls.

Table 1. Configurations with absorbent ceiling used in the study, with configurations without furniture to the left and with furniture to the right.

Conf.	Conf. Abbreviation	Configuration Description	Conf.	Conf. Abbreviation	Configuration Description
1	CA	52 m^2 Ceiling absorbers	18	CA_F	Conf 1 + furniture
2	CA_4VD	Conf 1 + 4 vertical diffusers	19	CA_F_4VD	Conf 2 + furniture
3	CA_4HD	Conf 1 + 4 horizontal diffusers	20	CA_F_4HD	Conf 3 + furniture
4	CA_8VD_SEP	Conf 1 + 8 vertical diffusers, separated	21	CA_F_8VD_SEP	Conf 4 + furniture
5	CA_8VD	Conf 1 + 8 vertical diffusers, connected	22	CA_F_8VD	Conf 5 + furniture
6	CA_8HD_SEP	Conf 1 + 8 horizontal diffusers, separated	23	CA_F_8HD_SEP	Conf 6 + furniture
7	CA_8HD	Conf 1 + 8 horizontal diffusers, connected	24	CA_F_8HD	Conf 7 + furniture

8	CA_12VD_SEP	Conf 1 + 12 vertical diffusers, separated	25	CA_F_12VD_SEP	Conf 8 + furniture
9	CA_12VD	Conf 1 + 12 vertical diffusers, connected	26	CA_F_12VD	Conf 9 + furniture
10	CA_12HD_SEP	Conf 1 + 12 horizontal diffusers, separated	27	CA_F_12HD_SEP	Conf 10 + furniture
11	CA_12HD	Conf 1 + 12 horizontal diffusers, connected	28	CA_F_12HD	Conf 11 + furniture
12	CA_16VD	Conf 1 + 16 vertical diffusers, connected	29	CA_F_16VD	Conf 12 + furniture
13	CA_16HD	Conf 1 + 16 horizontal diffusers, connected	30	CA_F_16HD	Conf 13 + furniture
14	CA_20VD	Conf 1 + 20 vertical diffusers, connected	31	CA_F_20VD	Conf 14 + furniture
15	CA_20HD	Conf 1 + 20 horizontal diffusers, connected	32	CA_F_20HD	Conf 15 + furniture
16	CA_24VD	Conf 1 + 24 vertical diffusers, connected	33	CA_F_24VD	Conf 16 + furniture
17	CA_24HD	Conf 1 + 24 horizontal diffusers, connected	34	CA_F_24HD	Conf 17 + Furniture

2.5. Measurements

The room acoustic parameters evaluated were reverberation time (T_{20}) and speech clarity (C_{50}), which were defined according to Equation (5) below. Measurements were performed using a DIRAC system (DIRAC type 7841, Ver.6.0). An exponential sweep signal was used as excitation. An omnidirectional loudspeaker with dodecahedron geometry was used. The center of the loudspeaker was 1.55 m from the floor. An omnidirectional microphone was used as a receiver 1.20 m from the floor. The loudspeaker and microphone used in the measurements can be seen in Figure 16.

Figure 16. Loudspeaker and microphone used in the room acoustic measurements. The loudspeaker had its center at 1.50 m from the floor. The microphone was placed at a height of 1.20 m from the floor.

Two source positions and six receiver positions were used. The positions in the room are seen in Figure 17.

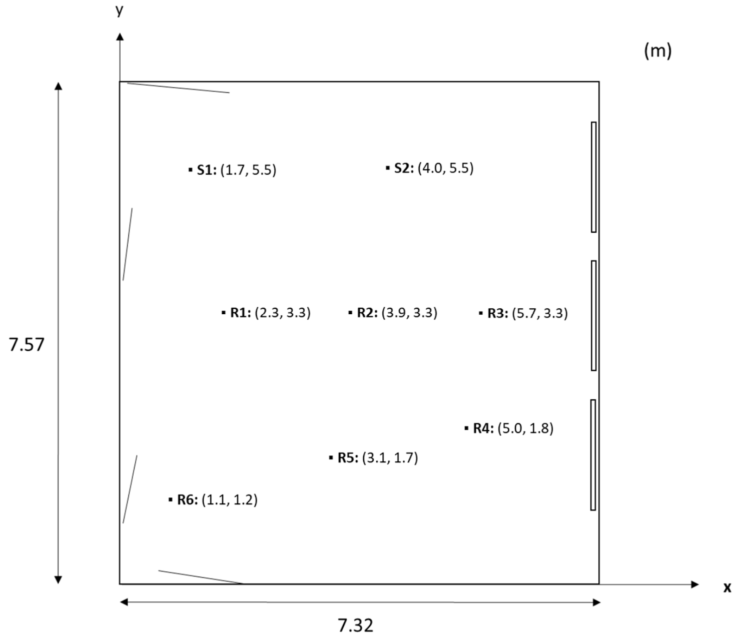

Figure 17. The dimensions of the classroom where measurements were performed. The source positions S1 and S2 can be seen as well as the six receiver positions R1–R6.

The reverberation time evaluated from the measurement was used in the analysis of A_{sc} using Equation (4). In addition, speech clarity, C_{50}, was evaluated to investigate whether this room acoustic parameter could be related to A_{sc} values.

Speech clarity C_{50} is defined as

$$C_{50} = 10\log\left(\frac{\int_0^{50ms} h^2(t)dt}{\int_{50ms}^{\infty} h^2(t)dt)}\right)\ \text{(dB)} \quad (5)$$

where $h(t)$ is the impulse response.

In speech clarity, early reflections are included. When evaluating T_{20}, according to ISO 3382-2 [44], the evaluation interval is −5 to −25 dB, given that the early reflections are excluded. The evaluation concerns octave bands in the range 125–4000 Hz, which were averaged over source and microphone positions.

In a previous study, repeatability was evaluated [1]. The repeatability interval for a 95% confidence interval is shown in Table 2.

Table 2. Interval of repeatability for the room acoustic measurements performed in the classroom.

	$T_{20,avg}$ (s)	$C_{50,avg}$ (dB)
125 Hz	±0.077	±0.56
250 Hz	±0.018	±0.29
500 Hz	±0.010	±0.29
1000 Hz	±0.006	±0.27
2000 Hz	±0.010	±0.38
4000 Hz	±0.008	±0.36

3. Results

The following sections present the principal results from the study with a selection of the configurations representing the trends. However, all configurations shown in Table 1 were evaluated, and complete results can be found in Appendix A.

3.1. Equivalent Scattered Absorption Area Depending on the Orientation and Quantity of Diffusers

The equivalent scattering absorption area, A_{sc}, calculated by using Equation (4), derived above, varied significantly depending on the diffuser orientation; i.e., the diffusing characteristics change. This difference is seen at the higher frequencies where the diffusing elements are most effective as diffusers. In the lower frequency range, the diffusing elements have resonance absorption properties. The difference in diffusing characteristics starts at 1000 Hz and increases with increased frequency. At 2000 Hz and 4000 Hz, the difference between vertically and horizontally oriented diffusers is significant. Results for 12 and 24 diffusers, mounted connected to each other in rows, are shown in Figure 18. However, the same differences are obtained for the pattern "separated" (see Appendix A).

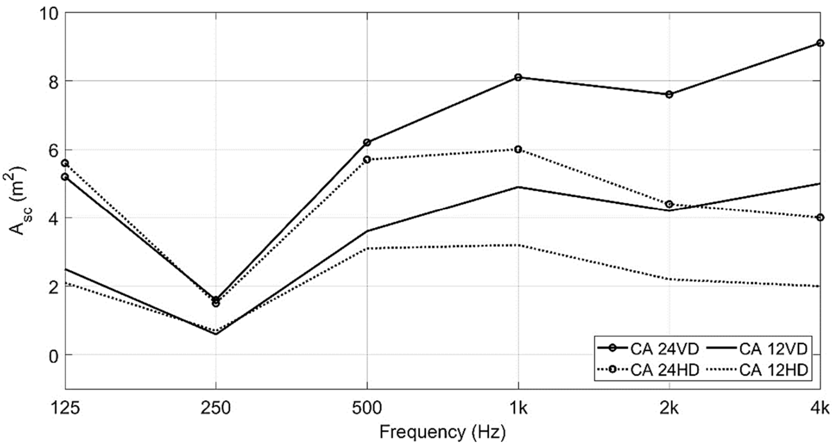

Figure 18. Comparison of the effect for vertically (denoted VD) and horizontally (denoted HD) oriented diffusers. The diffusers are mounted connected to each other in rows for all the configurations demonstrated in this graph.

Evaluating the quantity of diffusers showed a trend of lower effect in equivalent scattering absorption area per element when increasing the quantity of diffusers. This is valid for both vertically and horizontally oriented diffusers. The results in effect per element are shown in Figure 19.

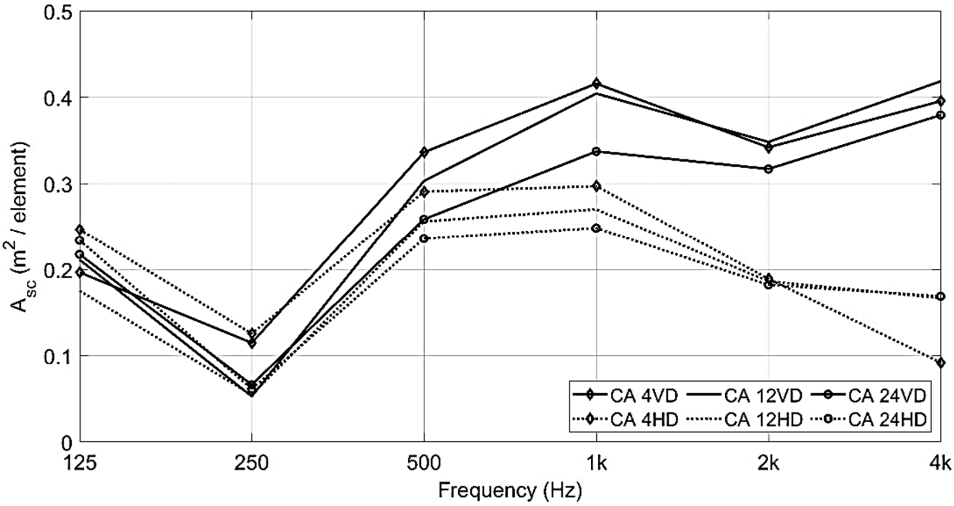

Figure 19. Effect per element for vertically oriented diffusers when a different quantity of diffusers is used. Configurations with 12 and 24 diffusers are demonstrated in this figure. The diffusers are mounted connected to each other in rows.

3.2. Effect of Diffuser Mounting Pattern

Evaluation of the effect that the pattern had on scattering showed a greater effect when the diffusers were mounted separately from each other, instead of connected. This applies to both vertically and horizontally oriented diffusers. Figure 20 shows the scattering effect depending on pattern. The results presented in the graph show the effect per element, which was calculated from configurations using 12 diffusers. The configurations ending with "SEP" correspond to the pattern with diffusers mounted separately from each other, as shown in Figure 14b.

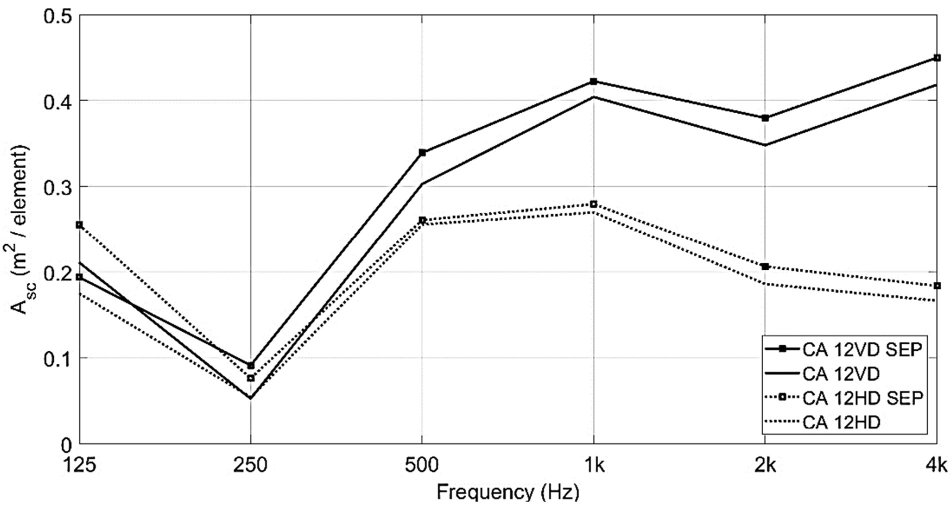

Figure 20. Equivalent scattering absorption area, A_{sc}, per diffuser for two different installation patterns. The graph shows results for 12 diffusers. The index "SEP" corresponds to the case when diffusers are installed separately from each other. The vertically oriented diffusers are denoted VD, and horizontally oriented diffusers are denoted HD.

3.3. The Effect of Combining Diffusers and Furniture

Combining diffusers and furniture (furniture set-up as in Figure 5) gives an additional effect in terms of the equivalent scattering absorption area, A_{sc}. The A_{sc} is shown in Figure 21 for configurations with 12 diffusers, vertically (VD) and horizontally (HD), with furniture (F) and without furniture. The figure shows a significant increase in equivalent scattering absorption area when furniture is added. The diffusers in the configurations demonstrated in the figure are mounted connected to each other in rows; however, the same trends are seen for diffusers mounted in pattern “separated” (see Appendix A).

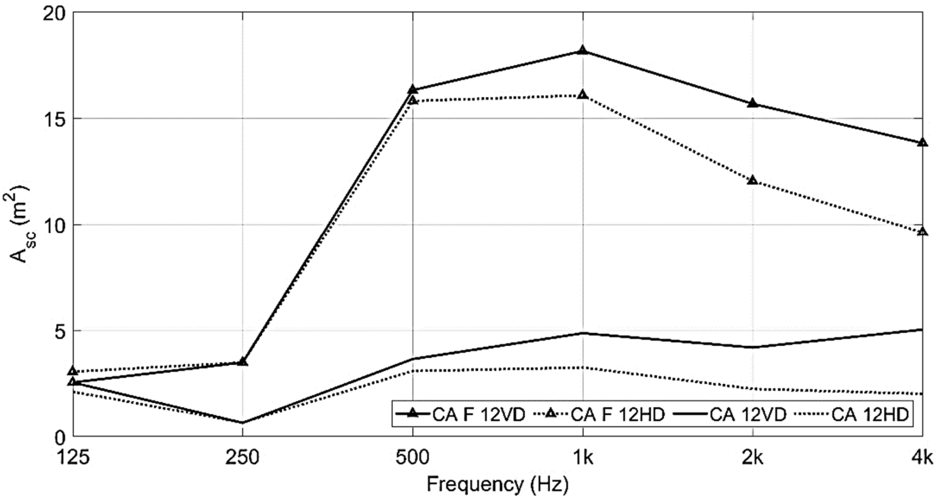

Figure 21. The A_{sc} relating to the diffusers with furniture (F) and without furniture. Vertically oriented (VD) and horizontally oriented (HD) diffusers. A significant increase in A_{sc} is seen when furniture is added. The diffusers are mounted connected to each other in rows in the configurations demonstrated in this figure.

Investigation of the effect of the *combination* of furniture and diffusers showed that the use of these different objects together provided an additional effect in terms of A_{sc}. Addition of the separate contribution in A_{sc} for each type of object, i.e., diffusers and furniture, gives a lower total value than that measured for frequencies 2000–4000 Hz. This is valid for both horizontally and vertically oriented diffusers. The effect of each type of object, i.e., diffusers and absorbers when measured separately and combined, as well as calculation of adding the two separate contributions, can be seen in Figure 22a (vertically oriented diffusers) and (b) (horizontally oriented diffusers). The diffusers are mounted connected to each other in rows for the configurations demonstrated in the figures.

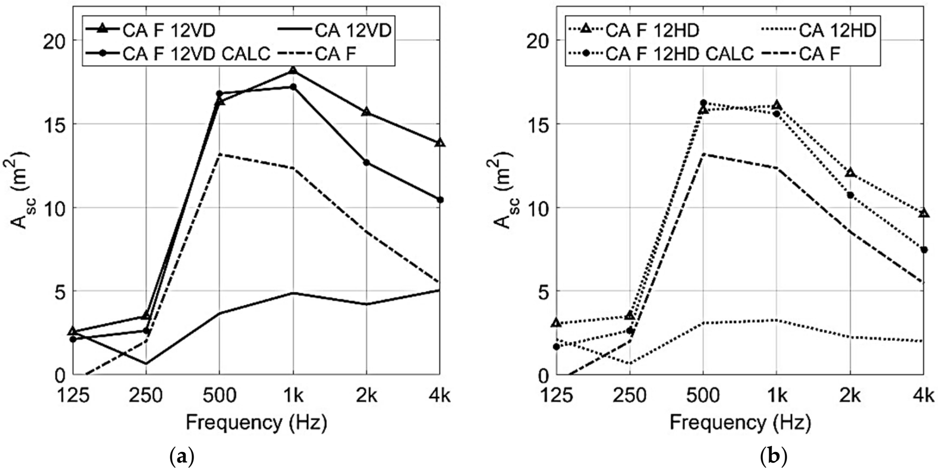

Figure 22. The effect on A_{sc} of configuration with furniture (CA_F) and 12 diffusers, vertically oriented (**a**) and horizontally oriented (**b**). Adding (calculated) the contribution for the two separate objects diffusers and furniture is denoted "CALC". A_{sc} from measured values, CA_F_12VD/12HD shows higher values than the separate contribution to A_{sc}; i.e., an additional effect on A_{sc} is achieved when combining furniture and diffusers.

3.4. Effect on Room Acoustic Parameters

Investigating the different configurations of diffusers with room acoustic parameters shows a relation between those parameters and A_{sc}. The higher scattering effect using vertically oriented diffusers resulted in a lower reverberation time, T_{20}, and higher speech clarity, C_{50}, compared to configurations with horizontally oriented diffusers. The two different patterns, separated and connected, where separated gave higher A_{sc}, which also showed a greater effect on the room acoustical parameters. Figure 23 shows T_{20} and C_{50} for a configuration with furniture, CA_F, the lowest quantity of diffusers, CA_F_4VD, the horizontally oriented diffusers, CA_F_12HD, and the vertically oriented diffusers, CA_F_12VD, which furthermore can be compared with the other pattern, CA_F_12VD_SEP. The scattering effects evaluated in previous sections affect the room acoustic parameters with the same trends; for example, a greater effect is seen when the diffusers are separated compared to connected as well as a greater effect for vertically oriented compared to horizontally oriented diffusers. Furthermore, it is shown that the room acoustic properties are similar at frequencies 125–500 Hz when the same number of diffusers are used, as the diffusers do not scatter at these low frequencies. The effect from absorption is dependent on how many absorbing elements are used, thereby the T_{20} lowered as the number of diffusers increased.

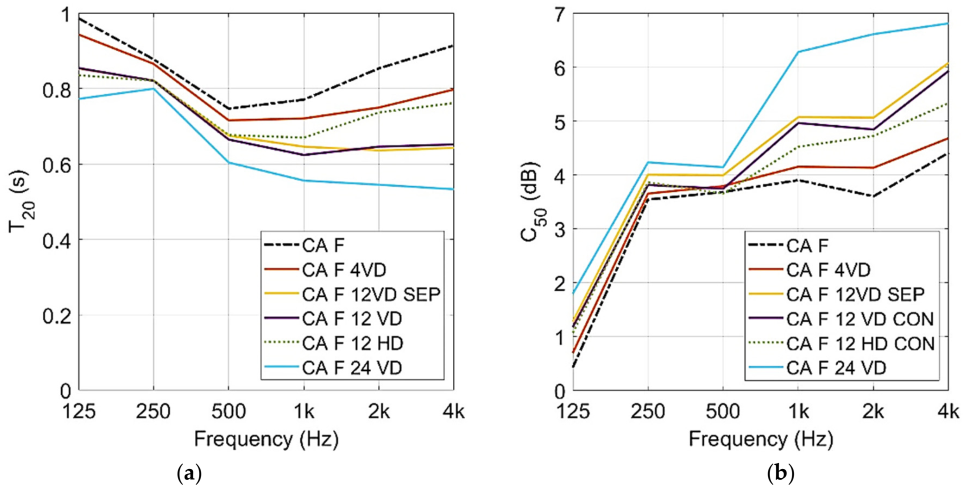

Figure 23. T_{20} (**a**) and C_{50} (**b**) for configurations with furniture. Configurations with varied numbers of diffusers, installation pattern, and orientation.

An evaluation of the relation between the equivalent scattered absorption area and room acoustic parameters shows a dependency on the A_{sc} for the room acoustical parameters investigated. One example is shown in Figure 24 where the results for all configurations measured with furniture and vertically oriented diffusers are shown.

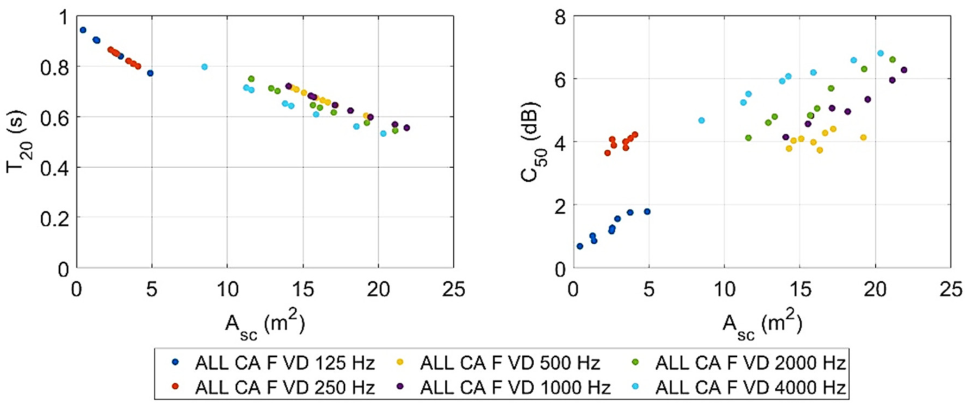

Figure 24. Relation between A_{sc} and room acoustical parameters T_{20} and C_{50} for all configurations with vertically oriented diffusers, furniture, and absorbent ceiling.

3.5. *A_{sc} in Classroom Mock-Up Versus Reverberation Chamber*

The effects of the diffusers in the classroom mock-up and in a reverberation chamber were compared. Twelve diffusers were used in vertical as well as horizontal orientation in the two different environments. In both cases, the diffusers were mounted connected to each other in rows.

Values in the same range in terms of A_{sc} per element were obtained for the two different environments. The results at the lowest frequency deviate, where the measurement in the reverberation chamber resulted in a lower A_{sc} compared to the classroom measurement. This could be explained by the small dimension of the reverberation chamber. However, the fact that the same trends are found for the two environments and that similar values are obtained for the higher frequency range indicates that it can be possible to quantify the effect of the diffusers in a smaller, laboratory environment. The comparison of the effect on A_{sc}/element for the two different environments can be found in Figure 25.

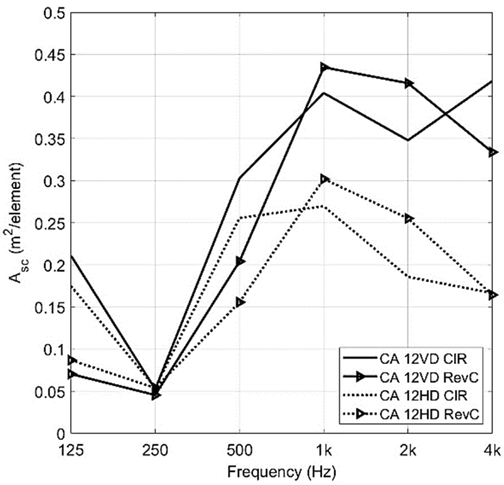

Figure 25. Effect in terms of A_{sc} per element for measurement in a classroom mock-up (ClR) and reverberation chamber (RevC) showing that the values obtained from the different environments are in the same range. The diffusers were mounted connected to each other in rows.

4. Discussion

The aim of this study has been to investigate whether the measure A_{sc} is sensitive enough to be used as an estimation of how the diffusers affect scattering and absorption in a room with absorbent ceiling and, if so, it could further be used in the SEA model from which the A_{sc} originates to estimate room acoustic parameters.

The evaluation of the different orientations, i.e., vertically and horizontally, giving different diffusing characteristics, showed significant differences in scattering. These results are obtained due to the fact that there is an absorbent ceiling installed, which is a typical treatment in ordinary rooms. The absorption of the diffusers, low frequency in this case, is independent of orientation yet related to the quantity of diffusers.

The scattering effect per element decreased with a greater number of diffusers; however, the total scattering in the room must of course be considered in the acoustic design, as scattering still increased with the addition of more diffusers. Whether there is a limit of when the effect of additional diffusers can be neglected has not been investigated in this case.

With different patterns, the effect per element differed, with more scattering in pattern "SEP", where the elements are separated from each other; all sides of the diffusers are exposed in this pattern. Thus, the pattern of the installation of diffusers is an aspect to be considered in acoustic design. For ordinary rooms, on which this study is focusing, the space available for acoustic treatment is often limited, and thus, the most effective placement can be particularly important for such environments.

Adding furniture further increased the effect; the total scattering was not only due to the addition of the two different types of objects, but an extra effect could be seen that also had an impact on the room acoustical parameters. This additional effect was seen at the higher frequencies where the diffusing properties are the greatest but also where the absorption from the ceiling and furniture contributes most. In this investigation, one set-up of furniture has been investigated: a furnishing that could be described as sparse. Due to the extra effect seen on A_{sc} when combining the two types of objects, i.e., diffusers and furniture, it would be of interest to investigate the effect when using a denser furnishing set-up.

Altogether, A_{sc} could be related to the variation of diffuser configurations. Investigating the A_{sc} in relation to room acoustic parameters showed a dependency: with higher A_{sc}, the T_{20} decreased and C_{50} increased. In this case, two room acoustic parameters were investigated, in the work going forward, other parameters, such as STI, could be investigated as well.

The aspects described above show how A_{sc} is a parameter sensitive to changes in diffuser set-ups, but in order to use the model for the estimation of acoustic parameters, the A_{sc} for a diffuser must be quantified beforehand. For this purpose, the A_{sc} values obtained in full-scale classroom were compared to those obtained in a reverberation chamber. Similar values are seen for the high frequencies, while a deviation is obtained in the lower frequency range. This deviation can be due to the small scale of the reverberation room. However, the comparison indicated a possibility of quantifying the diffusers in a laboratory environment. Thus, to establish such a method of transforming data from laboratory environment scale to full scale, a number of aspects must be defined for the test room such as the absorption properties of the ceiling, number of elements to be used, and volume of the room. The findings on the decreased effect per element and its installation pattern should be accounted for, and further, the interaction between furniture and diffusers must be considered in the calculation model.

An absorbent ceiling is a good baseline as regards the room acoustics for these types of rooms, with additional treatment such as diffusers being a good complement. The fact that these elements can be designed to operate either as scattering objects, diffusing elements with specific directivity properties, or as absorbers in a specified and limited frequency makes this type of treatment suitable in the fine tuning of the acoustic design, also in environments such as ordinary public rooms.

In future applications, using this model would allow architects and other practitioners to get estimations of how the use of diffusers in an ordinary room affects the room's acoustic properties. The fast results obtained from a calculation model, compared to simulation models, would give the opportunity to test several different designs of diffusers and set-up patterns of diffusers within a limited timeframe. The possibility to include these elements, as well as other acoustic treatments, already in the design phase increases the possibility of achieving good acoustics, and good aesthetics, in the final room.

5. Conclusions

It has been found in this study that the effect of diffusers installed in a mock-up of a classroom with a sound-absorbing ceiling could be quantified by calculating the equivalent scattering absorption area, A_{sc}. The A_{sc} value is defined on the basis of a two-system SEA model where the sound field is subdivided into a grazing and non-grazing part. The A_{sc} is related to the coupling loss factor between the two sub-systems. A relation between A_{sc} values, the quantity of diffusers, their orientation, and their installation pattern has been obtained. The A_{sc}/element decreased with the number of diffusers. Higher effects in terms of the A_{sc}/element were seen for vertically oriented diffusers, i.e., when the diffusers direct sound to the ceiling. In patterns where all sides of the diffusers were exposed, the effect of the A_{sc}/element was higher compared to when the diffusers were mounted direct to each other. The evaluation also showed that the combination of diffusers and furniture increased the effect on A_{sc} by more than the separate contribution of each type of object.

In addition, a dependency between A_{sc} and the room acoustic parameters reverberation time T_{20}, and speech clarity, C_{50}, can be seen. The variation in the A_{sc}/element due to the pattern, amount, and orientation as well as the effect of furniture was reflected in the room acoustic parameters measured. Thus, the A_{sc} measure could be an appropriate way of quantifying the effect of the diffusers, taking the above-mentioned design aspects of the diffusers and its installation into account.

Furthermore, it was seen that quantification in terms of A_{sc} of the diffusers obtained in a reverberation chamber with absorbent ceiling treatment gave similar values as in the classroom measurement. This indicates that the quantification of diffusers in terms of A_{sc} is possible in a laboratory environment. In the work going forward, for applying this method in real cases, the test procedure must be defined. The effect per element depending on the number of diffusers and installation pattern is to be included, and further, the combined effect of diffusers and furniture must be considered. Applying the model would support fast estimations of the room acoustic properties when different designs of the treatment are evaluated and thereby increase the possibility of achieving good room acoustics in ordinary rooms.

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Abbreviations

Acoustic Configurations

CA	Ceiling absorptive
F	Furniture, the room is sparsely furnished
VD	Vertical diffusers
HD	Horizontal diffusers
SEP	Separated diffuser pattern
CALC	Calculated values
ClR	Classroom
RevC	Reverberation chamber

Appendix A

Table A1. Complete results, measurements of T_{20} and C_{50} as well as A_{sc} values.

		CA	CA_4VD	CA_8VD_SEP	CA_8VD	CA_12VD_SEP	CA_12VD	CA_16VD	CA_20VD	CA_24VD
	Frequency [Hz]	Avg	Avg	Avg	Avg	Avg	Avg	Avg	Avg	Avg
	125	0.965	0.928	0.886	0.891	0.863	0.855	0.84	0.793	0.763
	250	0.966	0.944	0.924	0.951	0.915	0.936	0.926	0.911	0.894
	500	1.549	1.396	1.276	1.29	1.163	1.195	1.157	1.083	1.029
	1000	1.545	1.361	1.218	1.218	1.094	1.108	1.058	0.976	0.932
	2000	1.382	1.257	1.142	1.151	1.038	1.06	1.011	0.93	0.89
T20	4000	1.24	1.124	1.005	1.016	0.917	0.934	0.881	0.819	0.778
		CA	CA_4HD	CA_8HD_SEP	CA_8HD	CA_12HD_SEP	CA_12HD	CA_16HD	CA_20HD	CA_24HD
	Frequency [Hz]	Avg	Avg	Avg	Avg	Avg	Avg	Avg	Avg	Avg
	125	0.965	0.919	0.876	0.896	0.835	0.872	0.834	0.784	0.751
	250	0.966	0.942	0.923	0.944	0.923	0.935	0.934	0.913	0.899
	500	1.549	1.415	1.307	1.3	1.234	1.239	1.174	1.101	1.06
	1000	1.545	1.409	1.312	1.281	1.214	1.223	1.16	1.096	1.041

	2000	1.382	1.31	1.237	1.24	1.171	1.189	1.148	1.094	1.049
	4000	1.24	1.211	1.142	1.144	1.084	1.097	1.045	1.019	0.981
		CA_F	**CA_F_4VD**	**CA_F_8VD_SEP**	**CA_F_8VD**	**CA_F_12VD_SEP**	**CA_F_12VD**	**CA_F_16VD**	**CA_F_20VD**	**CA_F_24VD**
	Frequency [Hz]	Avg	Avg	Avg	Avg	Avg	Avg	Avg	Avg	Avg
	125	0.987	0.944	0.906	0.902	0.853	0.855	0.84	0.81	0.773
	250	0.878	0.866	0.854	0.85	0.822	0.821	0.821	0.81	0.8
	500	0.747	0.716	0.695	0.708	0.675	0.665	0.657	0.645	0.604
	1000	0.771	0.721	0.678	0.683	0.646	0.624	0.598	0.569	0.556
	2000	0.854	0.75	0.702	0.713	0.636	0.646	0.617	0.576	0.545
	4000	0.915	0.798	0.715	0.706	0.643	0.652	0.609	0.561	0.533
		CA_F	**CA_F_4HD**	**CA_F_8HD_SEP**	**CA_F_8HD**	**CA_F_12HD_SEP**	**CA_F_12HD**	**CA_F_16HD**	**CA_F_20HD**	**CA_F_24HD**
	Frequency [Hz]	Avg	Avg	Avg	Avg	Avg	Avg	Avg	Avg	Avg
	125	0.987	0.923	0.893	0.89	0.852	0.836	0.824	0.789	0.754
	250	0.878	0.875	0.845	0.85	0.833	0.821	0.816	0.813	0.794
	500	0.747	0.734	0.699	0.695	0.677	0.677	0.659	0.629	0.635
	1000	0.771	0.734	0.711	0.715	0.676	0.67	0.643	0.631	0.622
	2000	0.854	0.804	0.767	0.766	0.719	0.737	0.7	0.682	0.663
	4000	0.915	0.86	0.81	0.799	0.757	0.762	0.729	0.705	0.686
C50		**CA**	**CA_4VD**	**CA_8VD_SEP**	**CA_8VD**	**CA_12VD_SEP**	**CA_12VD**	**CA_16VD**	**CA_20VD**	**CA_24VD**
	Frequency [Hz]	Avg	Avg	Avg	Avg	Avg	Avg	Avg	Avg	Avg
	125	0.7	1.01	1.12	1.22	1.69	1.5	1.78	1.93	2.04
	250	3.23	3.51	3.2	3.16	3.13	3.28	3.03	3.35	2.96
	500	0.45	0.82	1.13	1,0	0.97	1.59	1.65	2.01	2.11
	1000	0.38	1.17	1.75	1.67	2.21	2.65	2.73	3.7	4.06
	2000	1.51	2.01	2.75	2.47	3.37	3.06	3.48	3.57	4.43
	4000	2.7	3.17	3.57	3.42	3.73	3.84	4.12	4.53	4.83
		CA	**CA_4HD**	**CA_8HD_SEP**	**CA_8HD**	**CA_12HD_SEP**	**CA_12HD**	**CA_16HD**	**CA_20HD**	**CA_24HD**
	Frequency [Hz]	Avg	Avg	Avg	Avg	Avg	Avg	Avg	Avg	Avg
	125	0.7	0.9	1.33	1.22	1.53	1.55	1.98	2.23	2.43
	250	3.23	2.94	3.07	3.12	3.1	3.19	3.25	3.1	3.3
	500	0.45	0.6	1.01	0.91	1.34	1.12	1.58	1.57	2.06
	1000	0.38	1.01	1.12	1,0	1.74	1.64	2.06	2.44	3.16
	2000	1.51	1.91	2.04	2.08	2.45	2.44	2.5	2.66	3.23
	4000	2.7	2.81	2.91	3.02	3.22	3.05	3.19	3.44	3.82
		CA_F	**CA_F_4VD**	**CA_F_8VD_SEP**	**CA_F_8VD**	**CA_F_12VD_SEP**	**CA_F_12VD**	**CA_F_16VD**	**CA_F_20VD**	**CA_F_24VD**
	Frequency [Hz]	Avg	Avg	Avg	Avg	Avg	Avg	Avg	Avg	Avg
	125	0.42	0.69	1.02	0.86	1.27	1.17	1.56	1.76	1.79
	250	3.54	3.65	4.08	3.89	4,0	3.81	4.01	4.11	4.23
	500	3.68	3.79	4.1	4.04	3.99	3.74	4.28	4.41	4.14
	1000	3.9	4.15	4.83	4.57	5.07	4.96	5.35	5.96	6.28
	2000	3.6	4.13	4.8	4.61	5.06	4.84	5.7	6.31	6.61
	4000	4.41	4.68	5.25	5.52	6.08	5.93	6.2	6.59	6.81
		CA_F	**CA_F_4HD**	**CA_F_8HD_SEP**	**CA_F_8HD**	**CA_F_12HD_SEP**	**CA_F_12HD**	**CA_F_16HD**	**CA_F_20HD**	**CA_F_24HD**

	Frequency [Hz]	Avg	Avg	Avg	Avg	Avg	Avg	Avg	Avg	Avg
	125	0.42	0.6	1.14	0.8	1.27	1.06	1.58	1.65	1.96
	250	3.54	4.05	3.81	3.59	4.16	3.86	4.07	4.32	4.25
	500	3.68	3.66	4.18	4.05	4.31	3.65	3.96	4.05	3.94
	1000	3.9	4.16	4.71	4.44	4.92	4.52	4.52	4.86	5.3
	2000	3.6	4.26	4.05	4.23	4.3	4.72	4.74	4.99	5.16
	4000	4.41	4.55	4.35	4.74	4.83	5.33	4.87	5.4	5.42
Asc	**Frequency [Hz]**	**CA**	**CA_4VD**	**CA_8VD_SEP**	**CA_8VD**	**CA_12VD_SEP**	**CA_12VD**	**CA_16VD**	**CA_20VD**	**CA_24VD**
	125	0.0	0.8	1.8	1.6	2.3	2.5	2.9	4.3	5.2
	250	0.0	0.5	0.9	0.3	1.1	0.6	0.8	1.2	1.6
	500	0.0	1.3	2.6	2.5	4.1	3.6	4.2	5.3	6.2
	1000	0.0	1.7	3.3	3.3	5.1	4.9	5.7	7.2	8.1
	2000	0.0	1.4	2.9	2.8	4.6	4.2	5.0	6.7	7.6
	4000	0.0	1.6	3.6	3.4	5.4	5.0	6.2	7.9	9.1
	Frequency [Hz]	**CA**	**CA_4HD**	**CA_8HD_SEP**	**CA_8HD**	**CA_12HD_SEP**	**CA_12HD**	**CA_16HD**	**CA_20HD**	**CA_24HD**
	125	0.0	1.0	2.0	1.5	3.1	2.1	3.1	4.5	5.6
	250	0.0	0.5	0.9	0.5	0.9	0.7	0.7	1.1	1.5
	500	0.0	1.2	2.3	2.3	3.1	3.1	3.9	5.0	5.7
	1000	0.0	1.2	2.2	2.5	3.4	3.2	4.1	5.0	6.0
	2000	0.0	0.8	1.6	1.6	2.5	2.2	2.8	3.6	4.4
	4000	0.0	0.4	1.3	1.3	2.2	2.0	2.9	3.3	4.0
	Frequency [Hz]	**CA_F**	**CA_F_4VD**	**CA_F_8VD_SEP**	**CA_F_8VD**	**CA_F_12VD_SEP**	**CA_F_12VD**	**CA_F_16VD**	**CA_F_20VD**	**CA_F_24VD**
	125	-0.4	0.4	1.3	1.4	2.6	2.5	2.9	3.8	4.9
	250	2.0	2.3	2.6	2.7	3.4	3.5	3.5	3.8	4.1
	500	13.2	14.3	15.1	14.6	15.9	16.3	16.7	17.2	19.2
	1000	12.3	14.1	15.7	15.5	17.1	18.2	19.5	21.1	21.9
	2000	8.5	11.6	13.3	12.9	16.1	15.7	17.0	19.2	21.1
	4000	5.4	8.5	11.3	11.6	14.2	13.8	15.9	18.5	20.3
	Frequency [Hz]	**CA_F**	**CA_F_4HD**	**CA_F_8HD_SEP**	**CA_F_8HD**	**CA_F_12HD_SEP**	**CA_F_12HD**	**CA_F_16HD**	**CA_F_20HD**	**CA_F_24HD**
	125	-0.4	1.3	2.0	2.1	3.1	3.5	3.8	4.8	5.9
	250	2.0	0.1	0.8	0.7	1.2	1.5	1.6	1.7	2.3
	500	13.2	0.5	1.7	1.9	2.6	2.6	3.4	4.8	4.5
	1000	12.3	1.2	2.1	1.9	3.5	3.7	4.9	5.5	5.9
	2000	8.5	1.4	2.5	2.6	4.2	3.5	4.9	5.6	6.4
	4000	5.4	1.3	2.7	3.0	4.3	4.2	5.3	6.2	6.9

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