A MODEL FOR EARLY-REFLECTION-ORIENTED ACOUSTIC DESIGN OF ROOMS FOR SPEECH

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Mahmut SÖZER

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We approve the thesis of **Mahmut SÖZER**

Examining Committee Members:

Prof. Dr. Mustafa Emre İLAL
Department of Architecture, İzmir Institute of Technology

Prof. Dr. Serdar KALE
Department of Architecture, İzmir Institute of Technology

Assoc. Prof. Dr. Konca ŞAHER
Department of Architecture, Kadir Has University

Prof. Dr. Tuğçe KAZANASMAZ
Department of Architecture, İzmir Institute of Technology

Prof. Dr. Özgül YILMAZ KARAMAN
Department of Architecture, Dokuz Eylül University

11 December 2023

Prof. Dr. Mustafa Emre İLAL
Supervisor, Department of Architecture
İzmir Institute of Technology

Prof. Dr. Koray KORKMAZ
Head of the Department of Architecture

Prof. Dr. Mehtap EANES
Dean of the Graduate School of
Engineering and Sciences

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ABSTRACT

A MODEL FOR EARLY-REFLECTION-ORIENTED ACOUSTIC DESIGN OF ROOMS FOR SPEECH

The room acoustics treatments in conventional rectangular classrooms, if applied, usually appear as a sound-absorbing suspended ceiling in the entire ceiling. This approach to achieving a recommended reverberation time value underrates the importance of early reflections, particularly for speech intelligibility in the back rows.

The research proposes a room acoustics design methodology named early-reflection-oriented room acoustics design (ERORAD) for rooms for speech based on a model where early reflections are prioritised and quantified by the G_{50} parameter.

On-site measurements were conducted in the "IYTE Yeni Amfi" room. A 3D computer model of the sample room was created to simulate and test various acoustic conditions. Binaural listening tests were conducted using the auralised audio material of the relevant scenarios mixed with background noise signals at varying levels representing the active classroom background noise.

The study showed that an early-reflection-oriented room acoustics design (ERORAD) methodology increases relative sound levels of direct speech and its early reflections. This improves speech intelligibility at distant audience locations better than conventional approaches by categorising the room surfaces as functional surfaces (ERS) for early reflection of speech sound and as appropriate surfaces for absorption (SfA) for the absorption of the late reflections to control reverberation time. The findings suggested that G_{50} can be a primary parameter to determine the optimal trade-off point between speech sound energy and reverberation time to achieve required speech intelligibility in the audience positions away from the speaker at relatively high levels of active classroom background noise.

ÖZET

KONUŞMA AMAÇLI HACİMLERİN ERKEN YANSIMA ODAKLI AKUSTİK TASARIMI İÇİN BİR MODEL

Dörtgen geometriye sahip geleneksel dersliklerdeki hacim akustiği düzenlemeleri, eğer yapılmışsa, genellikle tüm tavana uygulanmış ses yutucu bir asma tavan olarak karşımıza çıkar. Belli bir yansışım süresi değerine ulaşmaya yönelik bu yaklaşım, konuşma anlaşılırlığı açısından özellikle arka sıralar için erken yansımaların önemini gözden kaçırmaktadır.

Araştırma, G_{50} parametresi ile ölçülebilen erken yansımalara öncelik verilen bir modele dayalı olarak, konuşma amaçlı hacimler için erken yansıma odaklı hacim akustiği tasarımı (EYOHAT) olarak adlandırılan bir hacim akustiği tasarım metodolojisi önermektedir.

"IYTE Yeni Amfi" dersliğinde akustik ölçümler yapılmış ve farklı akustik koşulları canlandırmak ve erken yansımaların konuşma anlaşılabilirliği üzerindeki etkisini ölçmek için dersliğin 3-boyutlu bir bilgisayar modeli oluşturulmuştur. Hacim akustiği tasarım senaryolarının işitselleştirilmiş ses dosyaları üretilmiş ve bu dosyalar farklı düzeylerdeki aktif derslik arka plan gürültüsünü temsil eden sinyalle karıştırılarak binaural dinleme testleri gerçekleştirilmiştir.

Oda yüzeylerinin, konuşma seviyesini artıran erken yansımalar için işlevsel yüzeyler (EYY) ve yansışım süresini kontrol eden geç yansımaların yutulması için ses yutucu kullanımı için uygun yüzeyler (YkY) olarak kategorize edildiği çalışmada , erken yansıma odaklı hacim akustiği tasarım (EYOHAT) metodolojisinin, konuşmanın bağıl ses seviyelerini artırdığını ve uzak dinleyici konumlarında konuşma anlaşılabilirliğini geleneksel yaklaşımlardan daha iyi geliştirdiğini göstermiştir.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

The significance of the early reflections on speech is shown by the numerous studies going back to the first quarter of the last century. Petzold (1927) referred to a "blurring threshold" and described the early-time limit as 50ms (17±3 meters) for speech. Aigner and Strutt (1935) pointed out the increase in the relative level of the direct sound due to reflections arriving within the early-time limit. Haas (1951) defined the phenomenon by the energy-adding law, called the Haas effect or the precedence effect. Lochner and Burger (1964) emphasised the importance of the reflection patterns in a room for their impact on speech intelligibility.

Barron (2009) proposed the concept of *early reflection ratio* based on (*Deutlichkeit*) *early energy fraction* (Thiele 1953) for the design of speech theatres. Barron refers to the significance of early reflecting surfaces, mainly when the speaker turns his head in a direction not facing the audience. Bradley et. al (2003) demonstrated that early reflections significantly improved the relative sound level of speech, particularly for seats far from the speaker and proposed a metric named *early reflection benefit, ERB*. Choi (2013) showed that higher relative sound levels and clarity were increased at rear seat positions in a rectangular classroom by promoting early reflections with various room acoustics arrangements, reducing the absorption by using the diffusers instead, while the reverberation time values remained similar.

The reverberation time has a two-way impact, acting like an adjustment slider moving positive and negative directions regarding speech intelligibility. While very low reverberation time dampens the speech signal, including supportive early reflections, excessive reverberation reduces speech intelligibility due to the temporal overlapping of syllables. It also amplifies the ambient noise, thus lowering SNR.

The signal-to-noise ratio would be meaningful in an active classroom if the speech level variance and active classroom noise levels were considered (Sooch San Souci et al. 2006). Recent studies showed that the ambient noise in active classrooms was much higher than in unoccupied classroom ambient noise levels proposed in the related standards. The common point of the studies in question is that the active classroom noise level is the determinant factor of the ambient noise level (Bayazit, Küçükçıfçı, and Şan 2011), (Shield et al. 2013), (Sala and Rantala 2016), (Choi 2020a).

Bradley et al. (2003) remarked that focusing on the reverberation time as a primary design criterion overlooks the early reflections, which are significant for the speech. The authors referred to an optimum reverberation time, which is not necessarily the minimum achievable reverberation time for a given room. Instead, the optimum reverberation time should be regarded as a range of values to maximise early reflections while controlling the late-arriving reflections for a given room size and ambient noise.

Additionally, San Souci et al. (2006) stated that the reverberation time also fails to represent the entire room when the room is non-diffuse, as is the case for most classrooms since a non-diffuse room will produce significantly different slopes for different measurement points.

In contrast to the large volume of the literature on the importance of early reflections for speech, a specific method aside, a set of instructions or guidelines on how acoustic planning of a classroom protects and redirects early reflections to improve speech intelligibility at listener positions away from the speaker are lacking. The general practice of planning a room for speech is still primarily based on obtaining a target reverberation time by applying absorption, where the reflection patterns based on room geometry are overlooked. While the reliability of the reverberation time is arguable for the non-diffuse rooms for speech, neither of the room acoustics metrics let the designers draft a room geometry considering the early reflections. Room acoustics planners go through iterative predictions, generally by room acoustic prediction software, to obtain the "recommended range".

Prioritising the reflections for early sound will inevitably let the planner consider the room geometry in terms of reflection patterns specific to the room shape, the position and directivity of the sound source and the position of the audience within the architectural context. Prioritising the reflections for early sound does not mean abandoning reverberation time consideration. Once the interior surfaces providing early reflections to the audience are determined, the rest of the areas will be available to control the late part of the reflections, meaning that the valuable early reflections can be kept, and excessive late reflections can be absorbed to control temporal masking and ambient noise for better intelligibility.

Consequently, early reflections should be identified and protected before controlling late-arriving reflections by fine-tuning the reverberation time. This can be fulfilled by the geometrical acoustic planning of the room, allowing a proper placement of reflecting and absorbing room surfaces. The early reflections should be aimed particularly towards distant student positions where the direct speech signal weakens.

This study proposes a methodology for room acoustics design for speech to prioritise early reflections by considering the reflection pattern before applying absorption to obtain a reverberation time target.

1.1. Problem

Room geometry is an indispensable element of architectural design. Room acoustics, as a function of the room geometry and room surfaces, is related to the architectural design process starting from the beginning. However, today, acoustic planning is regarded as a detached procedure in which the acoustic function is added after the architectural design. Acoustic “treatment” is a common term referring to this process. The word's meaning may also be interpreted as the illness of the architectural designs, which needs treatment. As a result of the detachment of room acoustics planning from the architectural design process, the acoustic design of rooms for speech, in particular classrooms, is reduced to the determination of absorbers based on numerical analysis to obtain a target reverberation time value. On the other hand, the reverberation time relates to the late energy, where the effect of the valuable early energy is averaged out. In order to take advantage of the early reflections, a geometrical approach prioritising the early reflections over absorption is necessary.

The primary objective of classroom acoustics is to achieve a good degree of speech intelligibility. This requires optimising two interrelated domains: the time domain and the energy or pressure domain. The time domain is quantified by the reverberation time. Excessive reverberation causes speech articulations to overlap and mask each other, reducing speech intelligibility. While a reverberation time target solves the temporal masking problem within the time domain, the valuable contribution of the early energy of the speech sound is overlooked. Therefore, to improve speech intelligibility for disadvantaged listening positions, it is essential to address the issue within the energy domain along with the time domain.

Increasing the speech sound pressure level (SPL) for better speech intelligibility, on the other hand, is a problem that falls into the energy or pressure domain. To increase the SPL at the listener locations via architectural design, surfaces that reflect the speaker's voice in the listener's area must be used. Therefore, consideration of the room geometry in terms of sound-reflecting patterns and room surfaces providing early reflections, in particular, according to the positions of the speaker and the audience, should be incorporated in the very early stages of the architectural design process to improve room acoustics for better speech intelligibility.

Despite the large volume of literature addressing the subject with numerical analyses and acoustic measurements, an architectural acoustics design methodology for classrooms prioritising early reflections still needs to be outlined.

1.2. Goals

This research aims to investigate a design methodology prioritising the reflections for early sound in a design procedure of rooms for speech to preserve the early reflections that contribute to speech intelligibility between listener and speaker points. This approach aims to identify areas where sound absorbers should not be placed, rather than the traditional approach of designing room acoustics by placing sound absorbers in vacant areas of a given architecture. The significant contribution of the early reflections to speech intelligibility is well known. Based on this knowledge, a design approach focused on preserving early reflections will be used to determine the room geometry with the proper locations of reflectors and absorbers within the room. Thus, the acoustic design of classrooms aims to guide the architectural design geometrically by reserving reflective surfaces functional for early reflections and areas outside these surfaces where absorbers are convenient. The goals are based on the following questions:

Is it sufficient to rely solely on reverberation time as a criterion for achieving satisfactory speech intelligibility? Can an acceptable level of speech intelligibility be attained without a specific reverberation time value, as mentioned in the literature?

Can the G_{50} parameter be the primary parameter in an early-reflection-oriented design approach? In other words, is satisfactory speech intelligibility ensured by a specific range of G_{50} values?

Furthermore, can the effect of background noise in the actual environment be replicated for binaural listening tests by mixing sound files of auralised scenarios with an artificial noise signal whose level difference is digitally measured? Would that test method be reliable?

1.3. Scope

The study's scope is limited to conventional rectangular classrooms that are large enough for the teacher's voice to become insufficient or unintelligible in the back rows.

The "IYTE Yeni Amfi" classroom, which has 168 seats, was chosen as a research sample. On-site measurements were conducted, and room acoustics scenarios were developed using room acoustic simulations. A 3D computer model of the sample room was created to simulate various acoustic conditions. The effect of early reflections on speech intelligibility was quantified by evaluating the results of the room acoustic simulations. The contribution of reflecting surfaces to early reflections was observed and quantified in terms of sound strength, G_{50}. Auralised audio files of relevant scenarios were played to participants in binaural listening tests to quantify the findings subjectively. The impact of early reflections on speech intelligibility was compared using objective and subjective measures.

CHAPTER 2

CONCEPTS

2.1. Free And Reverberant Sound Fields

The free field is the space where the sound comes directly from the source only, and there is no reflection in any direction, i.e. the sound is free of reflection and consists of the direct sound only. In contrast, a reverberant field is a space where the sound only consists of the reflected sound. In an ordinary room, the sound has two components: direct and reflected. The direct and reflected sound ratio changes with the distance to the sound source. Therefore, this distance determines whether the free field or reverberant field conditions dominate for a given point in a room, as Figure 2.1 below illustrates.

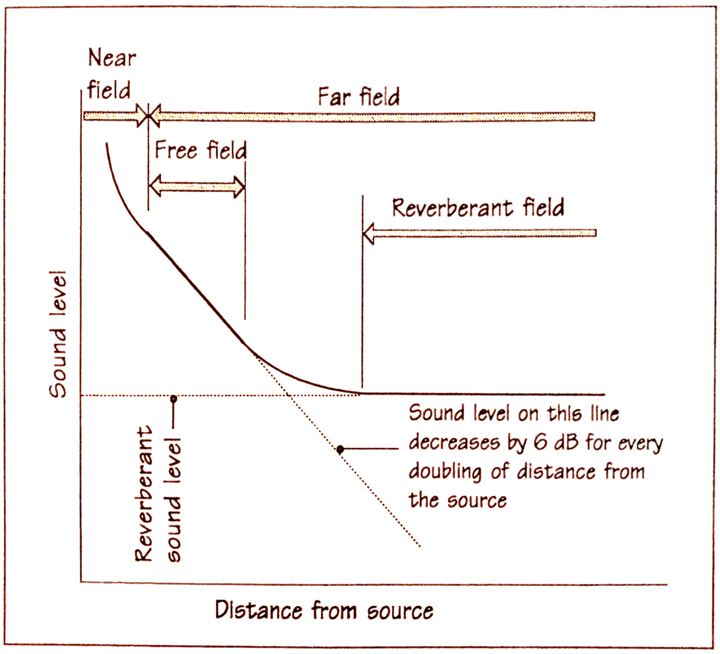


Figure 2.1. Sound Fields in a Room

(Source: Mehta, Johnson, and Rocafort 1999)

2.2. Diffuse Sound Field

A diffuse sound field is a space where the sound arrives at a listener's position from all possible directions, and the pressure of the sound is equal throughout the space. In other words, the energy density is the same everywhere in a diffuse sound field (Kuttruff 2009).

2.3. Critical Distance

In Figure 2.2, w_d is the energy curve as a function of distance r, and w_r is the energy density of the reverberant field excluding the direct sound. The 'critical distance' is where direct sound energy density, w_d, equals reverberation energy density, w_r. It is also called a 'diffuse-field distance' (Kuttruff 2009).

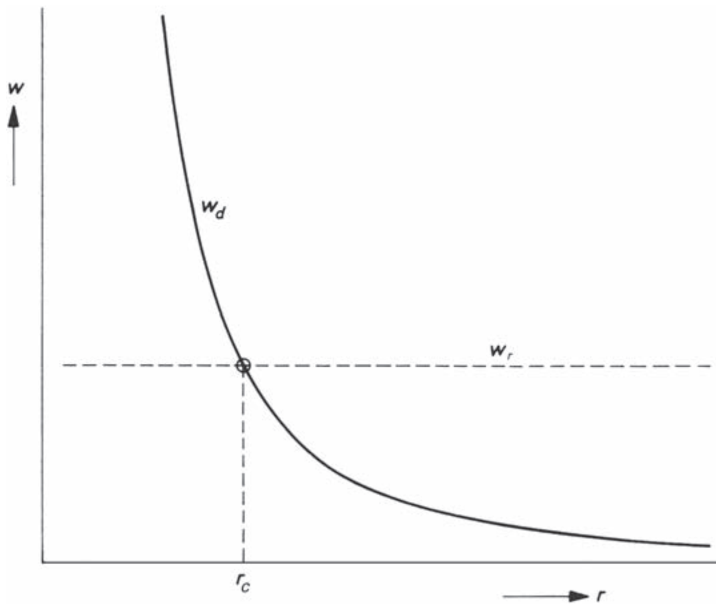


Figure 2.2. Critical Distance, r_c

(Source: Kuttruff 2009)

2.4. Impulse Response, IR

An impulse response illustrates the temporal distribution of a sound generated by an impulsive source in a room. The vertical axis of the diagram represents the sound level, and the horizontal axis represents the arrival time of the sequential responses, as seen in Figure 2.3 below. In a diffuse room, the impulse diagram shows a uniform sound level decay over time; in other words, the decay rate is uniform in perfectly diffuse rooms (Mehta, Johnson, and Rocafort 1999).

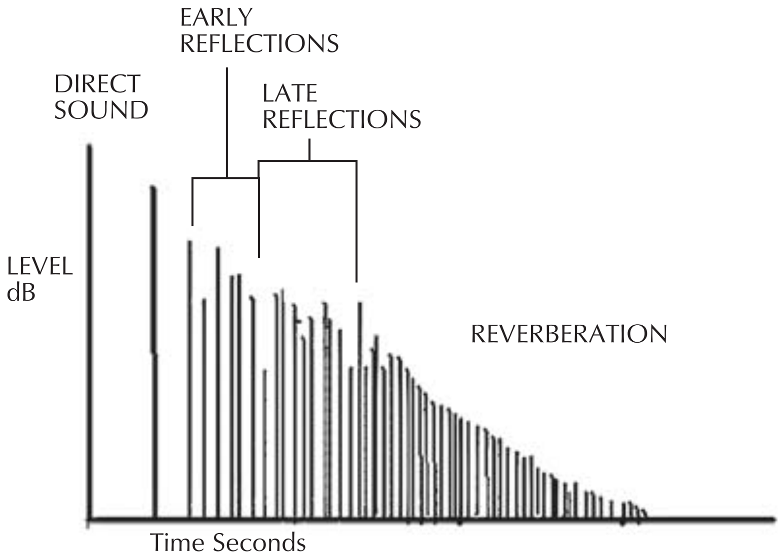


Figure 2.3. Impulse Diagram and Sound Field Components
(Source:Mapp 2008)

2.5. Reverberation Time, T

Sabine identified the decay rate as reverberation time, quantified by the time passed until the sound level is dropped by 60dB after the sound source is interrupted. The reverberation time is denoted as RT_{60}, referring to the time passed for a 60dB drop in the energy density. Practically, reverberation time is determined by the decay slope between -5dB and -35dB, which is then extrapolated to a 60dB drop. In this procedure, RT_{60} is denoted as T_{30} to indicate that RT_{60} was determined by extrapolating the decay slope for a 30dB drop between -5dB and -35dB. Because the decay slope is not uniform in most of the cases, a similar procedure is used for different ranges of the sound level decay to obtain various reverberation time metrics as follows: Early Decay Time, EDT, between 0dB and -10dB; T15, between -5dB and -20dB; T20, between -5dB and -25dB.

2.6. Speech Intelligibility, SI

Speech intelligibility relates to how well the message in a speech is transmitted to the listener in a room. The ratio of the level of the message-carrying voice of the speaker to the ambient sound level, known as the signal-to-noise ratio, SNR, is the critical factor determining speech intelligibility.

2.7. The Haas Effect

The Haas effect, or the integration and precedence effect, occurs due to the characteristic of the human hearing mechanism. Human hearing integrates two consecutive sounds and perceives them as one sound, adding their loudness if the delay is very short. Two sounds of the same level are integrated and perceived as one sound when the delay between two sounds is up to 50ms. If the second sound's level is 3dB lower, the integration occurs up to 80ms delay. Figure 2.4 below shows the integration zone due to the Haas effect. If the level of the second sound is close to that of the first, it is likely to be perceived as a distinct echo as the delay increases.

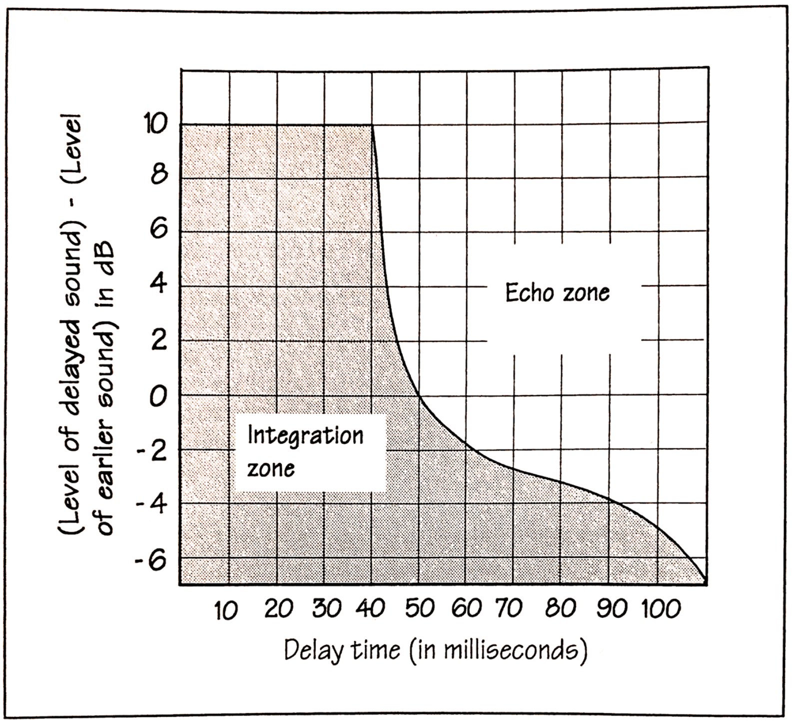


Figure 2.4. Integration and Echo Zone
(Source: Mehta, Johnson, and Rocafort 1999)

2.8. Direct Sound and Early Reflections

The reflections that reach the listener position within the first 50ms following the arrival of the direct sound are considered the early reflections in the speech context, as displayed in Figure 2.5. The early reflections are a valuable part of the reflections, contributing to speech intelligibility. (John S. Bradley 1998)

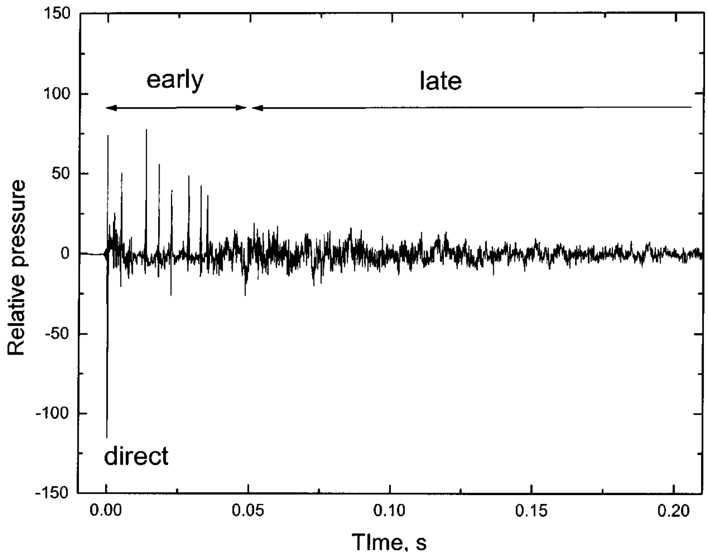


Figure 2.5. Direct Sound, Early and Late Reflections
(Source: J. S. Bradley, Sato, and Picard 2003)

2.9. Geometrical Acoustics

The basis of the geometrical room acoustics is replacing the wave concept with the ray concept. This is limited to relatively small wavelengths compared to the dimensions of the room boundaries and the distance travelled by the sound waves (Kuttruff 2009).

It is possible to analyse the shape of a room and its early reflections by drawing straight lines from a source point representing direct sound. The first few order reflections, which are the specular reflections from the room's surfaces, can be represented by the lines. The plan and section drawings of the room can be examined to do this. This technique was used throughout history when the plans were drawn by hand. The technique remains a valid feature of GA-based prediction software. (B. I. Dalenbäck 2018).

A prediction software based on geometrical acoustics takes the sound waves as rays, the straight lines representing direct sound emitted from a point source. GA-based prediction software calculates the geometrical reflection of the rays in a mathematical model of the room (Krokstad, Strom, and Sørsdal 1968).

2.10. Relative Sound Level, G

The relative sound level or sound strength, G, is the logarithmic ratio of the energy density in a room to the energy density measured in the free field at a point 10 meters away from the same sound source. This metric is used to evaluate the room amplification or the room gain.

CHAPTER 3

LITERATURE REVIEW

3.1. Early Reflections

The literature on the significance of the early reflections and their relation to speech intelligibility has a substantial history. However, today, applying this knowledge to the design of the geometry of a room for speech is not proportionate to the significance emphasised in the related literature.

The knowledge of the effect of the early reflections or a single echo on speech, as referred to by Haas (1951), goes back to the first quarter of the last century. Petzold (1927) refers to the "blurring threshold" for speech when the delay time of the echo is 50ms (±10ms), which corresponds to a path difference of 17 ± 3m between direct sound and the first arriving reflection. In other studies, integration of the early reflections was reported as an increase in the apparent strength of the direct sound (Aigner and Strutt 1935). Haas (1951) stated that the single echo arriving within 30ms after direct sound causes an increase in volume by the energy addition law and a change in the sound image in the sense of broadening the primary sound source. This phenomenon was documented in other studies such as "The precedence effect in sound localisation" (Wallach, Newman, and Rosenzweig 1949) and by others with different perspectives, as referred by Gardner (1968).

Lochner and Burger point out that it has long been known that reflection patterns in the room and background noise are determinative factors on speech intelligibility in their article published six decades ago. The authors particularly emphasise the significance of the reflection patterns of the room for speech intelligibility (Lochner and Burger 1964).

Bradley et al. (2003) prioritise maximising the total energies of the direct and early arriving reflections of the speech sound for the acoustic design of the room for speech.

The authors point out the potential pitfall of focusing on reverberation time as a primary design parameter since it can cause the designer to overlook more important details for the design. They defined the Early Reflection Benefit, ERB, as given in Figure 3.1, to quantify the contribution of early arriving reflections to useful speech sound energy.

$$ERB \; = 10\log\left(\frac{E_{50}}{E_{10}}\right) = G_{50} - G_{10}\; dB \tag{3.1}$$

ERB is defined as the increase in early arriving sound due to the energy of early reflections arriving within 50ms after the arrival of direct sound. It is quantified relative to the direct sound using sound strength measure, G, with an early time limit modifications such as G_{50} and G_{10} (John S. Bradley 2005). The authors concluded that the early reflection energy can increase the signal-to-noise ratio up to 9dB. The study shows that early reflections remarkably increase intelligibility concerning the case of direct speech sound without reflections. Figure 3.1 shows the significance of the early reflections during a lecture when the talker's head is turned and not facing the audience (J. S. Bradley, Sato, and Picard 2003).

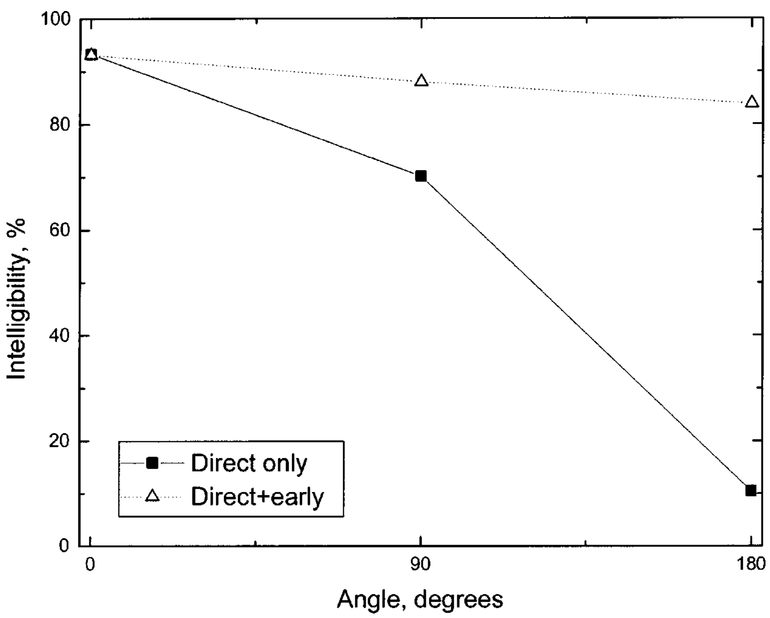


Figure 3.1. Early Reflection's Contribution to Speech Intelligibility
(Source: J. S. Bradley, Sato, and Picard 2003)

In a following study in elementary school classrooms, the authors used G_{50} as a metric for the relative energy of the direct sound combined with the useful early reflections, arriving within 50ms after the direct sound. G_{late} refers to the relative energy of the remaining part of the impulse response, excluding the part of the first 50ms. The study suggests that, before achieving an optimum reverberation time, a room design should aim to have G_{50} values larger than G_{late} values at the distant listening positions in the classrooms. Furthermore, the findings show that shorter reverberation time causes lower early reflection energy. According to the study, sound absorption should control the late-arriving reflections in the audience positions (Sato and Bradley 2008).

In another study in university classrooms, various absorptive and diffusing treatments were examined. Increased G_{50} values were reported when the part of the absorptive material was replaced with the diffusing material. The study revealed that G_{50} could be increased while maintaining the same mean reverberation time (T30) across different room acoustics design configurations (Choi 2013).

The effect of added early reflections was observed in a study using an active acoustic system. The system can selectively add late and early reflections to control the strength and direction of the reflections as well as frequency response and density. The study's findings support the early reflection benefit (ERB) concept of Bradley et. al (2003). The results suggest that added early reflections increased the strength of the early reflection in the back of the room, exceeding the strength of the late reflections (Ellison and Germain 2013).

In experiments conducted in the Université de Paris Sud classrooms, the authors indicate the advantages of prioritising reflections and treating absorbers as secondary. They point out the two-way benefit of reflective panel placement, which considers early reflections for teacher and student positions (Sooch San Souci et al. 2006).

3.2. Speech Intelligibility

3.2.1. Milestones Of Speech Intelligibility Studies

Objective speech intelligibility can be defined as the degree to which the listener correctly identifies the message conveyed by speech. Objective speech intelligibility criteria used today in room acoustics are not directly measurable quantities but rating methods based on the models used for evaluating the measured quantities.

Knudsen (1929) published his empirical experiments examining speech intelligibility in lecture halls in 1929. This study examined the joint effects of noise, speech level and reflection on speech perception in the lecture hall through speech recognition tests performed in a room. Findings included that consonants are consistent and dominant determinants of speech intelligibility compared to vowels and that increasing reverberation time reduces speech intelligibility.

Studies that constitute today's scientific literature on the evaluation of speech intelligibility began with the invention of the telephone. In an article, Alexander Graham Bell wrote about the incomprehensibility of articulations when used in unfamiliar sentences. He stated that vowel syllables are distinct, but most consonant syllables other than L and M needed to be understood. Bell set the first precedent for measuring articulation intelligibility in this article by isolating speech sounds. Reflection due to room volume was not a problem for speech intelligibility transmitted over a copper wire. However, studies up to 1940 laid the groundwork for today's Articulation Index, AI, metric used in room acoustics. Hawley (1995) considers the identification and measurement of speech power factors by Sacia (1925), the demonstration of sentence and syllable comparative intelligibility by Fletcher and Steinberg (1929), and studies forming the basis of AI by Dunn and White (1940), as the milestones.

One of the first efforts to standardise speech intelligibility rating was the Articulation Index, AI, developed by French and Steinberg, where the relation between signal-to-noise ratio, SNR, and speech intelligibility presented as a function of frequency (French and Steinberg 1947).

Steeneken (1992) points out the study by Licklider et al. (1959) as one of the earlier studies to define a numerical method for speech intelligibility, where a method called Pattern Correspondence Index, PCI, for comparing the pattern in the input and output channels along with a working measurement was presented.

Kryter (1962) and Ball (1964) described the speech communication index meter, SCIM, based on the AI method. Measurements in this system focus on determining the signal-to-noise ratio in the frequency range of 100-7000Hz with a dynamic range of 30 dB.

Lochner and Burger (1964) published their signal-to-noise ratio method. In this study, the effect of the sound reflection pattern of the room is considered for the determination of speech intelligibility.

Peutz (1972) published a method called Articulation Loss of Consonants, Alcons, for speech intelligibility estimation. This method uses direct-to-reverberant ratio, signal-to-noise ratio and reverberation time measurements to calculate speech intelligibility.

In 1971-72, Houtgast and Steeneken (2002) introduced the Speech Transmission Index, STI, a method based on the concept of the modulation transfer function, MTF, quantifying the modulation reduction of speech-like signal in a transmission channel.

3.3. Objective Speech Intelligibility Metrics

3.3.1. Articulation Index, AI

AI was developed by French and Steinberg (1947) to measure speech intelligibility in telephone communication. The main idea of the concept is the ratio of speech and noise intensities in the sound coming to the ear on a frequency basis. The method, later developed by Kryter (1962), is used to detect speech intelligibility under various transmission conditions such as noise, masking, low-frequency filtering and frequency shifts, at a frequency of 100-7000 Hz and a dynamic range of 30 dB (Steeneken 1992). Figure 3.2 shows the approximate relation between AI and the subjective measures of speech intelligibility. The ratio between AI and speech recognition percentage is non-linear; the change of the AI 0.1 - 0.4 range in the percentage of correct speech recognition follows a steep slope compared to the AI 0.4-1.0 range. One of the major limitations of AI is that the method does not account for the room's reverberation. Therefore, this criterion is reliable if the listener is closer than the critical distance.

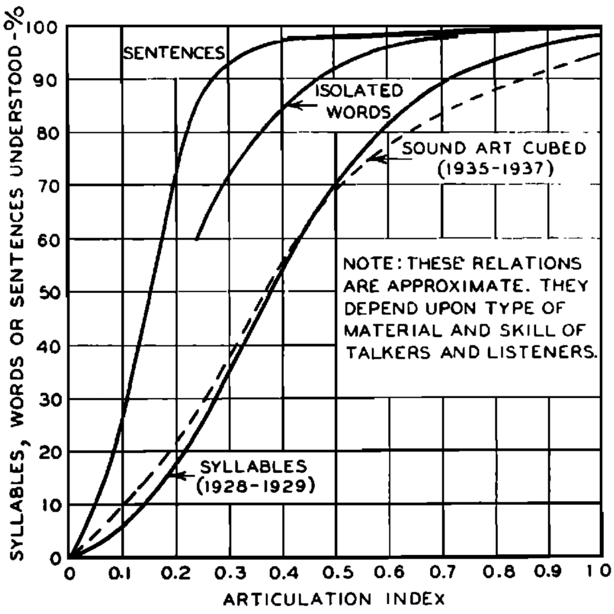


Figure 3.2. AI and Subjective Scores
(Source: French and Steinberg 1947)

Amlani et al. (2002) consider the study by Hawkings et al. (1988) as a remarkable finding in AI studies illustrating the contribution of visual information to the AI scores compared to the tests based on the audio-only. Figure 3.3 below shows the difference between A-V and A-only conditions.

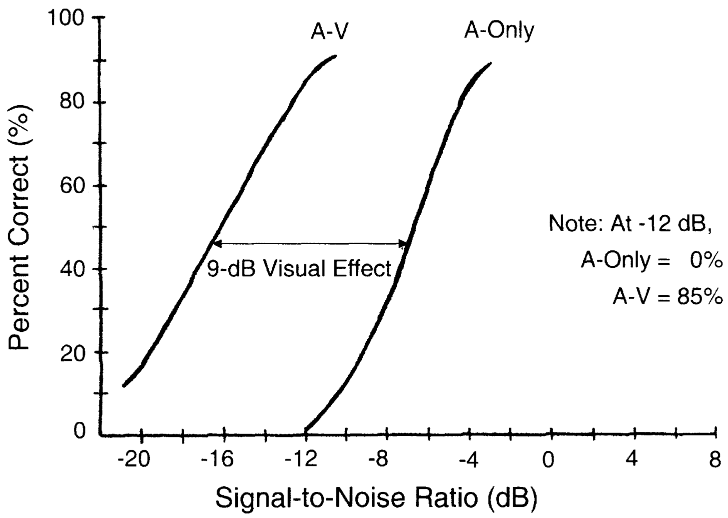


Figure 3.3. Visual Information’s Contribution to Speech Intelligibility
(Source: Amlani, Punch, and Ching 2002)

The AI method was the first standardised method for speech intelligibility estimation, as one of the methods recommended in the ANSI Standard S3.5 1969 standard. The method was refined with further studies leading to SII, Speech Intelligibility Index, where the effect of room reverberation along with other factors such as importance function, speech level, speech dynamic range, and spread of masking were taken into account, as presented in the ANSI 3.5 1997 (Pavlovic 1987).

3.3.2. Signal-To-Noise Ratio, SNR

Approaches that consider speech intelligibility according to acoustic energy rates are based on the findings put forward by Haas in the 1950s. Bistafa and Bradley (2000) refer to equation 3.2 by Aigner and Strutt (1935) as the first acoustic-energy ratio-based formula expressing the joint effect of room acoustics and background noise.

$$Q = \frac{E_d + E_e}{E_l + E_n} \tag{3.2}$$

where E_d is the direct sound energy, E_e is the useful part of the energy of the reflected sound (the part that reaches the ear no later than 1/16s after the direct sound), E_l is the remaining part of the reflected sound energy (the part that comes to the ear 1/16s after the direct sound) and E_n is the noise energy. Aigner and Strutt named this metric the Impression, Q.

Although the sound in the room is generally divided into two components, direct and reverberant sound, a subdivision of reverberant sound to identify, early and late reflections are essential in terms of subjective impression and speech intelligibility. The sound field components, as shown in Figure 2.3, are as follows: Directly arriving sound; early reflections (reflections reaching the listener in the 35-50ms interval); late reflections (reflections reaching the listener in the 50-100ms interval) and reverberation (intense reflections reaching the listener after 100ms) (Mapp 2008).

In the study focusing on the effects of the joint effect of reflection, noise and reflection patterns on speech intelligibility in a room, Lochner and Burger (1964) classified the energies of early and late reflections as useful and detrimental components. They developed the concept of useful-to-detrimental sound ratio regarding the intelligibility of speech. The part they call useful reflections is the interval where the direct and early arriving sound is heard as a whole due to the fusion of early reflections due to the hearing mechanism. This behaviour of the hearing mechanism is similar to that of flickering light. It is perceived by the visual mechanism as a continuous light depending on the blinking speed of the light. They identified the first 95ms interval of reflections as the fusion period, of which the first 30-40ms interval was defined as the full fusion interval, and the 40-95ms part was defined as the partial fusion interval. The total energy after 95ms was considered a noise component containing the rest of the signal and other external factors such as ambient noise. The authors proposed equation 3.3 for useful sound energy and equation 3.4 for signal-to-reverberant (noise) ratio.

$$E_e = \mathrm{K} \int_{t=0}^{95ms} \alpha P^2 dt \tag{3.3}$$

$$R'_{sn} = 10\lg \frac{\int_{t=0}^{95ms} \alpha P^2 dt}{\int_{95ms}^{\infty} P^2 dt} \tag{3.4}$$

In equation 3.3, α is the fraction of the early reflections integrated to direct sound, P is the instantaneous value of the sound pressure, and E_e is the useful sound energy. In equation 3.4, the noise is regarded as the reverberant part of the sound after direct sound and the integrated early reflections within the 95ms integration period.

The background noise is considered for the concept of the useful-to-detrimental sound ratio by equation 3.5, as proposed by Latham (1979).

$$\frac{S}{N} = 10log_{10} \frac{\int_{t=0}^{95ms} \alpha(p,t) p^2(t) dt}{\int_{95ms}^{\infty} p^2(t) dt + p_{PNC}{}^2 T} \tag{3.5}$$

Where p_{PNC} is the average maximum level of PNC-shaped (Preferred Noise Criterion) background noise, T is the speech intelligibility test passage duration.

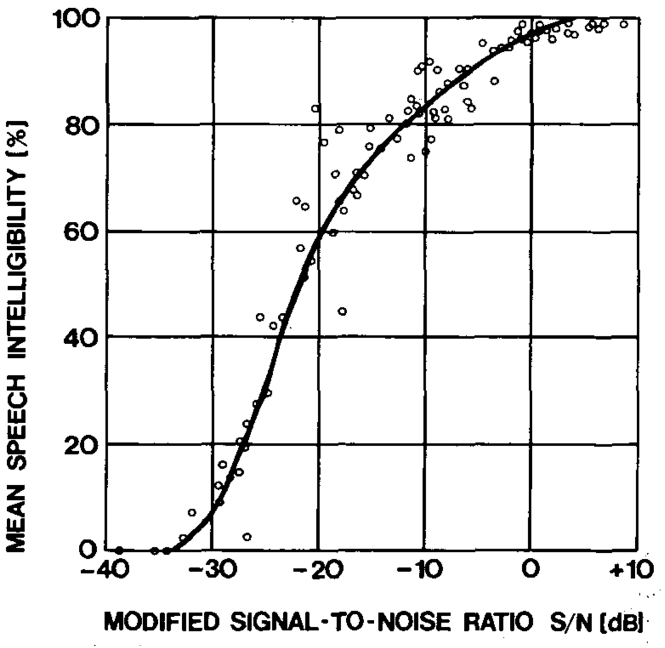


Figure 3.4. Relation between SNR and Speech Intelligibility
(Source:Smith 1981)

The SNR exhibits a high correlation with the subjective speech intelligibility tests. However, since sound pressure levels at 1000 Hz were used in this method, the variations in the frequency spectrum of the reflection pattern were not taken into account (Smith 1981).

3.3.3. Definition, D, and Clarity, C_{50}

There are different opinions regarding the division of early and late reflections regarding speech intelligibility. Some researchers suggested that the first 50ms is suitable for speech intelligibility. Thiele's Definition and Ahnert's Clarity metrics are based on early reflections within the first 50ms following the arrival of direct sound. These two very similar criteria are referred to as Definition, D, and Clarity, C_{50}, and are defined by the following equations (Mapp 2008).

$$D = \frac{E_{50}}{E_{\infty}} \tag{3.6}$$

$$C_{50} = 10\log\left(\frac{E_{50}}{E_{\infty} - E_{50}}\right) dB \tag{3.7}$$

Background noise is not addressed separately in either method; the energy components belong only to the signal of interest. Therefore, both D and C_{50} metrics are based on the early-to-late ratio.

3.3.4. Useful-To-Detrimental Ratio, U_{50}

C_{50} can be written in terms of the level of early and late reflections as given by the equation:

$$C_{50} = L_{p,early} - L_{p,late} \tag{3.8}$$

Bradley (1986) (1986a) developed the U_{50} criterion based on C_{50} by adding the ambient noise component, as seen in the equation below.

$$U_{50} = L_{p,early} - L_{p,late+noise} \tag{3.9}$$

The principle of U_{50} is identical to the principle proposed by Aigner and Strutt, as seen in equation 3.2.

In this model, it is assumed that noise is distributed uniformly throughout the room. The joint effect of reverberation time and background noise in classrooms have been comparatively discussed in studies such as (J. S. Bradley, Reich, and Norcross 1999), (Hodgson, Rempel, and Kennedy 1999), (Hodgson 1999), (Bistafa and Bradley 2000), (Hodgson 2002), (Sato and Bradley 2008), (Sato and Bradley 2004).

U_{50} metric was highly correlated to the Speech Transmission Index, STI, and the subjective speech recognition test results. The studies conducted in the active university classrooms supported the findings of previous studies, where the background noise of the active classrooms was taken into account (Cho 2017), (Choi 2020a), (Choi 2020b). Figure 3.6 illustrates the linear relationship between U_{50} and STI based on the measurements in eleven university classrooms.

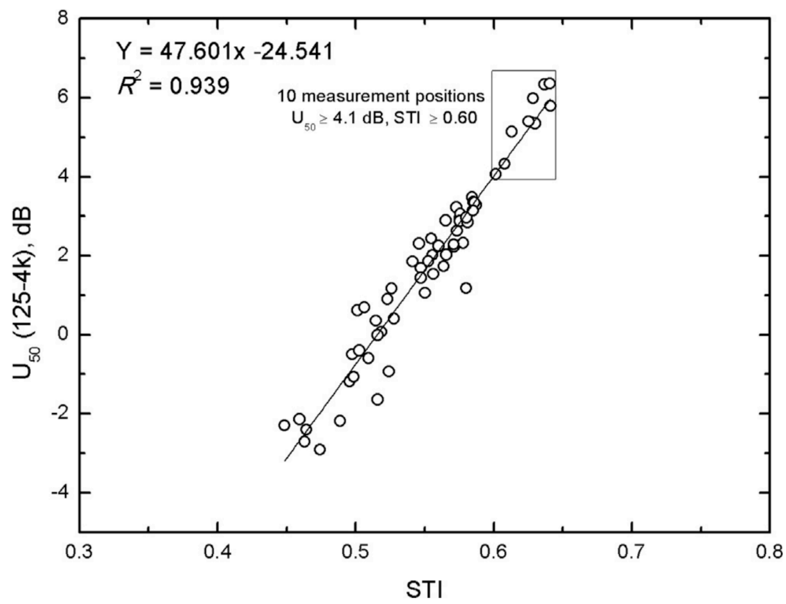


Figure 3.5. STI – U_{50} Relation

(Source: Choi 2020a)

In another study, based on the studies revealing the relationship between STI and U_{50}, U_{50} was used as a focus of classroom design to determine the optimal reverberation time for classrooms (Nijs and Rychtáriková 2011).

3.3.5. Articulation Loss of Consonants, Al_{cons}

Peutz (1972) conducted speech recognition experiments with CVC (consonant-vowel-consonant) word lists under various room acoustic conditions. He discovered that the loss of articulation in consonants is a determinant factor of speech intelligibility and proposed the following empirical relationship.

$$Al_{cons} = 0.652(\frac{r_{QH}}{r_H})^2 RT \ \% \tag{3.10}$$

Where r_{QH} is the distance between the speaker and the listener, r_H reflection radius or, in the case of a directional sound source, critical distance r_R; RT is the reverberation time. Figure 6 shows the relationship between D/D_c (the ratio of the distance between speaker and listener to the critical distance) and Al_{cons} under various reverberation time conditions.

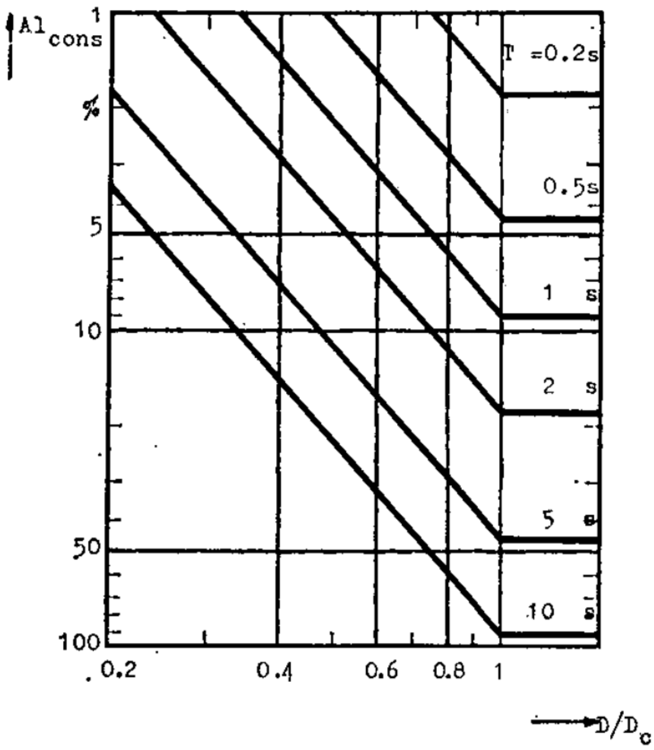


Figure 3.6. Alcons and D/D_c Relation
(Source: Peutz 1972)

Although the method provides easy calculation, it only uses the 2kHz band. It gives results with acceptable accuracy for situations where the directionality stays mostly the same (Mapp 2008).

3.3.6. Speech Transmission Index, STI

The development of the STI method coincides with the development of Al_{cons} in the early 1970s, and both studies were conducted in the Netherlands. STI was developed as a measurement method.

The basic principle of the STI method is based on measuring the decrease in the modulation frequency of an artificial speech-like signal. The method treats the source-room-receiver path, in other words, the audio transmission path, as a transmission channel where the decrease in modulation depth is measured via a specific test signal traversing the channel.

In the earlier stages of development, four frequency components with amplitude modulation (10Hz) were used in full octave bands, and the index was calculated by observing the decrease in the 10Hz modulation when the signal was transmitted through the transmission channel. In Figure 3.7, ΔL indicates 10Hz level fluctuations (Houtgast et al. 2002).

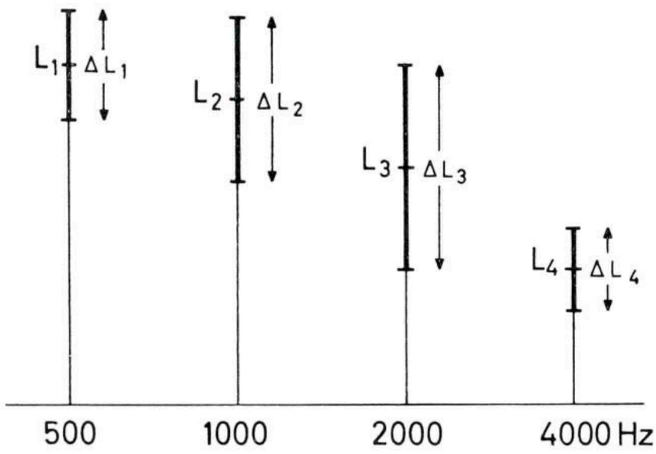


Figure 3.7. The First Test Signal in STI Studies
(Source: Houtgast et al. 2002)

Based on the knowledge that in speech, reverberation affects fast fluctuations more and slow fluctuations less, researchers began to search for a speech envelope to improve measurements. Observing that the amount of reduction in modulation depth is a function of various room effects and the modulation frequency, they defined a modulation transfer function, MTF, in the range of 0.25Hz-25Hz (updated to 0.5-16Hz). MTF expresses the relation between the input signal on a frequency basis and the output signal, to which room effects such as noise and reflections are added. MTF, in other words, is an attenuation filter based on the signal-to-noise ratio and reflection-induced distortions caused by the reduction in the speech envelope spectrum on the original signal. This principle is seen in the speech recognition scores from recognition tests performed with phonetically balanced (PB) word lists under different signal-to-noise ratios and reverberation time conditions. The upper curve seen in the graphs shows the original speech envelope, and the shaded lower part shows the part that is useful for speech intelligibility, remaining above the noise after disturbance effects fluctuations (Houtgast et al. 2002).

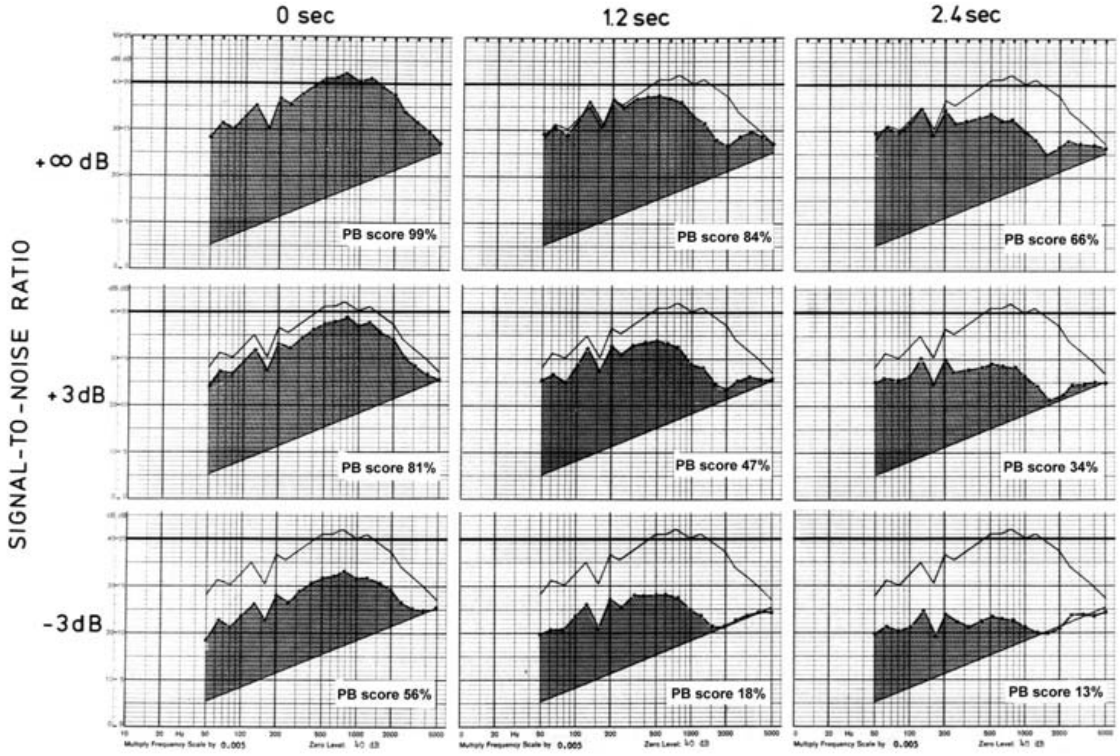


Figure 3.8. Effects of the Disturbances
(Source: Houtgast et al. 2002)

STI-14, STI-3, STITEL, STIPA and RASTI are versions of the same method developed for different purposes. 500Hz and 2kHz bands are used in RASTI, which is used as the Room Acoustics Speech Transmission Index. RASTI is abandoned today due to increasing processor capacity. Current STI, which measures with fourteen modulation frequencies in seven-octave bands, is widely used as a standardised method in handheld devices and software-based measurement applications as well as room acoustic prediction software (Mapp 2008)

3.4. Background Noise

Background noise or ambient noise, along with speech signal level and reverberation time, is one of the three main determinative factors of speech intelligibility in classrooms. Recent studies show that the activity of the participants is the dominating factor of the background noise in the occupied classrooms. In related studies, it was reported that the background noise in occupied classrooms was remarkably above the ranges recommended in the relevant literature and standards for unoccupied rooms.

The earlier studies on active classroom noise were conducted at British Columbia University by Hodgson (1994). The author reported a dramatic increase in background noise due to the presence of students in the classroom. In a subsequent study, the student activity noise was identified as the primary component of the total background noise, along with ventilation noise (Hodgson, Rempel, and Kennedy 1999). The following study discussed the role of noise and occupancy in determining an optimal reverberation time for the classrooms. The study referred to the positive and negative effects of reverberation time on speech intelligibility with the consideration of noise (Hodgson and Nosal 2002).

The UK study reported that the student's activity in a classroom is the dominating factor determining the background noise level. The researchers suggested L_{90} as the metric representing the active classroom background noise level. They categorised the activities into six groups according to the noise levels ranging from 43 dBA to 64 dBA according to L_{A90}. They reported a 20 dBA difference between the quietest and the noisiest classroom activities (Shield and Dockrell 2004).

In a study in the classrooms of Université de Paris Sud, the authors reported high levels of active classroom background noise, agreeing with previous studies on the same subject. The authors emphasised the inadequacy of standards that refer to the noise levels generated by building services, such as HVAC, in unoccupied classrooms. They also categorised active classroom background noise levels into five groups from very calm to very noisy according to the range of noise levels between 43 dBA and 63 dBA (Sooch San Souci et al. 2006).

In a study in Canada with conventional rectangular classrooms, the authors reported the noise levels in working classrooms as 49 dBA. They pointed out that students' activity is the dominant noise source in classrooms (Sato and Bradley 2008).

A study in Turkey conducted in high schools reported noise levels in occupied classrooms up to 63dBA as L_{Aeq}, including the outdoor noise transmitted through the boundaries of the classroom (Avsar and Gonullu 2010). In another study in Istanbul, student activity was identified as the primary source of high noise levels in active classrooms (Bayazit, Küçükçıfçı, and Şan 2011).

Another study in the UK showed active classroom background noise levels up to 51 dBA as L_{A90}, while the ambient noise was up to 65 dBA as L_{Aeq} (Shield et al. 2013).

A study conducted in school classrooms in Finland referred to L_{90} as the activity noise and reported as 42 dBA, while the L_{Aeq} was reported as 69 dBA as the background noise level (Sala and Rantala 2016).

A recent study reported the noise level and spectrum measured in active university classrooms in Korea (Choi 2020a). The study agrees with the earlier study conducted by Hodgson (1994) and reports the overall average level of active classroom noise as 44 dBA.

CHAPTER 4

METHODOLOGY

4.1. Overview

The ultimate goal of this research was to develop an acoustic design methodology that will guide architectural design at an early stage in determining room geometry and placement of reflective and absorbing room surfaces and to achieve the required level of speech intelligibility in classrooms.

More specifically, this research aimed to investigate a classroom design methodology that uses the room reflection pattern to enhance speech intelligibility by maximising early reflections. The design method focuses on identifying and selectively prioritising the room areas to reserve them as reflecting surfaces before placing absorbing surfaces.

The research was carried out in five stages, as illustrated in Figure 4.1. In the first stage, an appropriate classroom was selected, and room acoustics parameters in this classroom were measured. In the second stage, a 3-D acoustic model of the classroom was created, and geometrical acoustic analysis was carried out to identify early reflection surfaces (ERS) using the early reflection-oriented room acoustics design method (ERORAD). In the third stage, the acoustic simulation model was calibrated, and various room acoustics design scenarios were developed to observe the effect of early reflections on speech intelligibility at student positions. In the fourth stage, listening tests were conducted. Finally, in the fifth and last stages, the objective data collected in the first and third stages is compared to the subjective data collected in the fourth stage.

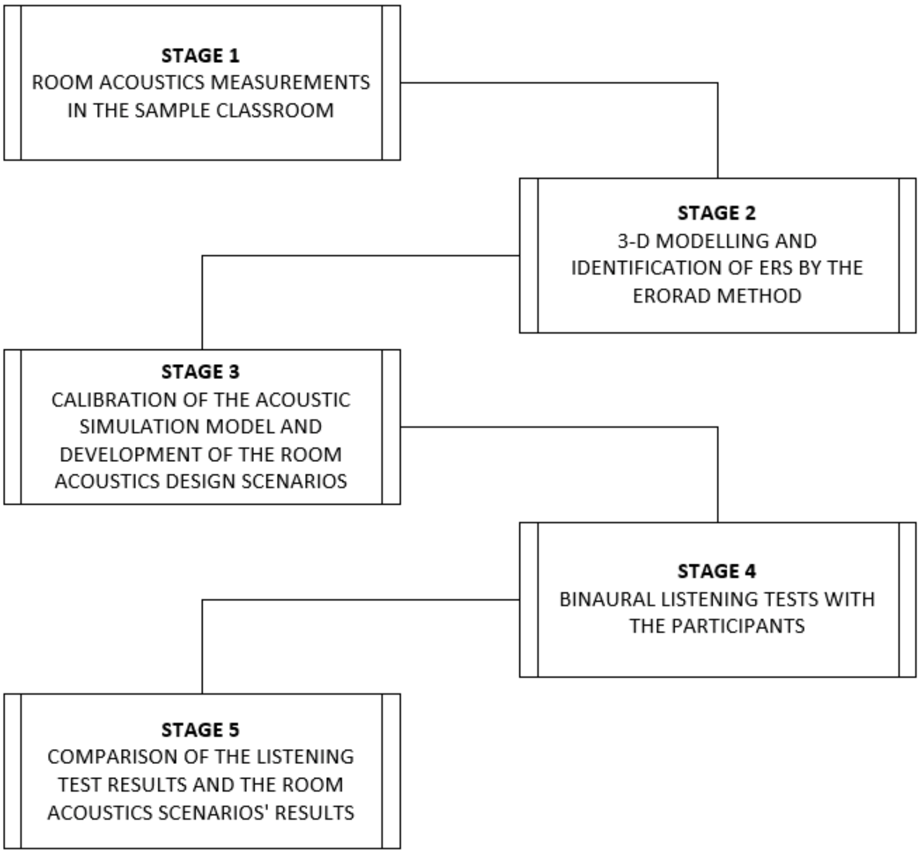


Figure 4.1. Methodology Flowchart

Initially, a classroom with no room acoustics design or treatment was selected. The goal was to evaluate outcomes by creating various room acoustics design scenarios, including traditional and researched design methodology. The unoccupied classroom was measured using handheld and software-based devices, and data on ISO3382 room acoustics parameters was collected. Next, the 3-D room acoustic model was constructed and calibrated using room acoustics software based on the measured ISO 3382 parameters. The room geometry was analysed using the image source method, and the room surfaces that can provide early reflections towards student locations from possible lecturer positions were identified. The calibrated room model was used as a base case to develop room acoustics design scenarios for comparative analysis of the effect of the changing intensity of reflections on direct sound and speech intelligibility at student positions. The simulated room acoustics design scenarios were then auralised for the listening tests with human participants. Anechoic recordings of the phonemically balanced Turkish Monosyllabic Word Recognition Test (TMWRT), developed in another study (Mungan 2010), were used for the auralisations. The auralised audio files were post-processed using a digital audio editor to mix background noise for various SNRs. The background noise signal was produced using a digital audio editor by shaping pink noise to have a similar spectrum to the background noise measured in active university classrooms, as reported in another study (Choi 2020a). The resulting test files are divided into sets according to SNR. Binaural listening tests were conducted using headphones, and the participants were asked to write the words they heard when the test audio was played. Finally, objective room acoustics simulation results of the design scenarios were compared to the subjective test results from binaural listening tests.

The sound strength parameter, G, as given by equation 4.1 (ISO 3382-1 2009), was modified with the early time limit of 50ms to quantify the relative level of early reflections with G_{50}, as given by equation 4.2.

$$\mathrm{G} = 10\log\frac{\int_0^{\infty} p^2(t)dt}{\int_0^{\infty} p_{10}^2(t)dt}\ dB \tag{4.1}$$

$$\mathrm{G}_{50} = 10\log\frac{\int_0^{50\mathrm{ms}} p^2(t)dt}{\int_0^{50\mathrm{ms}} p_{10}^2(t)dt}\ dB \tag{4.2}$$

In equations 4.1 and 4.2, *p(t)* is the instantaneous pressure in the impulse response. The G_{50} parameter is the relative level of the energy of the sound in the room, including direct sound and early reflections within the first 50ms, to the energy of the same source measured at a distance of 10 meters in a free field.

The experiment involves collecting and comparing objective and subjective data sets outlined in the methodology. Collection of the objective data involves on-site measurement of room impulse response and room acoustic simulations based on the 3D computer model initially calibrated to the on-site measurements. The subjective data collection consists of the listening tests with human participants using the audio files produced by the room acoustic simulations.

4.2. Measurements

The measurements were conducted in the classroom in Block A of the IYTE Department of Architecture. The classroom was selected as a sample space due to its known poor room acoustics in terms of speech intelligibility.

4.2.1. Sample Classroom

The classroom selected as the sample classroom was originally part of a hall that previously served as a cafeteria. The cafeteria hall was divided, rearranged and turned into a classroom with 168 seats. The seats are arranged in fourteen rows and three groups. The last six rows at the back are placed on podium steps rising gradually. There is no known acoustic design or subsequent acoustical treatment for this transformation.

The classroom is 18m x 12m with a linoleum-covered concrete floor and plaster-painted walls. An open-cell aluminium suspended ceiling grid carries the lighting elements and conceals the ceiling's AC unit cases and concrete beam structure. The ceiling grid does not contain any sound-absorbing elements. The height between the grid and the floor is 3m. The concrete slab above the grid is at a height of 3.8m from the floor. A single layer of flat gypsum board surrounds the grid, situated 2.7m above the floor.

The entrance to the classroom is through the double-leaf door located on the foyer side of Block A. The wall on the entrance side consists of painted brick walls with plaster between concrete columns. The east-facing exterior wall opposite the entrance door has three large windows covered with curtains. There are two whiteboards on the front wall of the classroom. The back wall of the classroom is the north façade wall with a curtained window. The classroom has two-column speakers on the sides of the whiteboards to reinforce the lecturer’s voice.

Figure 4.2. Sample Classroom – IYTE Department of Architecture

Dimensions of the classroom and existing acoustic conditions allow observing the effects of various room acoustics design scenarios that will be tested to investigate the efficacy of the proposed design methodology.

4.2.2. Measurement Setup

Two sets of measurement setups were used for the on-site room acoustic measurements. The first set consists of a Brüel&Kjaer 2260 handheld acoustic analyser, Brüel&Kjaer dodecahedral sound source and power amplifier. The other set, which is used in parallel to the first one, is a software-based setup including a PC running ARTA measurement and analysis software, a Minidsp UMIK-1 class-1 omnidirectional microphone and a Creative E-MU PM5 studio monitor as a directional sound source similar to a human speaker. Both sets were used to measure ISO3382 room acoustic parameters. Software-based with a 5-inch sound source was additionally used for STI measurements.

4.2.3. Measurement Points

The positions of the sound sources denoted as ‘s’, and the measurement microphone or receiver positions, designated as ‘R’, are illustrated in Figure 4.3 below.

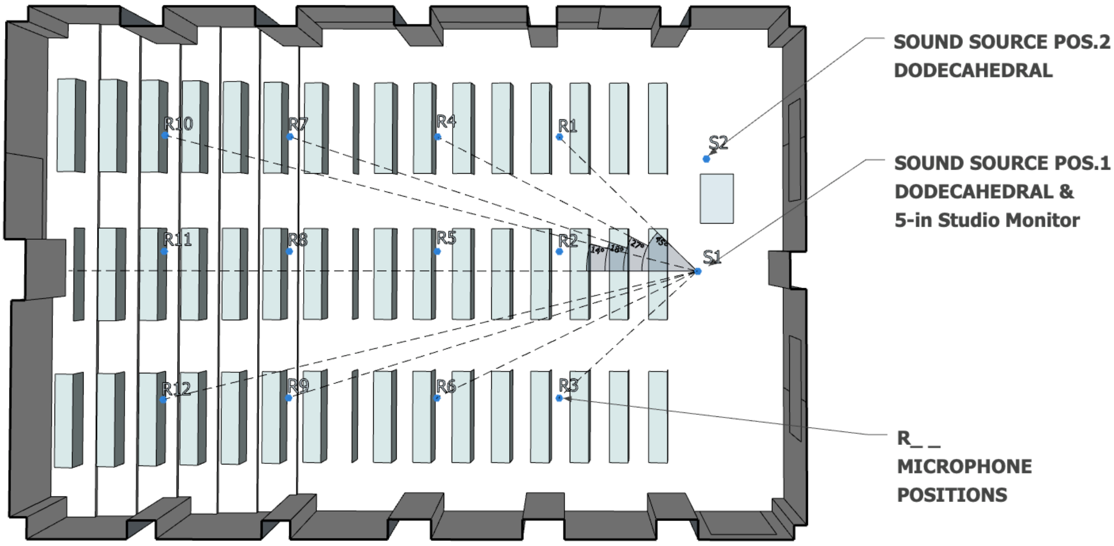


Figure 4.3. Sound Source and Microphone Positions In Sample Classroom

Figure 4.4. Dodecahedral Sound Source on Position-1

4.2.4. Measurement Of Background Noise

Background noise level measurements were conducted in the unoccupied classroom and with the air conditioning units turned off. The average of the measurements is 30.5 dBA within a deviation of ± 0.5 dB across the receivers, as seen in Figure 4.5 below.

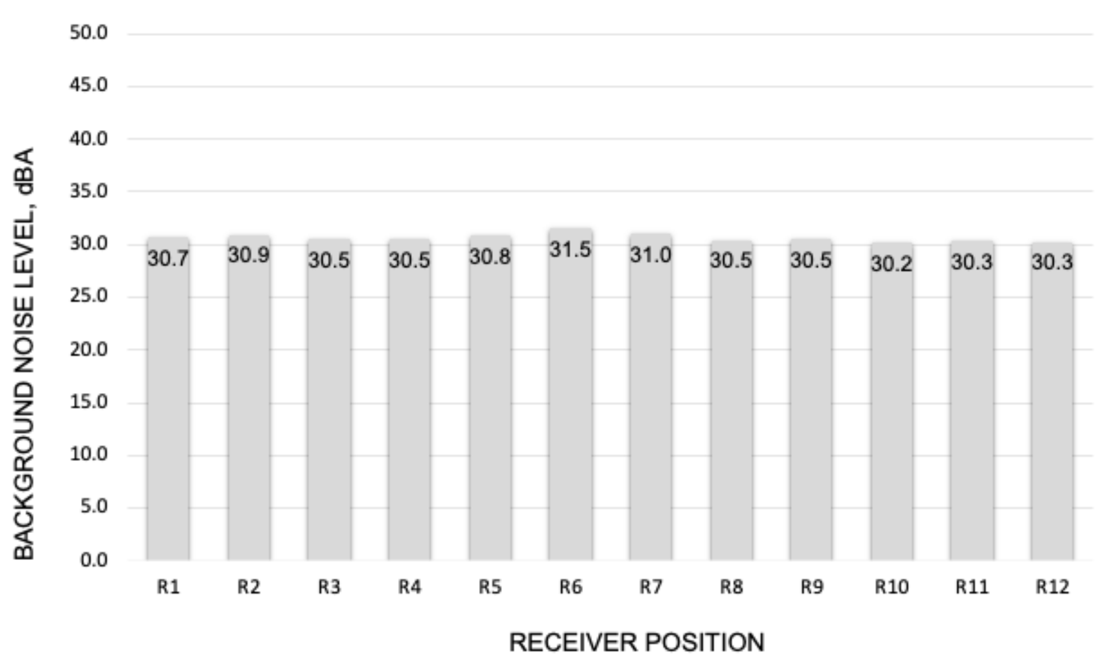


Figure 4.5. Background Noise Levels at the Receiver Positions

Table 4.1 displays the average background noise measured at twelve receiver positions.

Table 4.1. Averaged Background Noise in Unoccupied Classroom

f (Hz)	31.5	63	125	250	500	1000	2000	4000	8000	16000	A-weighted
Ln,u (dB)	38.7	37.6	32.4	28.1	24.1	22.3	21.4	22.3	24.4	26.6	30.6

4.2.5. Measurement Of Room Impulse Response

The interrupted noise method was used to measure room impulse response at each receiver position by ISO3382. The results are presented in Figure 4.6 and Figure 4.7.

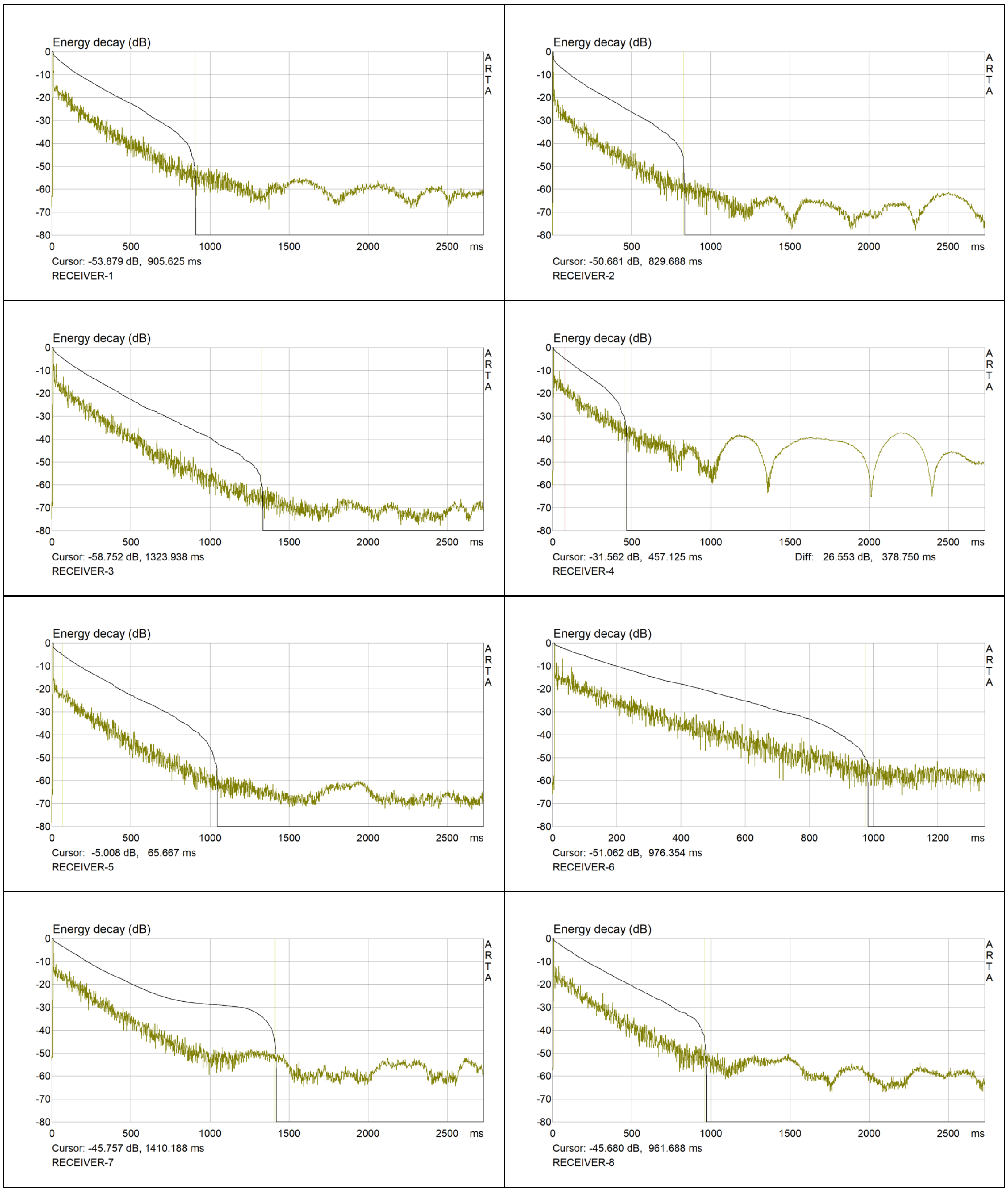


Figure 4.6. Measured Energy Decay Diagrams Receivers 1-8

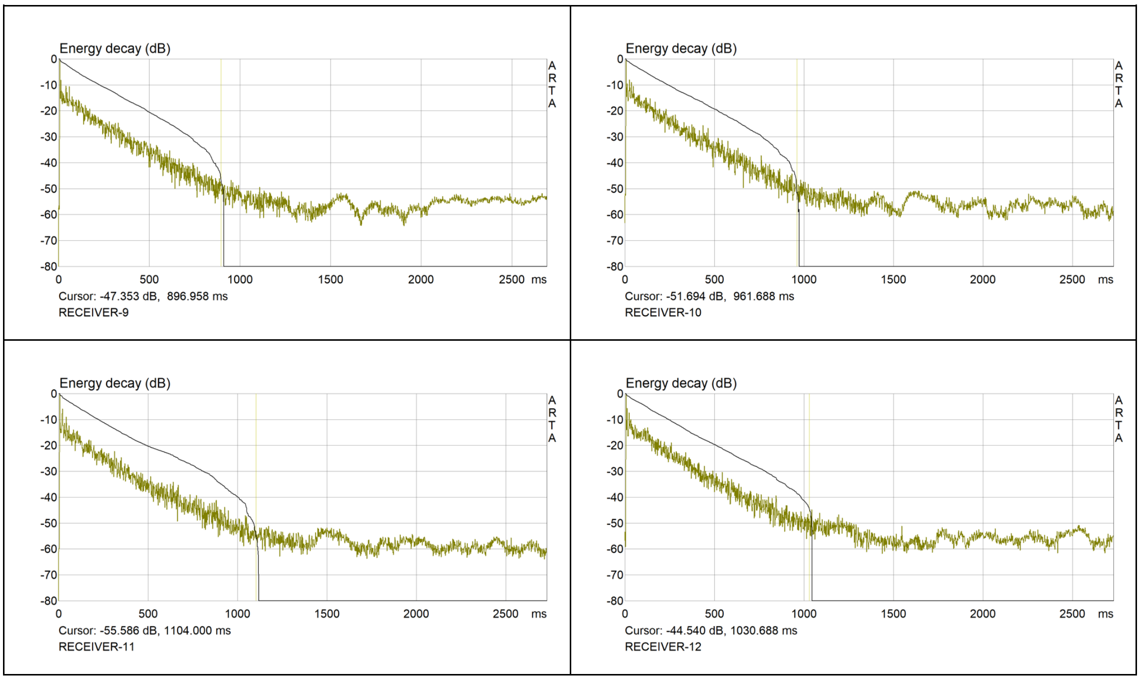


Figure 4.7. Measured Energy Decay Diagrams Receivers 9-12

Each receiver location's analysed reverberation time (T_{30}) for one-octave bands is displayed in Table 4.2 below. The rightmost column also shows the average of 500-1kHz two-octave bands. A graphical representation of the measured T_{30} parameter from Table 4.2 is shown in Figure 4.8.

Table 4.2. Measured T_{30} with Omnidirectional Sound Source Position s1

	REVERBERATION TIME T30 (s) ONE-OCTAVE BANDS							TWO OCTAVE BANDS
RECEIVER	125	250	500	1k	2k	4k	8k	500 - 1k
R1	2.05	2.05	1.89	1.63	1.31	1.12	0.77	1.76
R2	2.15	1.95	1.85	1.64	1.29	1.10	0.75	1.75
R3	2.01	2.04	1.88	1.68	1.32	1.09	0.74	1.78
R4	1.98	2.03	1.88	1.61	1.27	1.07	0.78	1.75
R5	1.96	2.15	1.86	1.63	1.32	1.12	0.80	1.74
R6	2.15	2.03	1.86	1.63	1.31	1.12	0.76	1.75
R7	2.03	2.08	1.84	1.67	1.35	1.14	0.79	1.76
R8	1.98	2.07	1.86	1.62	1.29	1.16	0.79	1.74
R9	2.04	1.95	1.85	1.66	1.35	1.13	0.81	1.75
R10	2.21	1.97	1.76	1.62	1.33	1.14	0.80	1.69
R11	2.01	1.96	1.89	1.64	1.35	1.15	0.83	1.77
R12	2.12	2.02	1.94	1.67	1.37	1.11	0.82	1.80
AVERAGE	2.06	2.02	1.86	1.64	1.32	1.12	0.79	1.75

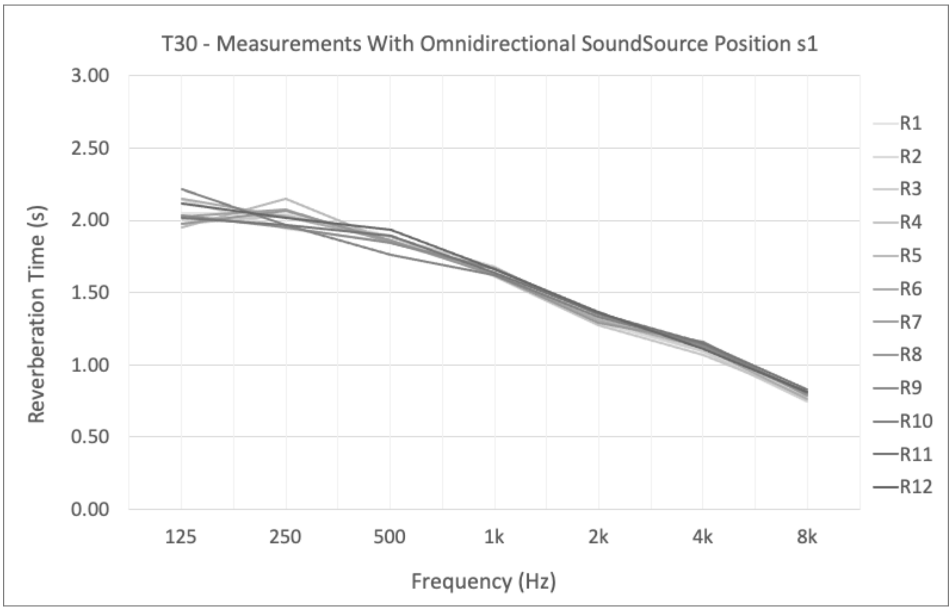


Figure 4.8. T_{30} at Twelve Receiver Positions with Sound Source Position s1

Table 4.3, presented below, illustrates the repeated measurement using an alternative sound source position, 's2', with its graphical representation in Figure 4.9.

Table 4.3. Measured T_{30} with Onidirectional Sound Source Position s2

REVERBERATION TIME T30 (s) | ONE-OCTAVE BANDS								TWO OCTAVE BANDS
RECEIVER	**125**	**250**	**500**	**1k**	**2k**	**4k**	**8k**	**500 - 1k**
R1	1.82	2.00	1.97	1.65	1.30	1.08	0.77	1.81
R2	2.00	2.14	1.93	1.63	1.28	1.12	0.76	1.78
R3	1.92	2.00	1.85	1.68	1.32	1.10	0.80	1.77
R4	2.20	2.11	1.89	1.66	1.36	1.12	0.78	1.77
R5	2.04	2.08	1.81	1.61	1.33	1.13	0.80	1.71
R6	2.01	2.04	1.85	1.64	1.33	1.13	0.79	1.75
R7	2.08	2.06	1.93	1.66	1.31	1.14	0.83	1.80
R8	2.10	2.02	1.88	1.66	1.34	1.14	0.81	1.77
R9	2.00	2.06	1.92	1.64	1.34	1.17	0.83	1.78
R10	2.09	2.07	1.89	1.65	1.35	1.15	0.81	1.77
R11	2.10	1.96	1.82	1.64	1.33	1.14	0.82	1.73
R12	2.18	1.98	1.90	1.66	1.33	1.11	0.81	1.78
AVERAGE	2.04	2.04	1.89	1.65	1.33	1.13	0.80	1.77

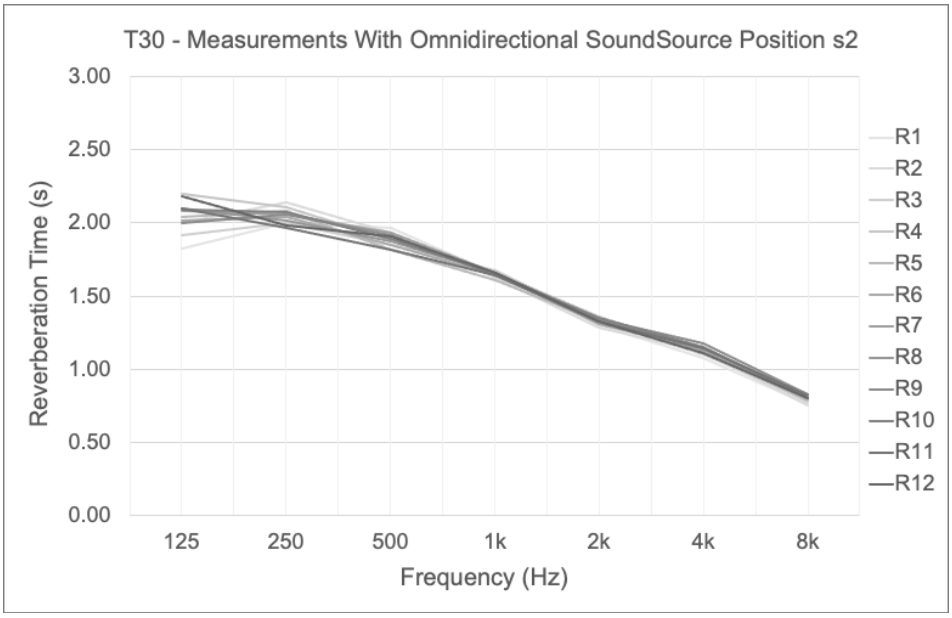


Figure 4.9. T_{30} at Twelve Receiver Positions with Sound Source Position s2

4.2.6. Measurement Of Speech Transmission Index, STI

A software-based measurement setup was used for STI measurements. The setup consists of software for impulse response measurement and real-time analysis of spectrum and frequency software ARTA, a PC running the measurement application, an omnidirectional microphone Minidsp UMIK-1 and a 5-in flat response loudspeaker (Creative studio monitor E-MU PM5) as a sound source.

ARTA software provides a speech-like signal for STI measurements (Mateljan 2011). Table 4.4 shows the octave-band spectrum for the 'Speech PN' signal in reference to the IEC standard (IEC 60268-16 2011). The male spectrum was selected for the measurements.

Table 4.4. Speech noise spectrum for males and females

Octave band (Hz)	125	250	500	1000	2000	4000	8000	A-weighted
Referent levels of male speech (dB)	2.9	2.9	-0.8	-6.8	-18.8	-12.8	-24.0	0.0
Referent levels of female speech (dB)	-	5.3	-1.9	-9.1	-15.8	-16.7	-18.0	0.0

The male speech spectrum was selected to prepare for the tests, and the test signal level was adjusted to read an A-weighted level of 70 dBA at 1m from the sound source.

This was done in accordance with Annex J.3 of the IEC standard (IEC 60268-16 2011). The selected level corresponds to a level between raised and loud vocal effort defined by ANSI (S3. 5-1997 1997), which are 66.5 dBA and 73.6 dBA, respectively.

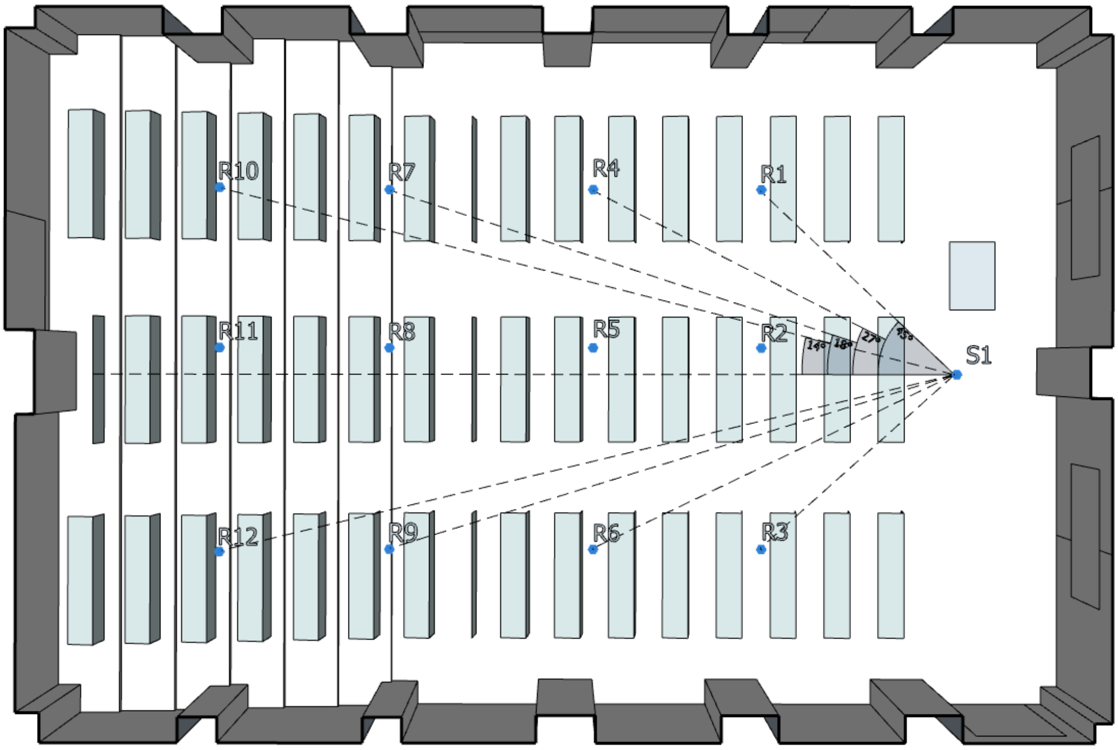


Figure 4.10. Source Axis Azimuth Relative to Receiver Locations

Figure 4.10 shows the receivers' and sound source positions, with the source axis azimuth relative to the receiver positions, indicating the horizontal angle between the receiver and the centre axis of the sound source.

The speech signal and noise levels measured at each receiver position for STI measurements are displayed as octave-SPL diagrams in Figure 4.11 and Figure 4.12 below.

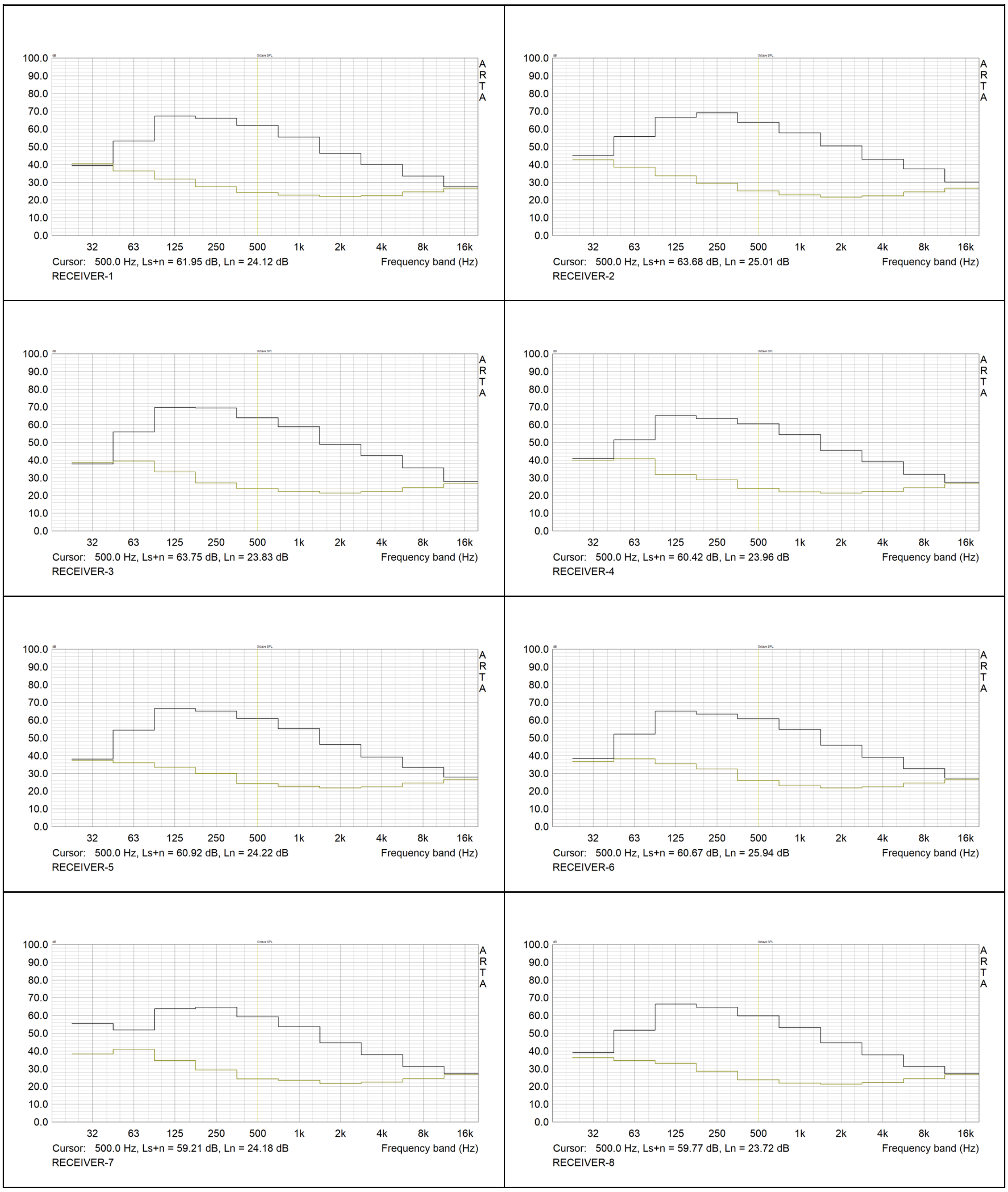


Figure 4.11. Round 1 | Speech and Noise Levels Measured at Receivers 1-8

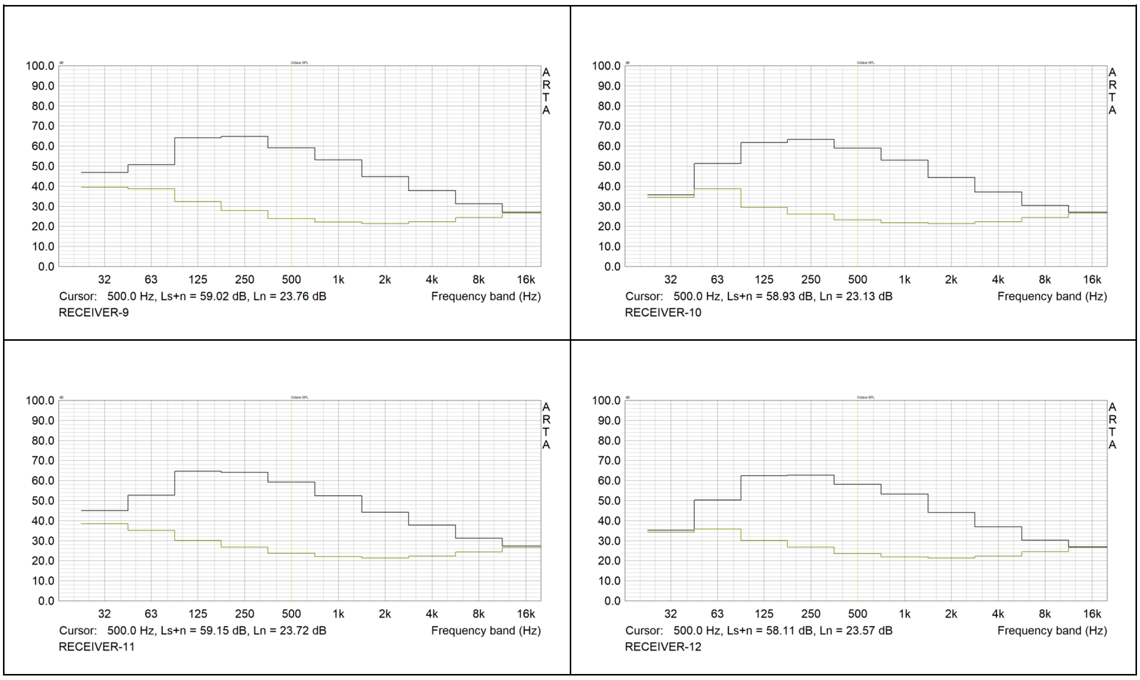


Figure 4.12. Round 1 | Speech and Noise Levels Measured at Receivers 9-12

Table 4.5 and Figure 4.13 display signal level L_s, background noise level L_n and STI measurements at each receiver location. The azimuth column indicates the horizontal angle between the receiver and the centre axis of the sound source.

Table 4.5. Round-1 | STI Measurement Data

SOURCE POS.	AZIMUTH REL. TO RECEIVER	RECEIVER POS.	Ls (dBA)	Ln (dBA)	STI
s1	45°	R1	62.52	30.66	0.56
	0°	R2	64.79	30.92	0.62
	-45°	R3	65.11	30.50	0.56
	27°	R4	60.81	30.49	0.52
	0°	R5	61.74	30.84	0.54
	-27°	R6	61.04	31.52	0.51
	18°	R7	60.25	31.00	0.48
	0°	R8	60.82	30.47	0.49
	-18°	R9	60.24	30.50	0.49
	14°	R10	59.62	30.17	0.48
	0°	R11	59.95	30.31	0.50
	-14°	R12	59.25	30.26	0.47

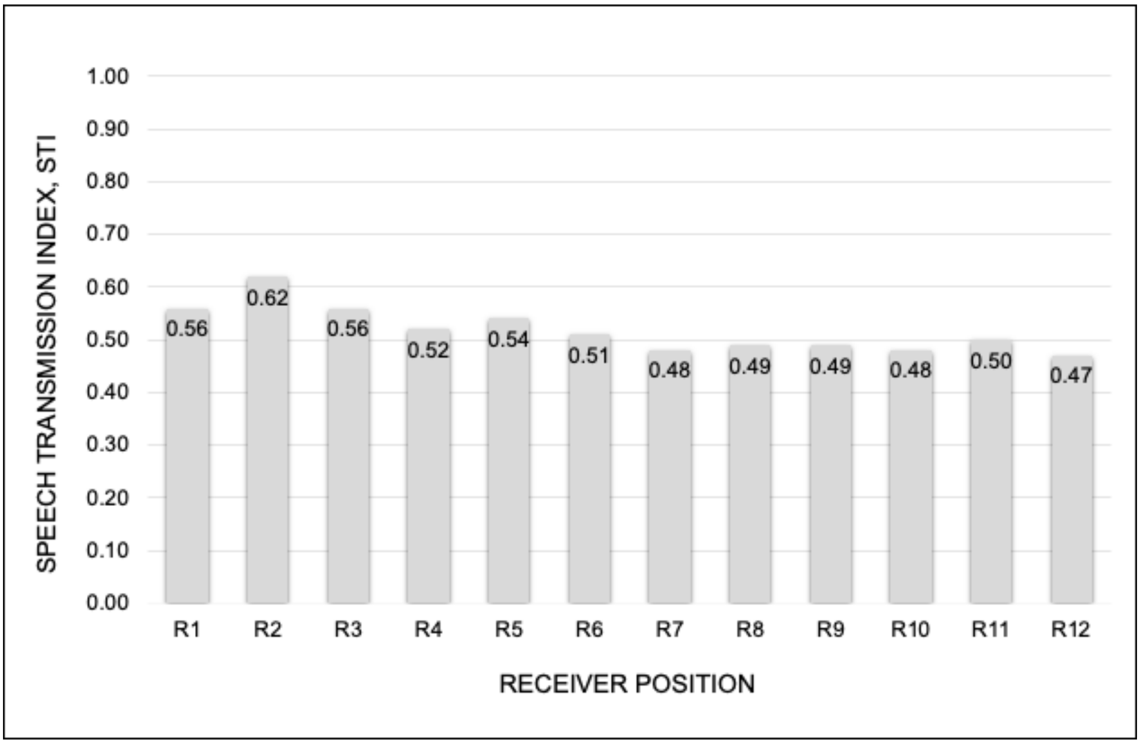


Figure 4.13. Round 1 | STI values at Receiver Locations

During the first round of measurements, the sound source was placed in line with the longitudinal axis and aimed towards the receivers in the middle desk group. In the second round of STI measurements, the sound source was horizontally rotated to target the receiver locations on the right and left desk groups, as illustrated in Figure 4.10.

The speech signal and noise levels measured during the second round of STI measurements are displayed as octave-SPL diagrams in Figure 4.14 below.

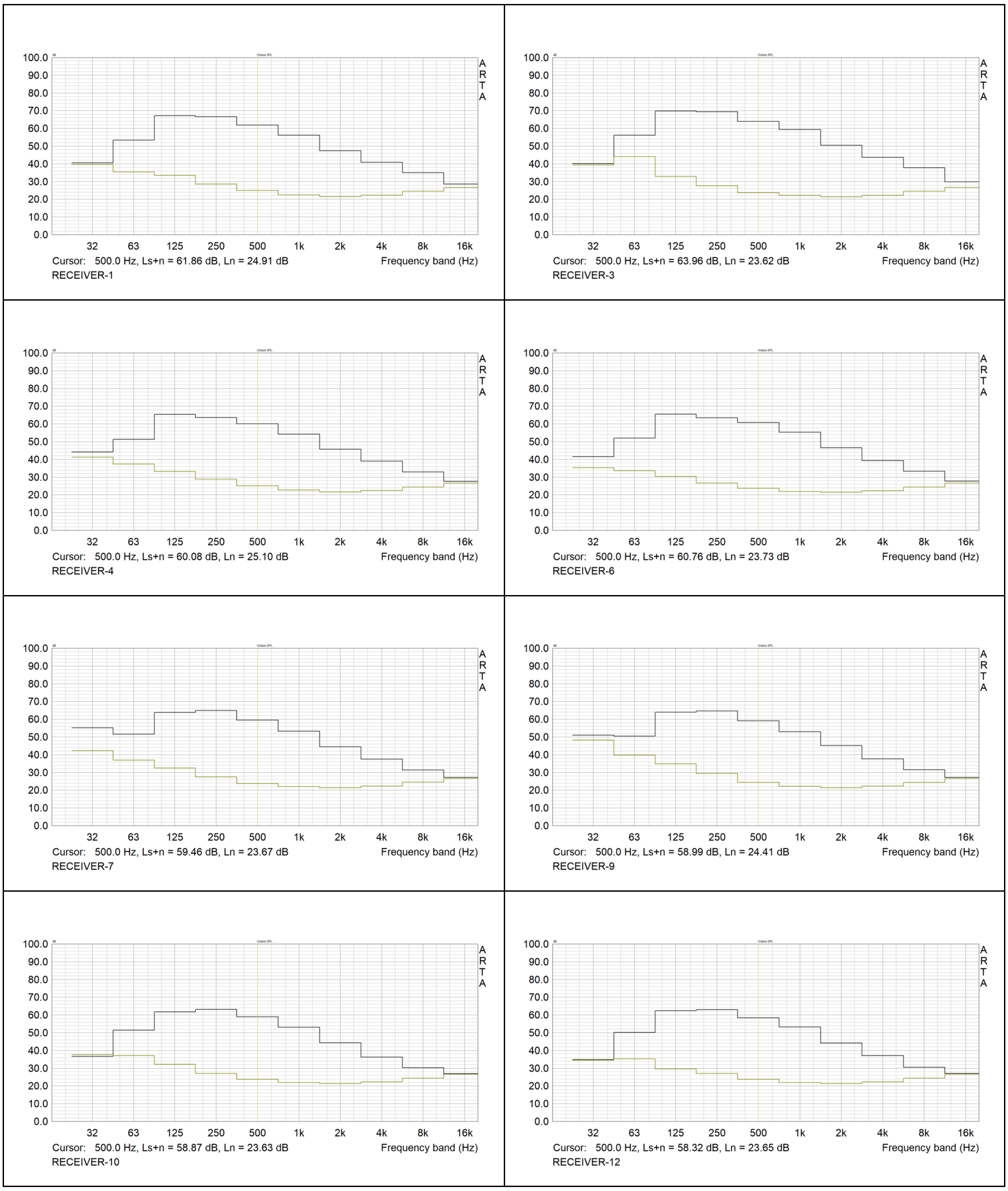


Figure 4.14. Round 2 | Speech and Noise Levels at Receivers 1, 3, 4, 6, 7, 9, 10, 12

Table 4.6 displays signal level Ls, background noise level Ln and STI measurements conducted in round 2, where the sound source was rotated towards the receivers on the sides. The azimuth column indicates the horizontal angle between the receiver and the centre axis of the sound source.

Table 4.6. Round 2 | STI measurement data

SOURCE POS.	AZIMUTH REL. TO RECEIVER	RECEIVER POS.	Ls (dBA)	Ln (dBA)	STI
s1	0°	R1	62.88	30.69	0.61
	0°	R3	65.34	30.66	0.61
	0°	R4	60.70	30.84	0.54
	0°	R6	61.31	30.30	0.53
	0°	R7	60.37	30.42	0.49
	0°	R9	60.25	30.79	0.50
	0°	R10	59.60	30.35	0.48
	0°	R12	59.42	30.25	0.48

The STI values obtained in round 2 are illustrated in Figure 4.15.

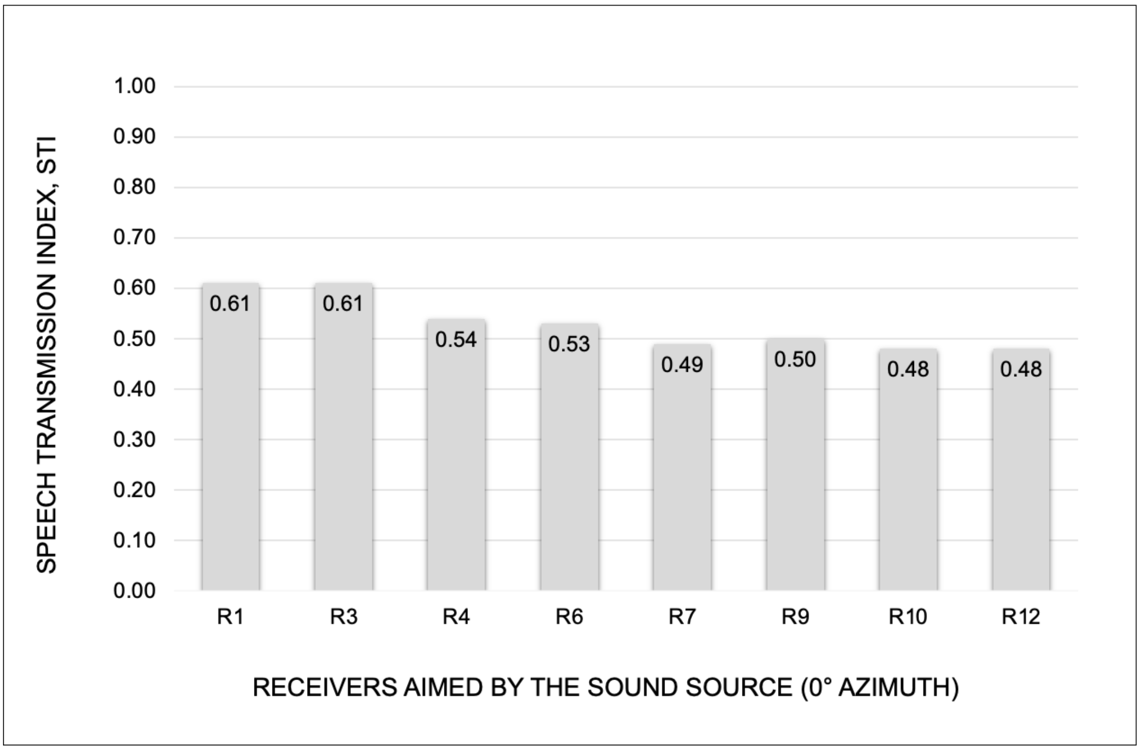


Figure 4.15. Round 2 | STI values at aimed receivers on sides

4.3. Early Reflection-Oriented Room Acoustics Design Method

The Early Reflection-Oriented Room Acoustics Design (ERORAD) method is based on identifying room surfaces in terms of reflection patterns in the room. The room surfaces that provide early reflections towards audience positions are designated as early reflection surfaces, ERS. The room surfaces outside the ERS are designated as the surfaces available for the placement of absorbers and denoted as SfA. SfA can be used to control reverberation time via absorbers.

Figure 4.16 shows the 3-D room model constructed using SketchUp software.

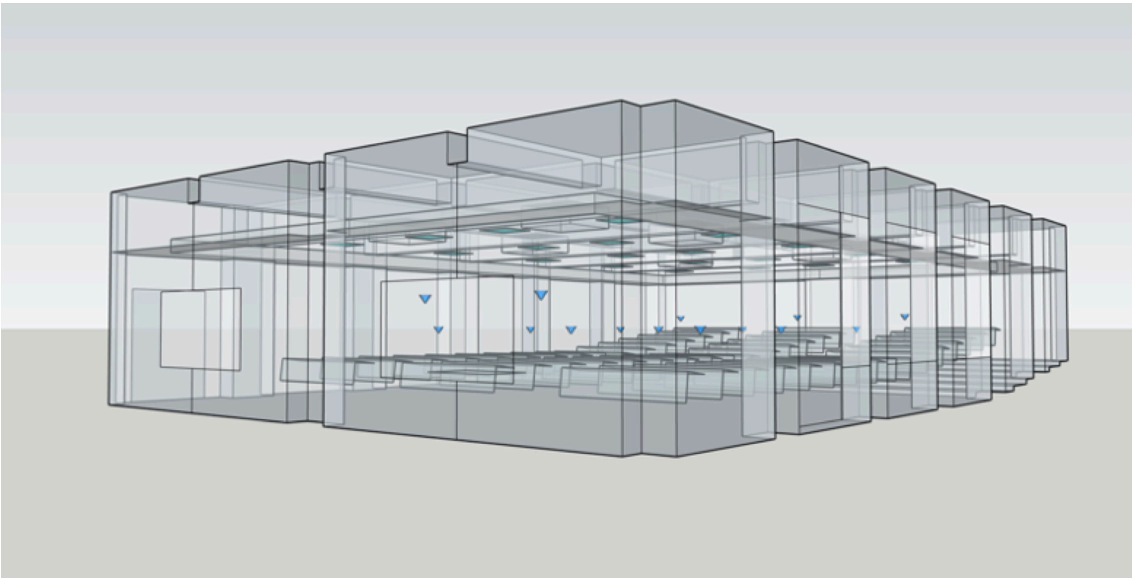


Figure 4.16. 3-D Room Model by SketchUp

Figure 4.17 shows the front, left, back and right interior walls inside the 3-D model.

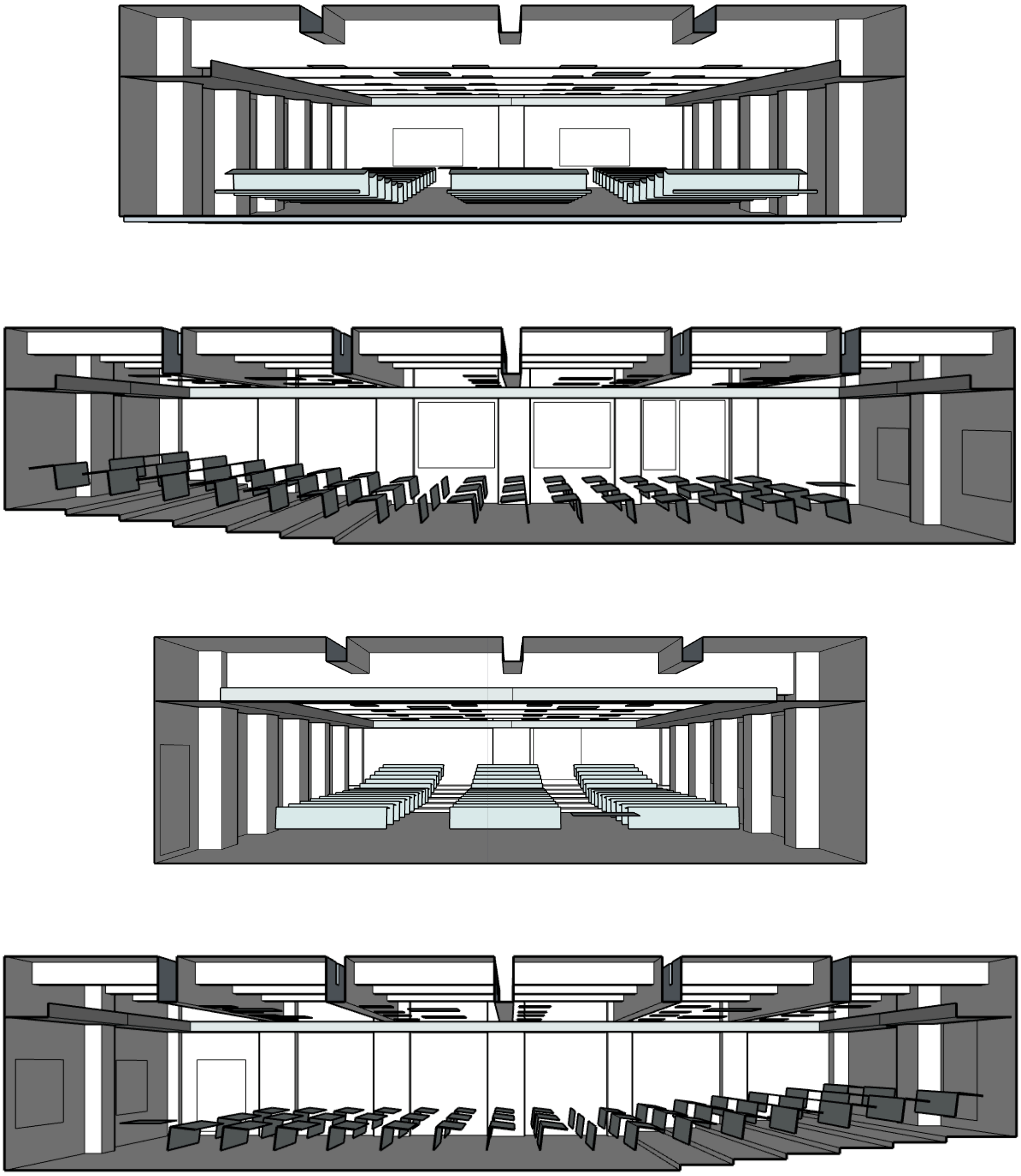


Figure 4.17. Front, Left, Back and Right Views of 3-D Room Model

The image source method, ISM, was used to identify ERS on the room surfaces based on the listener and speaker positions. In this technique, the symmetrical image of the sound source in the room is marked with respect to the plane surface, which is assumed to be specularly reflective. The straight line connecting the symmetrical image of the sound source and the listener's position determines the point of reflection in the plane. The method involves iterating from previously identified image sources and retaking their image with respect to a reflecting surface to discern higher-order reflections (Savioja and Svensson 2015). Figure 4.18 illustrates the method for the first-order reflections from the four walls. Dashed lines labelled '1st' represent image rooms, 'x' is the source, '+' is the first-order image source, 'O' is the receiver, and 'R' is the location of reflection from the respective walls.

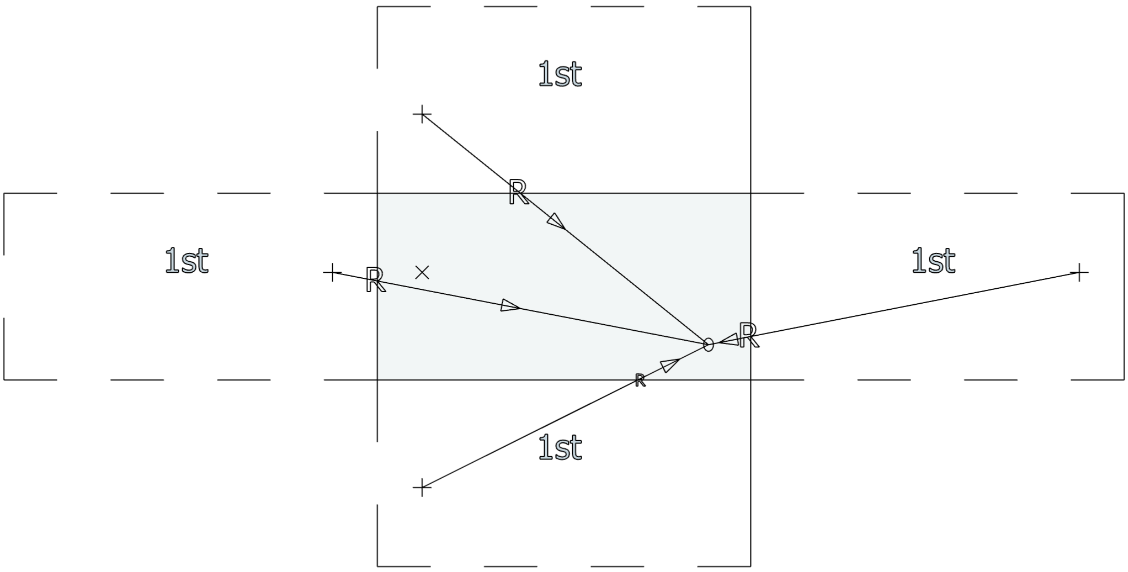


Figure 4.18. Identification of first-order reflections by the image-source method

4.3.1. Identification Of ERS On Sidewall Areas

In Figure 4.19, the grey rectangular space on the floor represents the area where the lecturer can stand during the lecture. The projection of the corners of this area marks the boundaries of the sound source locations that will be used in the ISM. In this example, the sound source is positioned at the height of 1.5 meters to represent the standing lecturer.

The audience area to be covered starts from the third row to the back. The edge points of the third and back rows were projected to 1.2 meters from the ground, representing the ear level of the sitting listeners.

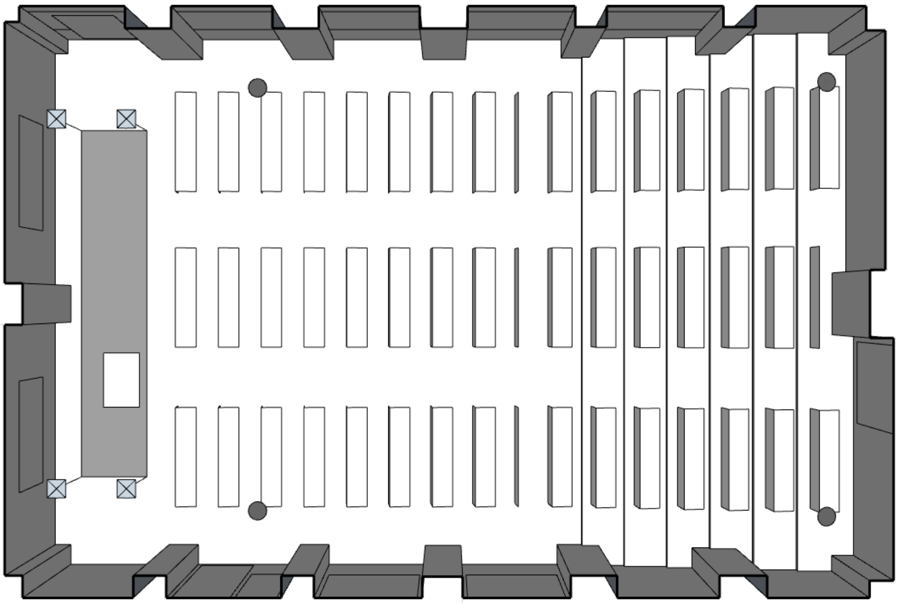


Figure 4.19. The Area Where the Teacher Stands While Lecturing

The image sources of the lecturer's locations were identified by marking them as mirror images symmetrical to the wall where the reflections were investigated. The image sources were combined with the receiver points to determine the points where the first-order reflections from the side wall cover the defined listener area.

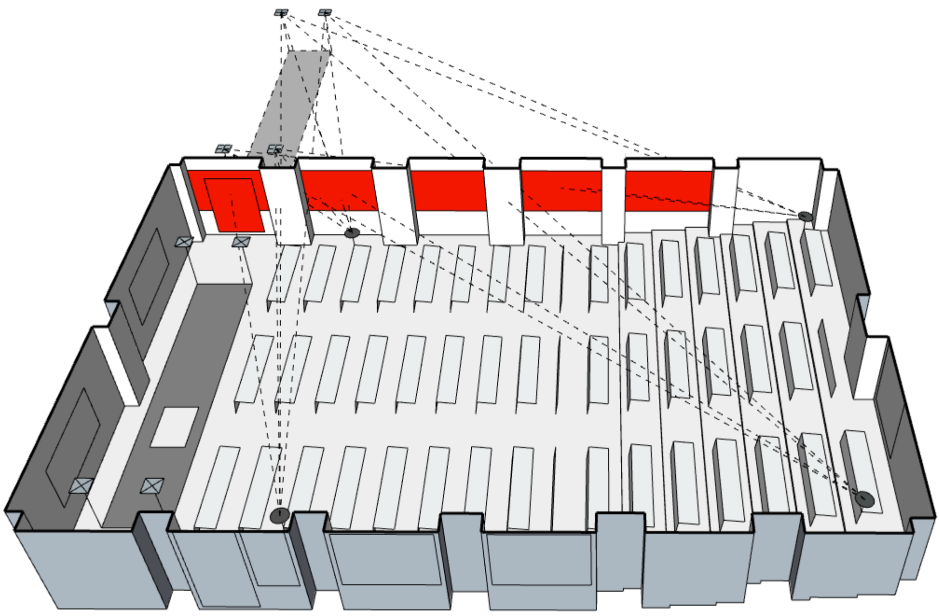


Figure 4.20. ERS in the Sidewall

Following the determination of the first-order wall reflection points covering the designated listener area, the size of the wall area to reflect the wavelength of 500Hz and above was determined. Accordingly, the reflective panel size should be at least 68cm. However, since the back rows are on the podium, which gradually increases in height, the reflective area size was expanded to cover the highest audience positions relative to the floor. Thus, the side wall area, whose lower level is 90 cm above the ground and whose height is 1.4 meters, is reserved as a first-order reflection area. This reflective belt on the side wall ends 2.5 meters from the back wall, as illustrated in Figure 4.20.

4.3.2. Identification of ERS On The Front Wall

Repeating the procedure for the side walls, the front wall area providing first-order reflections covering the designated listener area was identified, as illustrated in Figure 4.21.

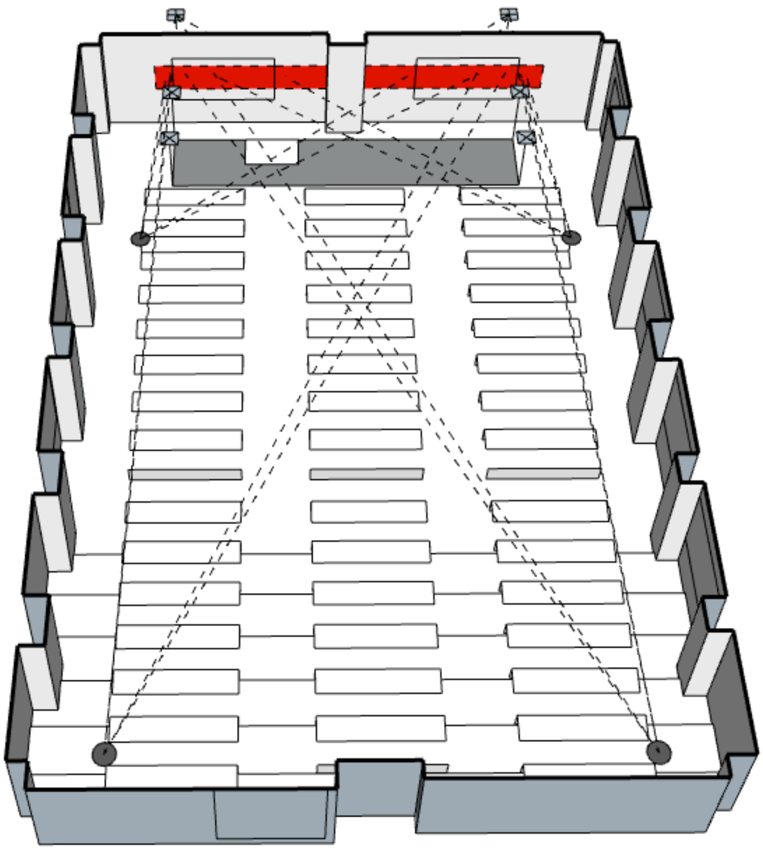


Figure 4.21. ERS in the Front Wall

4.3.3. Identification Of ERS In The Ceiling

Ceiling acoustic treatment is often achieved by installing suspended ceilings. However, installing absorbing suspended ceilings over the entire ceiling leads to losing early reflections, which is essential for speech intelligibility. In the diagram below, a regular suspended ceiling has replaced the open-cell suspended ceiling. Ceiling areas to direct first-order reflections towards the designated listener area were identified using the same procedure as in previous sections, as displayed in Figure 4.22.

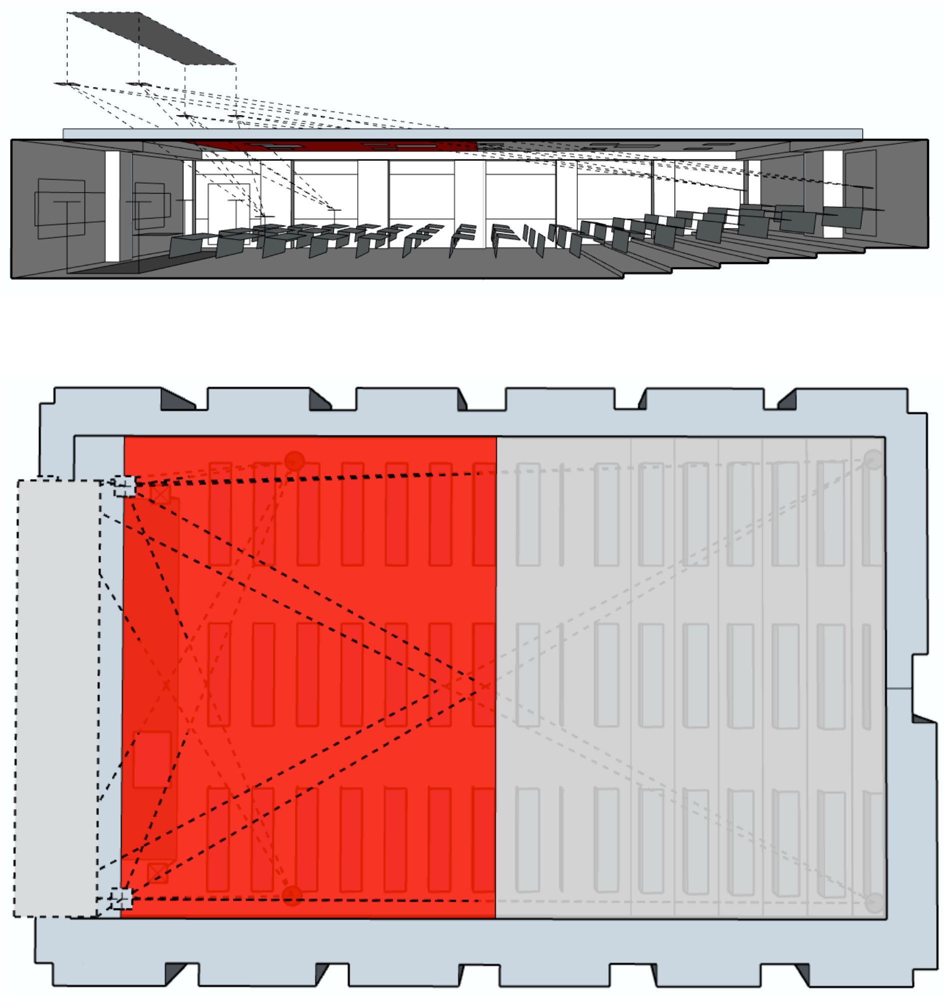


Figure 4.22. ERS in the Ceiling

4.4. Construction Of The Simulation Model

Figure 4.23 shows the simulation model for the existing classroom that was prepared considering acoustical modelling guidelines outlined in the CATT v9.1g user's manual (B.-I. Dalenbäck 2020). In addition to the existing classroom, three additional room acoustics design scenarios were created and tested using CATT v9.1g. These scenarios aimed to test the effectiveness of the early-reflections-based room acoustics design by analysing the relative level sound level of the direct sound and its early reflections represented by the G_{50} parameter. The room acoustics design scenarios also generated the listening test audio material through auralisation and audio post-processing.

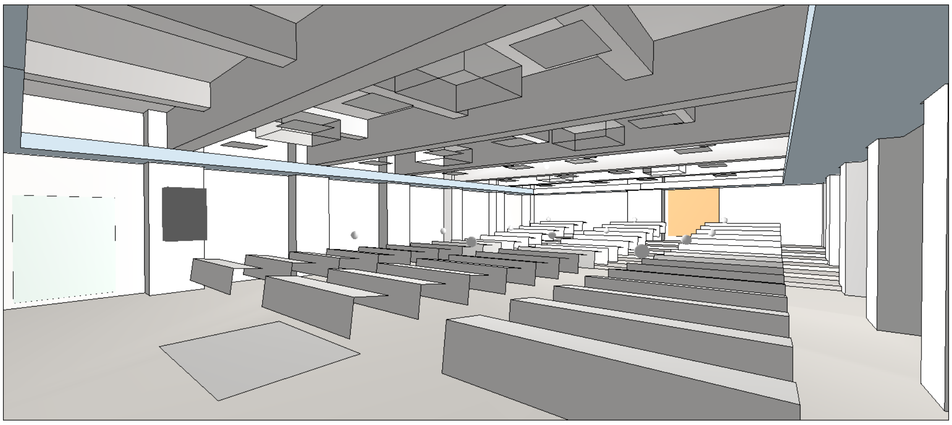


Figure 4.23. 3-D Model Interior View Generated by CATT 3D-Viewer v2.3f

4.4.1. Calibration Of The Room Model

The first step in creating the room acoustics design scenarios is to calibrate the room model to match the identified initial conditions from site measurements.

The calibration process aims to determine the sound absorption coefficients of the surfaces in the 3-D computer model to match the actual situation. In the first step of the process, data from the literature (Cox and D'Antonio 2009) and the software library (CATT-A v9.1g) were initially used for the internal surfaces. Then, the T_{30} results obtained with the initially entered data were compared to the T_{30} values from the physical measurements. The goal was to achieve field measurements within ±5% tolerance referring to JND (Seraphim 1958; ISO 3382-1 2009) for reverberation time while making minimal adjustments to the assigned data.

The calibration process, illustrated in Figure 4.24, was based on comparing the computed data to physical measurements. The surfaces in the room were classified according to the type of material and ranked by surface area, from largest to smallest. Initially, sound absorption coefficients were assigned using literature and the software's library data. The average T_{30} values of all listener points were calculated using the initial data and compared with T_{30} values obtained from physical measurements on an octave band basis. No calibration is needed if the difference between the calculated and measured data is within 5%. If the difference exceeds 5%, the sound absorption coefficient of the material with the largest surface area is modified by 1%. If the calculated data is larger than the measured data, the coefficient is reduced by 1%. If the computed data is smaller than the measured data, the coefficient is increased by 1%. The calculation is then repeated, and the data is compared again. Only the material with the largest surface area that had not been changed was modified during each iteration. Different octave bands of the same material were modified within one iteration to reduce computational time.

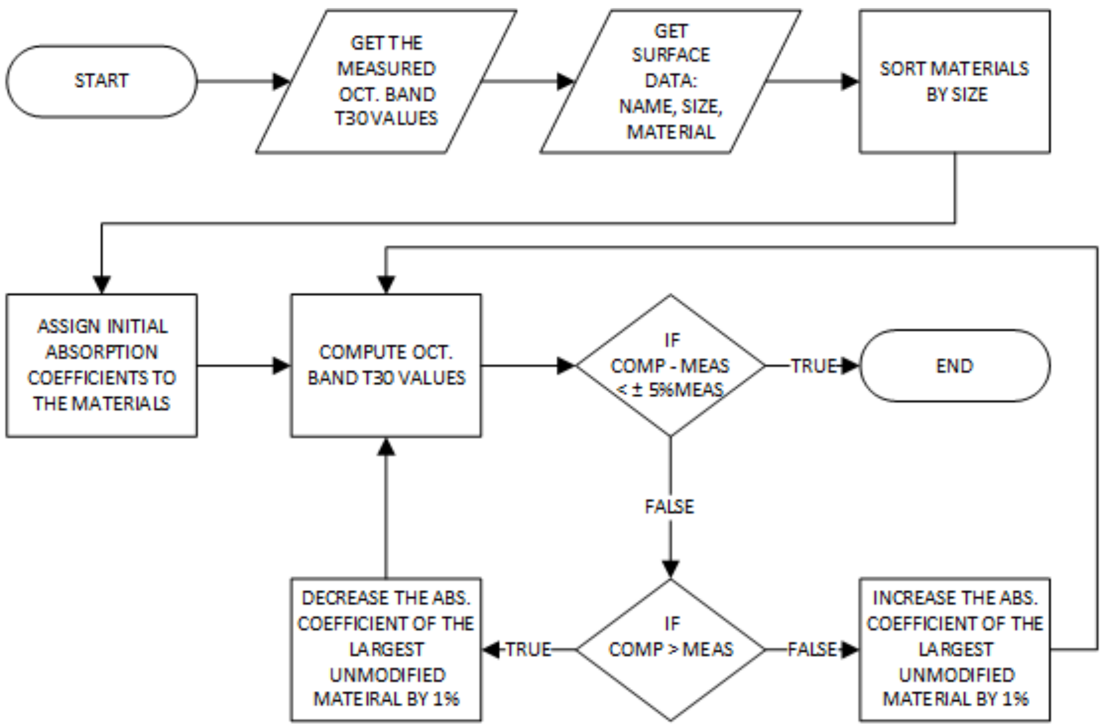


Figure 4.24. Calibration Process Flowchart

The 3-D computer model has the exact dimensions of the physical hall, with sound source and receiver points located at the exact coordinates of the physical measurements. Figure 4.25 below shows the room geometry generated by CATT-A v9.1g software.

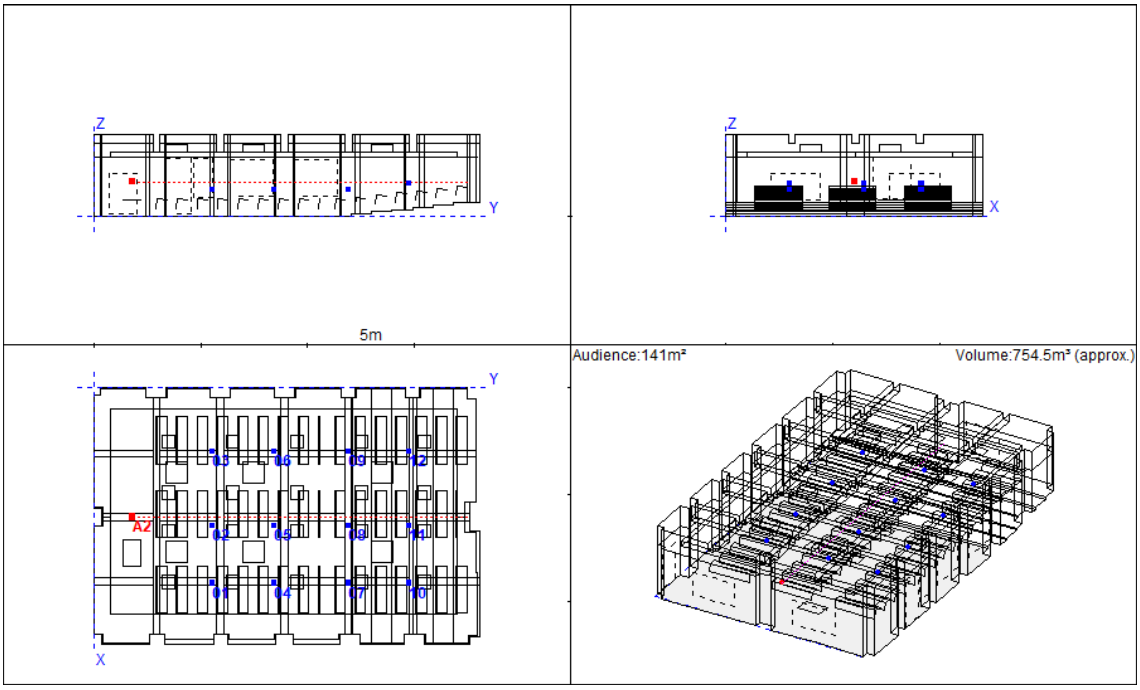


Figure 4.25. The Initial Simulation Model with the Source and Receiver Positions

Table 4.7 displays the model's interior surfaces and the assigned library data.

Table 4.7. Initially Assigned Absorption Coefficients

Surface	Description	Area	Absorption Coefficient					
		sqm.	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz
Ceiling Concrete Slab	Concrete	175.35	0.02	0.02	0.03	0.03	0.04	0.05
Concrete Beam	Concrete	160.52	0.02	0.03	0.03	0.03	0.04	0.07
Floor	Linoleum on concrete floor	141.48	0.02	0.02	0.03	0.04	0.04	0.05
Wall	Plastered and painted brick	137.46	0.02	0.02	0.03	0.03	0.04	0.05
Ceiling Mesh	Open cell aluminium grid, 10x10cm cell size	133.43	ACOUSTICALLY TRANSPARENT					
Desk	Laminated MDF mounted on metal frame	89.93	0.02	0.02	0.03	0.03	0.04	0.05
Concrete_Pillar	Plastered and painted concrete	84.4	0.02	0.02	0.03	0.03	0.04	0.05

(cont. on next page)

Table 4.7. (Cont.)

Surface	Description	Area	Absorption Coefficient					
		sqm.	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz
Raised podium on the floor	Linoleum on floor podium	76.14	0.02	0.02	0.03	0.04	0.04	0.05
Periphery of open cell ceiling	12.5mm gypsum board with airspace above	64.53	0.20	0.15	0.10	0.08	0.04	0.02
AC_Unit	Cassete type AC unit	20.4	0.02	0.02	0.03	0.03	0.04	0.05
Curtain	Cotton fabric curtain	19.77	0.06	0.10	0.38	0.63	0.70	0.79
Lighting	60x60cm lighting unit with plastic surface	7.2	0.02	0.02	0.03	0.03	0.04	0.05
White Board	White board directly mounted on the wall	5.9	0.02	0.03	0.03	0.03	0.04	0.05
Door	Wooden door	3.15	0.14	0.10	0.06	0.08	0.10	0.10
Glass	Window glass	0.95	0.02	0.06	0.03	0.03	0.02	0.02

Figure 4.26 shows the simulated T_{30} outcomes using the initial absorption coefficients, while the dotted line labelled 'Ref RT' represents the actual measurement results. The initial analysis shows that the results for the 125Hz and 2kHz octave bands exceed the specified tolerance.

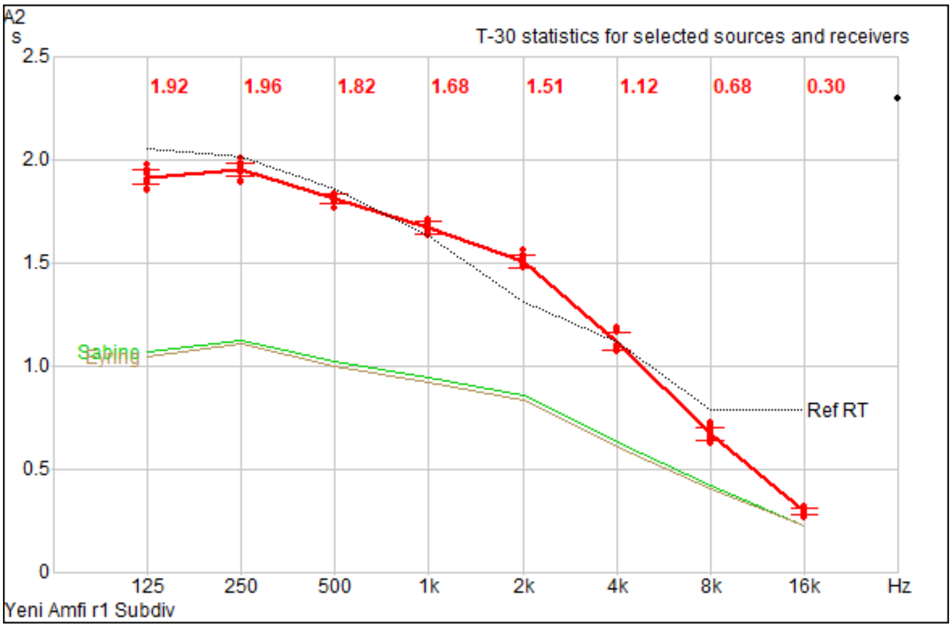


Figure 4.26. Initial T_{30} results in the Calibration Process

The calibration approach involved iteratively adjusting absorption data by 1%, starting from the largest surface and moving to the next largest surface until satisfactory results were achieved. The absorption of the ceiling concrete slab, which has the largest area, was modified for the first iteration. The 125Hz, 250Hz and 500Hz octave bands were decreased by 1% in absorption, while the 2kHz octave band was increased by 1%.

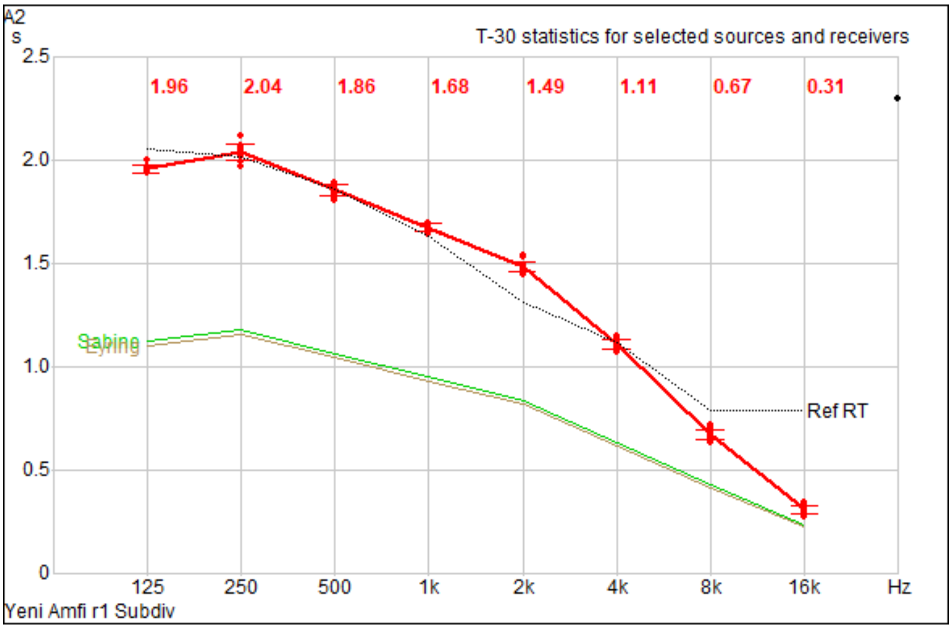


Figure 4.27. Calibration Process First Iteration T_{30} Results

Figure 4.27 shows the result of the first iteration. In the next iteration, the result of which is illustrated in Figure 4.28, the data of the concrete beam, the second-largest surface area, was altered. The 125Hz octave band absorption was reduced by 1%, and the 2kHz band absorption was increased by 1%.

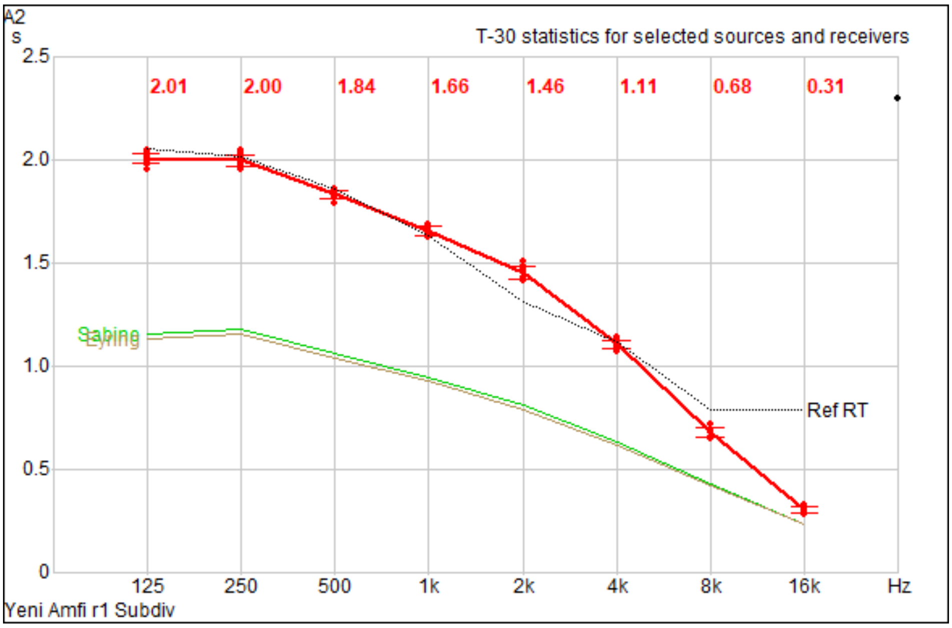


Figure 4.28. Calibration Process Second Iteration T_{30} Results

The subsequent iterations followed the same procedure until the goal was achieved in the sixth iteration, as shown in the figure below.

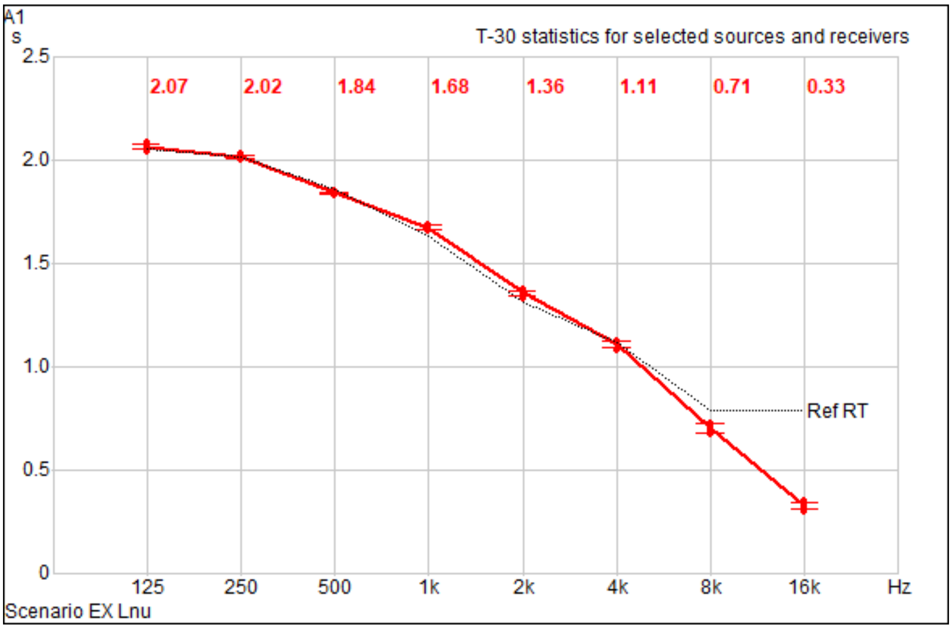


Figure 4.29. Calibration Process Sixth Iteration T30 Results

Table 4.8 displays the calibrated absorption coefficients with the order of the iterations. The shaded and bold cells under the 'altered' rows display adjusted data.

Table 4.8. Altered Absorption Coefficients for the Calibration of the Room Model

Surface	Description	Area sqm.	Absorption Coefficient 125Hz	250Hz	500Hz	1kHz	2kHz	4kHz
Ceiling Concrete Slab	Concrete	175.35	0.02	0.03	0.03	0.03	0.04	0.07
altered	first iteration		**0.01**	**0.02**	**0.02**	0.03	**0.05**	0.07
Concrete Beam	Concrete	160.52	0.02	0.03	0.03	0.03	0.04	0.07
altered	second iteration		**0.01**	0.03	0.03	0.03	**0.05**	0.07
Floor	Linoleum on concrete floor	141.48	0.02	0.02	0.03	0.04	0.04	0.05
altered	fourth iteration		0.02	0.02	0.03	0.04	**0.05**	0.05
Wall	Plastered and painted brick	137.46	0.02	0.02	0.03	0.03	0.04	0.05
altered	third iteration		**0.01**	0.02	0.03	0.03	**0.05**	0.05
Ceiling Mesh	Open cell aluminium grid, 10x10cm cell size	133.43	ACOUSTICALLY TRANSPARENT					
Desk	Laminated MDF mounted on metal frame	89.93	0.02	0.02	0.03	0.03	0.04	0.05
altered	fifth iteration		0.02	0.02	0.03	0.03	**0.05**	0.05
Concrete_Pillar	Plastered and painted concrete	84.4	0.02	0.02	0.03	0.03	0.04	0.05
altered	sixth iteration		0.02	0.02	0.03	0.03	**0.05**	0.05
Floor	Linoleum on floor podium	76.14	0.02	0.02	0.03	0.04	0.04	0.05
altered	fourth iteration		0.02	0.02	0.03	0.04	**0.05**	0.05
Periphery of open cell ceiling	12.5mm gypsum board with airspace above	64.53	0.20	0.15	0.10	0.08	0.04	0.02
AC_Unit	Cassete type AC unit	20.4	0.02	0.02	0.03	0.03	0.04	0.05
Curtain	Cotton fabric curtain	19.77	0.06	0.10	0.38	0.63	0.70	0.79
Lighting	60x60cm lighting unit with plastic surface	7.2	0.02	0.02	0.03	0.03	0.04	0.05
White Board	White board directly mounted on the wall	5.9	0.02	0.03	0.03	0.03	0.04	0.05
Door	Wooden door	3.15	0.14	0.10	0.06	0.08	0.10	0.10
Glass	Window glass	0.95	0.02	0.06	0.03	0.03	0.02	0.02

4.4.2. Verification Of The Calibrated Model

In order to verify the calibration, simulated T_{30} and STI values were compared to physically measured sets. The speech spectrum was selected as IEC male at 70 dBA signal level, per Annex J.3 of the IEC standard (IEC 60268-16 2011) to match the case in the physical measurements. The sound source used a human talker's directivity, with zero-degree azimuth facing the middle desk group. The JND for STI was determined to be 0.03 in the study on C_{80} (J S Bradley, Reich, and Norcross 1999), and the STI values were compared according to this JND. Similarly, the JND for the reverberation time was determined to be 5% (Seraphim 1958; ISO 3382-1 2009). Measured and simulated T_{30} values are compared in Table 4.9.

Table 4.9. Comparison Measured and Simulated T_{30} Values

1/1 Oct	MEA. / SIM.	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	AVE.
125	M	2.05	2.15	2.01	1.98	1.96	2.15	2.03	1.98	2.04	2.21	2.01	2.12	**2.06**
	S	2.05	2.06	2.06	2.05	2.07	2.07	2.07	2.08	2.07	2.06	2.09	2.08	**2.07**
	Diff. %	*0.00*	*3.96*	*2.32*	*3.74*	*5.86*	*3.81*	*2.15*	*5.26*	*1.70*	*6.87*	*3.77*	*1.90*	***0.53***
250	M	2.05	1.95	2.04	2.03	2.15	2.03	2.08	2.07	1.95	1.97	1.96	2.02	**2.02**
	S	2.01	2.01	2.00	2.03	2.01	2.02	2.02	2.02	2.02	2.04	2.02	2.04	**2.02**
	Diff. %	*0.02*	*3.29*	*1.88*	*0.23*	*6.48*	*0.26*	*2.73*	*2.32*	*3.45*	*3.54*	*2.82*	*1.19*	***0.22***
500	M	1.89	1.85	1.88	1.88	1.86	1.86	1.84	1.86	1.85	1.76	1.89	1.94	**1.86**
	S	1.84	1.84	1.83	1.84	1.84	1.84	1.85	1.86	1.85	1.85	1.85	1.84	**1.84**
	Diff. %	*0.03*	*0.58*	*2.83*	*2.30*	*0.90*	*1.25*	*0.40*	*0.18*	*0.16*	*4.84*	*2.32*	*4.93*	***1.11***
1k	M	1.63	1.64	1.68	1.61	1.63	1.63	1.67	1.62	1.66	1.62	1.64	1.67	**1.64**
	S	1.67	1.66	1.66	1.68	1.68	1.67	1.67	1.68	1.69	1.69	1.69	1.69	**1.68**
	Diff. %	*0.02*	*1.26*	*1.11*	*4.37*	*3.17*	*2.54*	*0.24*	*3.62*	*1.64*	*4.41*	*3.26*	*1.48*	***2.20***
2k	M	1.31	1.29	1.32	1.27	1.32	1.31	1.35	1.29	1.35	1.33	1.35	1.37	**1.32**
	S	1.33	1.34	1.35	1.37	1.36	1.36	1.38	1.37	1.37	1.37	1.37	1.37	**1.36**
	Diff. %	*0.02*	*3.82*	*2.30*	*7.68*	*2.95*	*3.87*	*2.45*	*6.31*	*1.53*	*2.70*	*1.16*	*0.15*	***3.00***
4k	M	1.12	1.10	1.09	1.07	1.12	1.12	1.14	1.16	1.13	1.14	1.15	1.11	**1.12**
	S	1.08	1.09	1.09	1.11	1.12	1.11	1.13	1.12	1.13	1.13	1.13	1.13	**1.11**
	Diff. %	*0.03*	*0.70*	*0.15*	*3.84*	*0.33*	*1.04*	*0.50*	*3.20*	*0.18*	*1.28*	*2.14*	*1.41*	***0.58***
8k	M	0.77	0.75	0.74	0.78	0.80	0.76	0.79	0.79	0.81	0.80	0.83	0.82	**0.79**
	S	0.68	0.68	0.68	0.70	0.70	0.71	0.72	0.72	0.72	0.73	0.73	0.72	**0.71**
	Diff. %	*0.12*	*9.87*	*8.60*	*9.91*	*12.01*	*6.82*	*9.21*	*8.51*	*11.44*	*8.92*	*12.47*	*11.66*	***10.17***
500 - 1k	M	1.76	1.75	1.78	1.75	1.74	1.75	1.76	1.74	1.75	1.69	1.77	1.80	**1.61**
	S	1.76	1.75	1.75	1.76	1.76	1.76	1.76	1.77	1.77	1.77	1.77	1.77	**1.57**
	Diff. %	*0.00*	*0.29*	*2.02*	*0.77*	*1.00*	*0.52*	*0.09*	*1.59*	*0.86*	*4.63*	*0.26*	*1.96*	***2.90***

The STI calculation uses background noise data from physical measurements for measured and simulated data sets. The measurement was made in an unoccupied classroom. Table 4.10 shows the background noise measured at each receiver location.

Table 4.10. Background Noise level ($L_{n,u}$) Measured in the Unoccupied Classroom

REC.	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	AVE.
Ln,u (dBA)	30.66	30.92	30.50	30.49	30.84	31.52	31.00	30.47	30.50	30.17	30.31	30.26	30.60

Table 4.11 displays a comparison of measured and simulated STI values.

Table 4.11. Comparison of Measured and Simulated STI values

RECEIVER POSITION	STI		
	MEASURED	SIMULATED	DIFFERENCE
R1	0.56	0.54	0.02
R2	0.62	0.56	0.06
R3	0.56	0.55	0.01
R4	0.52	0.50	0.02
R5	0.54	0.49	0.05
R6	0.51	0.50	0.01
R7	0.48	0.45	0.03
R8	0.49	0.44	0.05
R9	0.49	0.47	0.02
R10	0.48	0.43	0.05
R11	0.50	0.43	0.07
R12	0.47	0.43	0.04

4.5. Room Acoustics Design Scenarios

Room acoustics design scenarios were developed to test room acoustic treatment plans using G_{50}, T_{30}, U_{50} and STI parameters. The scenarios also involved the auralization of the anechoic word list recordings. The auralised audio material was used in the listening tests with human participants to quantify subjective speech recognition.

All scenarios were based on the calibrated room model with the modifications required for the acoustic treatment plans. The EX Scenario represents the existing classroom described in section 4.2.1. The ABS-C scenario replaces the open cell ceiling grid and surrounding plain gypsum board frame in the EX scenario with a sound-absorbing suspended ceiling, converting the entire ceiling to an absorptive surface. In addition to the absorptive ceiling in the ABS-C scenario, the ABS-CW scenario introduces additional wall absorption to the back and side walls. The ER scenario represents the early reflections-oriented room acoustics design where the absorption was assigned to wall and ceiling areas identified according to the ERORAD method.

4.5.1. Background Noise Consideration

A major factor affecting speech intelligibility in classrooms is background noise. As discussed in section 3.4, the participants' noise generated during lectures was the primary contributor to background noise. The studies have reported that the noise levels are much higher than the recommended levels in the literature. The simulation scenarios used the background noise data measured in the unoccupied classroom ($L_{n,u}$) and the background noise data ($L_{n,a}$) published in studies (Sooch San Souci et al. 2006, Choi 2020a) conducted in active classrooms, as displayed in Table 4.12 and Table 4.13.

Table 4.12. Measured Unoccupied Classroom Background Noise Level ($L_{n,u}$)

f (Hz)	125	250	500	1000	2000	4000	A-weighted
Ln,u (dB)	32.4	28.1	24.1	22.3	21.4	22.3	30.6

Table 4.13. Active Classroom Background Noise Level ($L_{n,a}$)

f (Hz)	125	250	500	1000	2000	4000	A-weighted
Ln,a (dB)	45.2	42.8	40.1	36.8	34.6	38.2	43.7

Table 4.14 displays two additional background noise levels (50dBA as Ln,a-v1 and 55dBA as Ln,a-v2) for testing obtained by shifting up the spectrum in Table 4.13.

Table 4.14. Active Classroom Background Noise Level Variations

f (Hz)	125	250	500	1000	2000	4000	A-weighted
Ln,a-v1 (dB)	51.0	48.5	46.0	42.5	40.5	44.0	49.9
Ln,a-v2 (dB)	56.0	53.5	51.0	47.5	45.5	49.0	54.9

$L_{n,a}$ (44 dBA), $L_{n,a\text{-}v1}$ (50 dBA) and $L_{n,a\text{-}v2}$ (55 dBA) fall into the "calm", "normal", and "noisy" categories for the active classroom noise ranges as described by San Souci et al. (2006).

Thus, the room scenarios were tested with four different background noise levels, including the unoccupied classroom background noise level $L_{n,u}$ (30.5 dBA). The background noise was assumed to be uniform across the classroom.

4.5.2. Scenario: EX

The 'EX' scenario simulates the classroom's existing state. Figure 4.30 illustrates the existing state of the classroom with the curtains unfolded in front of the windows. The model excludes the open-cell suspended ceiling grid since it is considered acoustically transparent.

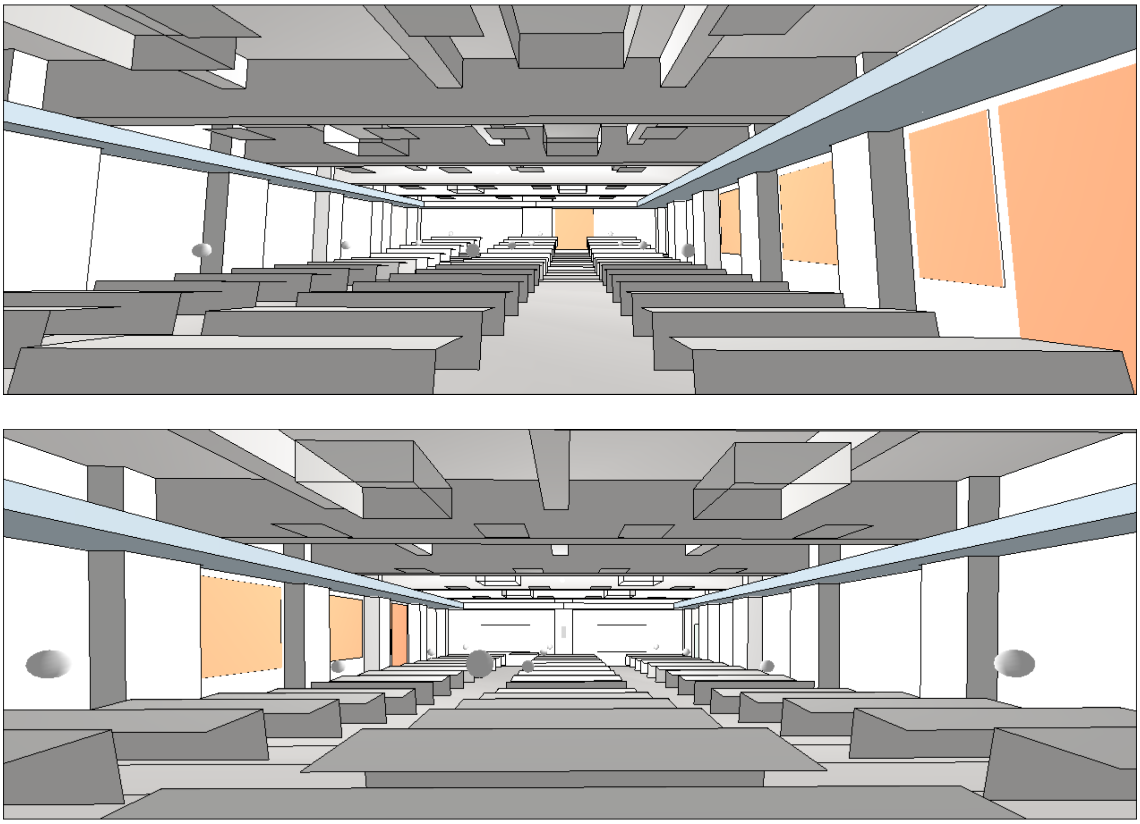


Figure 4.30. Front and Back Interior 3-D Views of Scenario EX

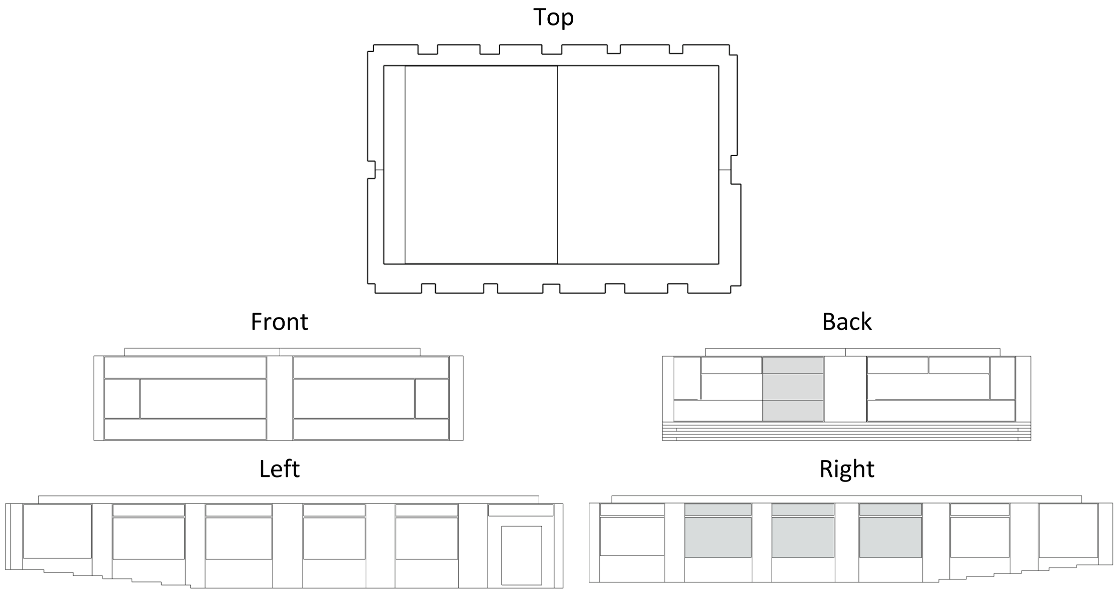


Figure 4.31. Interior Views of Scenario EX

Shaded areas represent the cotton fabric curtain in the existing classroom (Scenario EX).

Table 4.15. Scenario EX | Interior Surfaces and Absorption Coefficients

Surface	Description	Area sqm.	Absorption Coefficient 125Hz	250Hz	500Hz	1kHz	2kHz	4kHz
Ceiling Concrete Slab	Concrete	175.35	0.01	0.02	0.02	0.03	0.05	0.07
Concrete Beam	Concrete	160.52	0.01	0.03	0.03	0.03	0.05	0.07
Floor	Linoleum on concrete floor	141.48	0.02	0.02	0.03	0.04	0.05	0.05
Wall	Plastered and painted brick	137.46	0.01	0.02	0.03	0.03	0.05	0.05
Ceiling Mesh	Open cell aluminium grid, 10x10cm cell size	155.62	Acoustically Transparent					
Desk	Laminated MDF mounted on metal frame	89.93	0.02	0.02	0.03	0.03	0.05	0.05
Concrete_Columns	Plastered and painted concrete	84.4	0.02	0.02	0.03	0.03	0.05	0.05
Floor	Linoleum on floor podium	76.14	0.02	0.02	0.03	0.04	0.05	0.05
Periphery of open cell ceiling	12.5mm gypsum board with airspace above	64.53	0.20	0.15	0.10	0.08	0.04	0.02
AC_Unit	Cassete type AC unit	20.4	0.02	0.02	0.03	0.03	0.04	0.05
Curtain	Cotton fabric curtain	19.77	0.06	0.10	0.38	0.63	0.70	0.79
Lighting	60x60cm lighting unit with plastic surface	7.2	0.02	0.02	0.03	0.03	0.04	0.05
White Board	White board directly mounted on the wall	5.9	0.02	0.03	0.03	0.03	0.04	0.05
Door	Wooden door	3.15	0.14	0.10	0.06	0.08	0.10	0.10
Glass	Window glass	0.95	0.02	0.06	0.03	0.03	0.02	0.02

4.5.3. Scenario: ABS-C

The ABS-C scenario was implemented to model the impact of a sound-absorbing suspended ceiling throughout the entire ceiling area. To isolate the effect of the ceiling treatment, the curtains in the classroom's original setup were removed. Figure 4.32 illustrates the ABS-C scenario, where the dark-coloured ceiling indicates the presence of sound-absorbing material throughout the entire ceiling area.

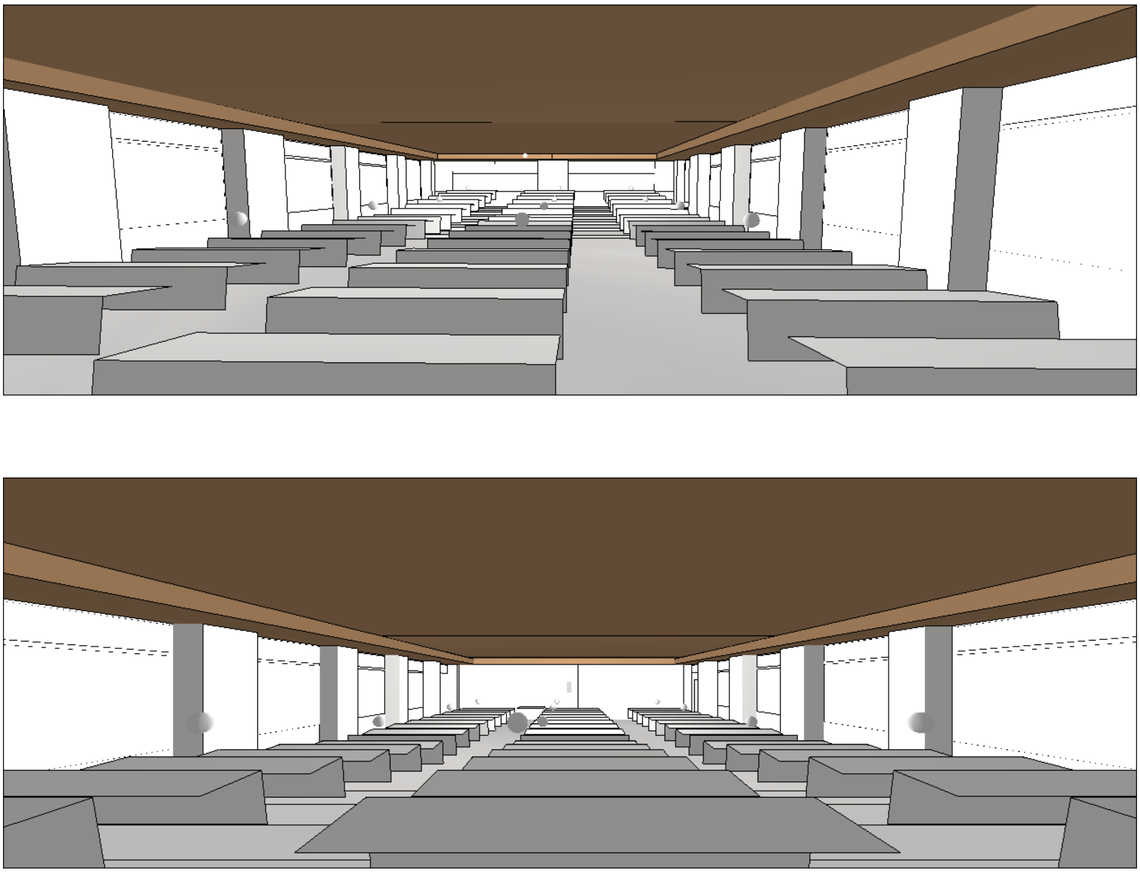


Figure 4.32. Front and Back Interior Views of Scenario ABS-C

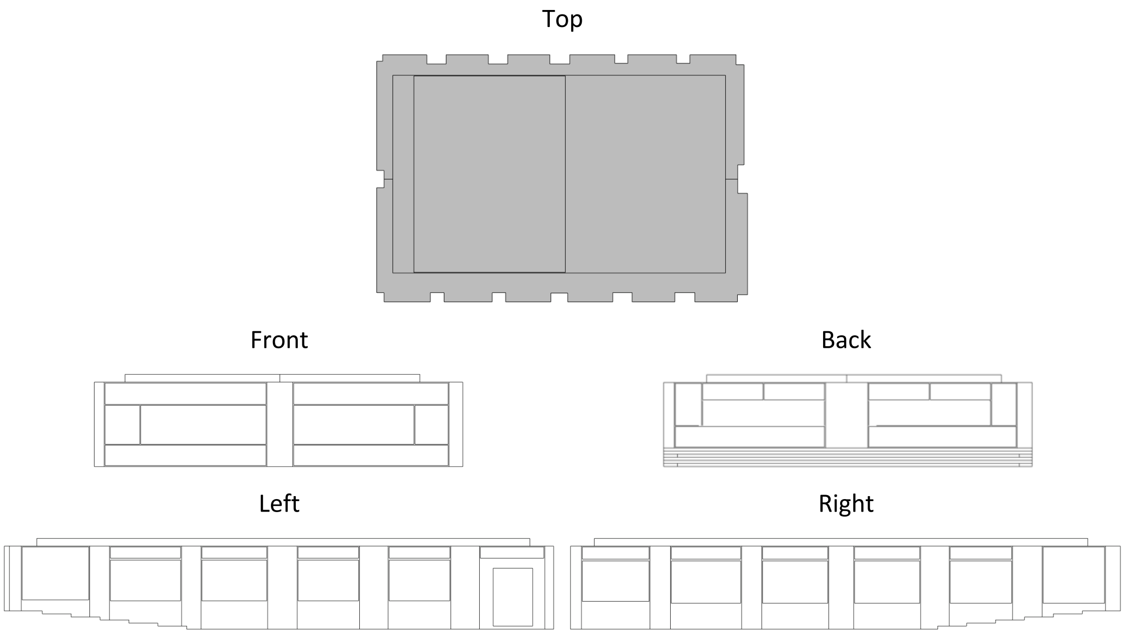


Figure 4.33. Interior Views of Scenario ABS-C

Shaded areas in the figure above show absorbing areas and are indicated with the shaded rows in the table below.

Table 4.16. Scenario ABS-C | Interior Surfaces and Absorption Coefficients

Surface	Description	Area	Absorption Coefficient					
		sqm.	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz
Ceiling	Suspended Ceiling with Mineral Fiber Tiles	210.59	0.53	0.49	0.57	0.82	0.90	0.83
Floor	Linoleum on concrete floor	141.48	0.02	0.02	0.03	0.04	0.05	0.05
Wall	Plastered and painted brick	106.47	0.01	0.02	0.03	0.03	0.05	0.05
Desk	Laminated MDF mounted on metal frame	89.93	0.02	0.02	0.03	0.03	0.05	0.05
Concrete_ Columns	Plastered and painted concrete	61.61	0.02	0.02	0.03	0.03	0.05	0.05
Floor	Linoleum on floor podium	76.14	0.02	0.02	0.03	0.04	0.05	0.05
White Board	White board directly mounted on the wall	5.9	0.02	0.03	0.03	0.03	0.04	0.05
Door	Wooden door	3.15	0.14	0.10	0.06	0.08	0.10	0.10
Glass	Window glass	0.95	0.02	0.06	0.03	0.03	0.02	0.02

4.5.4. Scenario: ABS-CW

The ABS-CW scenario simulates the treatment of the entire ceiling area and the side and back wall areas, focusing on achieving the optimum reverberation time. Bistafa and Bradley (2000) suggest an optimum reverberation time in the 0.4-0.5s range. This goal requires the use of acoustic absorbers in the ceiling and walls.

Figure 4.34 illustrates the absorbing suspended ceiling over the desks, side wall and back walls covered with curtains and fabric wall panels.

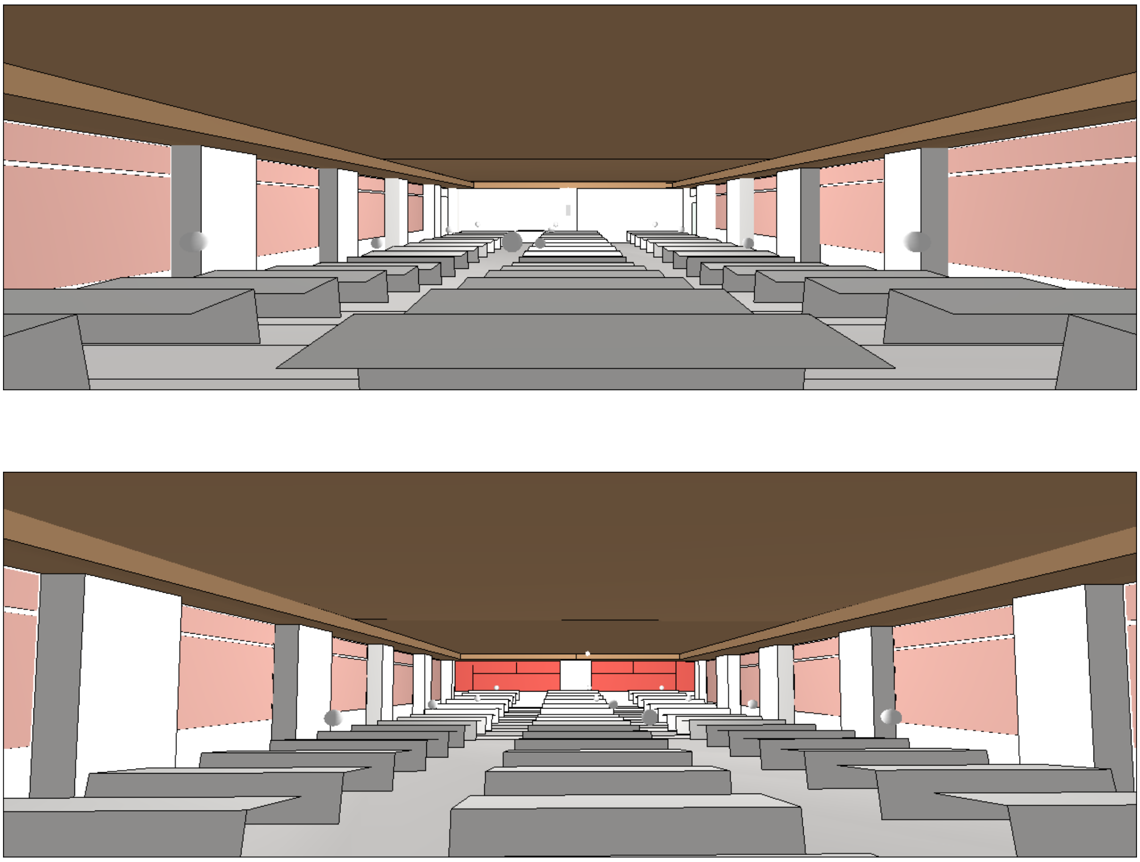


Figure 4.34. Front and Back Interior Views of Scenario ABS-CW

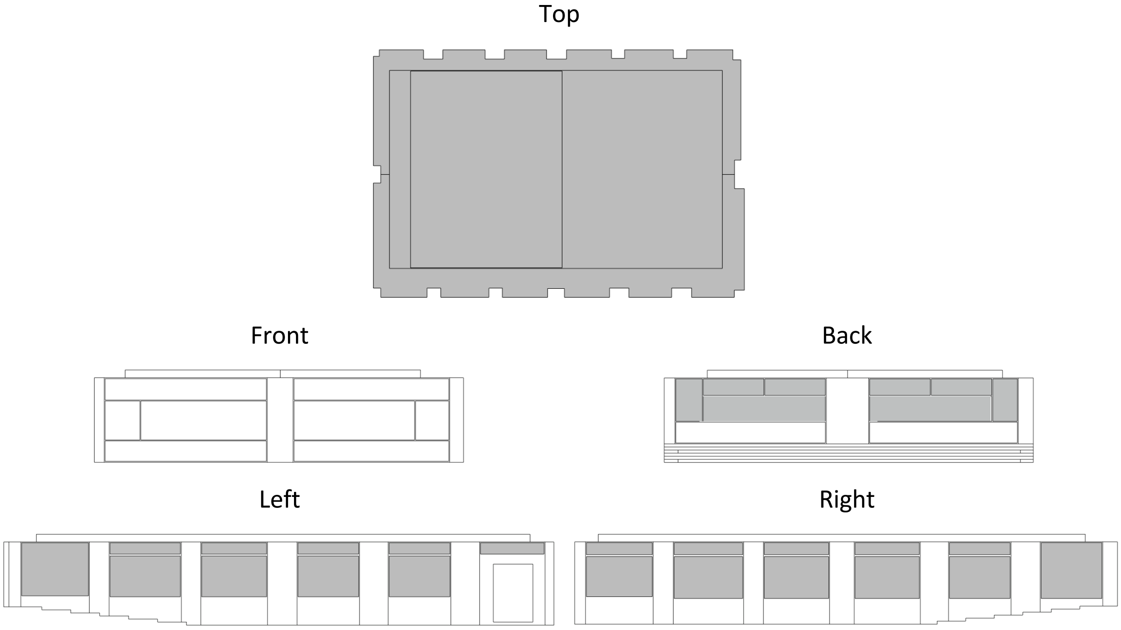


Figure 4.35. Interior Views of Scenario ABS-CW

Shaded areas in the figure above show absorbing areas and are indicated with the shaded rows in the table below.

Table 4.17. Scenario ABS-CW | Interior Surfaces and Absorption Coefficients

Surface	Description	Area	Absorption Coefficient					
		sqm.	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz
Ceiling	Suspended Ceiling with Mineral Fiber Tiles	210.59	0.53	0.49	0.57	0.82	0.90	0.83
Floor	Linoleum on concrete floor	141.48	0.02	0.02	0.03	0.04	0.05	0.05
Wall	Plastered and painted brick	56.29	0.01	0.02	0.03	0.03	0.05	0.05
Wall_ABS	Absorbing wall panels	50.18	0.15	0.56	0.88	0.99	0.99	0.95
Desk	Laminated MDF mounted on metal frame	89.93	0.02	0.02	0.03	0.03	0.05	0.05
Concrete_ Columns	Plastered and painted concrete	61.61	0.02	0.02	0.03	0.03	0.05	0.05
Floor	Linoleum on floor podium	76.14	0.02	0.02	0.03	0.04	0.05	0.05
White Board	White board directly mounted on the wall	5.9	0.02	0.03	0.03	0.03	0.04	0.05
Door	Wooden door	3.15	0.14	0.10	0.06	0.08	0.10	0.10
Glass	Window glass	0.95	0.02	0.06	0.03	0.03	0.02	0.02

4.5.5. Scenario: ER

In section 4.3, the early reflection surfaces (ERS) were identified. Figure 4.36 shows the position of reflecting and absorbing areas needed to protect these early reflections. The absorbing materials are represented by coloured areas on the figure, with darker colours indicating higher absorption. The first step involves reserving surface areas that direct early reflections towards the audience. Reflective materials made of flat and hard materials are then provided to these reserved areas. Furthermore, sound-absorbing materials were applied to the wall and ceiling areas outside the reserved zones to control reverberation.

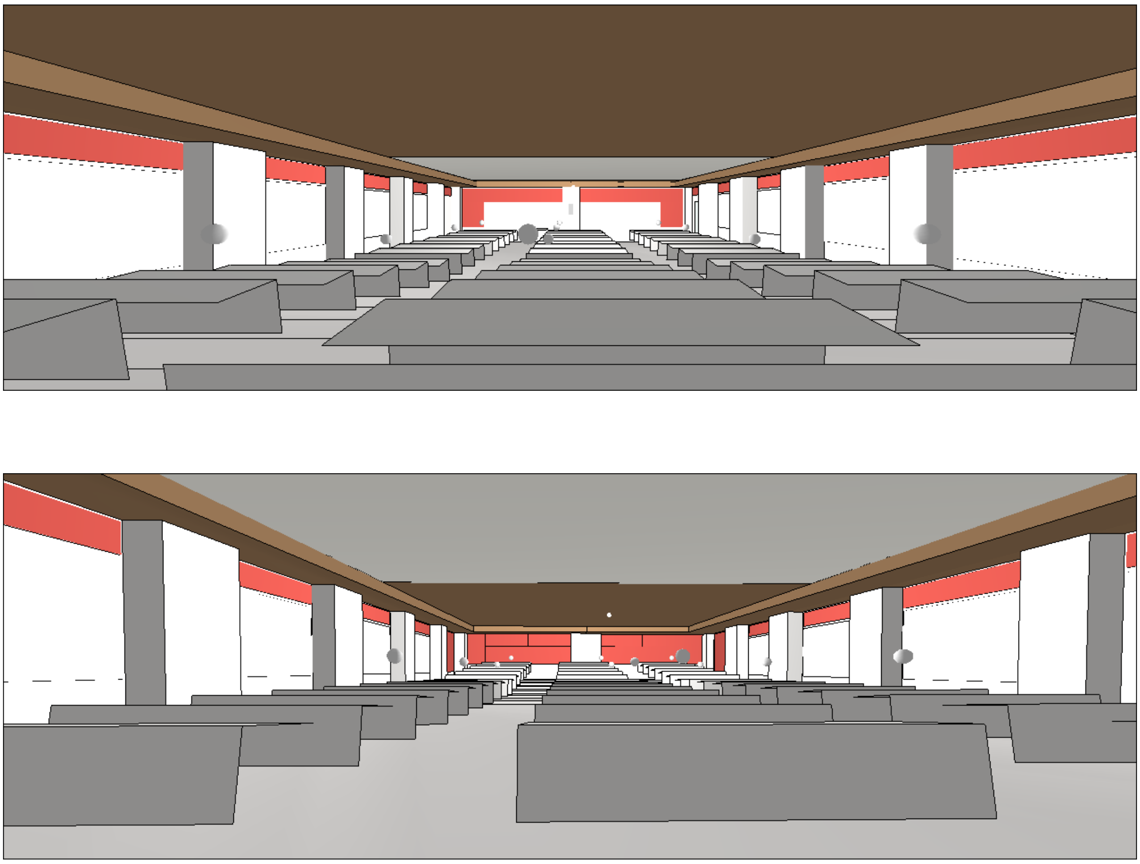


Figure 4.36. Front and Back Interior Views of Scenario ER

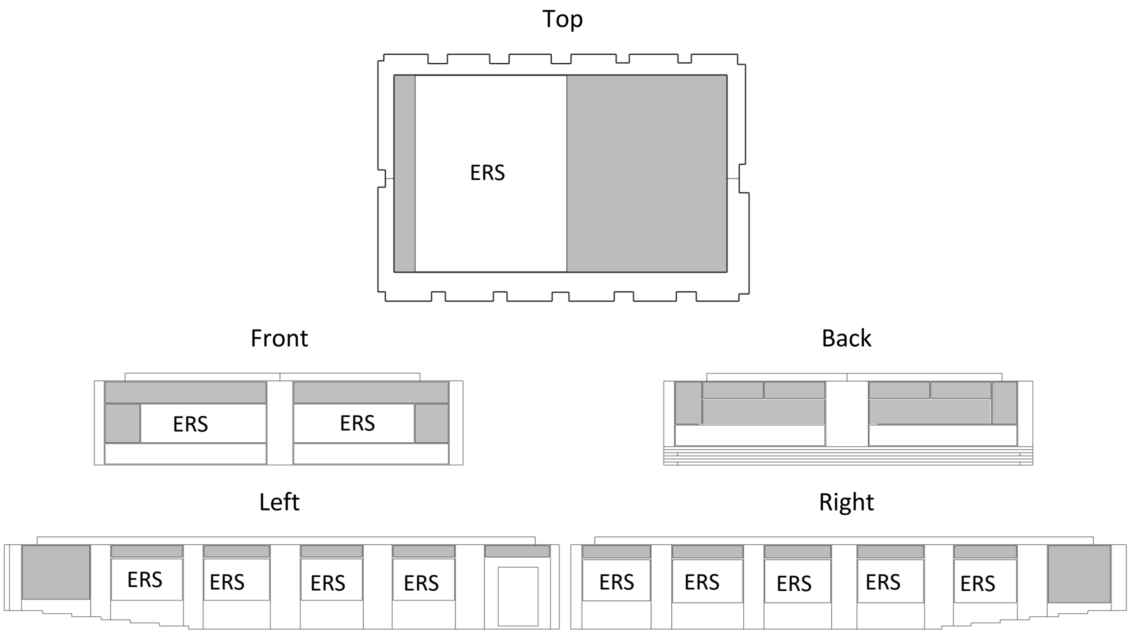


Figure 4.37. Interior Views of Scenario ER

The room surfaces denoted as ERS, are the early reflection surfaces. The rest of the surfaces are considered as the surfaces appropriate for absorption (SfA).

Shaded areas in the figure above show absorbing areas and are indicated with the shaded rows in the table below.

Table 4.18. Scenario ER | Interior Surfaces and Absorption Coefficients

Surface	Description	Area sqm.	Absorption Coefficient 125Hz	250Hz	500Hz	1kHz	2kHz	4kHz
Ceiling	Suspended Ceiling with Mineral Fiber Tiles	140.2	0.53	0.49	0.57	0.82	0.90	0.83
Floor	Linoleum on concrete floor	141.48	0.02	0.02	0.03	0.04	0.05	0.05
Wall	Plastered and painted brick	111.27	0.01	0.02	0.03	0.03	0.05	0.05
Wall_ABS	Absorbing wall panels	38.41	0.15	0.56	0.88	0.99	0.99	0.95
Desk	Laminated MDF mounted on metal frame	89.93	0.02	0.02	0.03	0.03	0.05	0.05
Concrete_ Columns	Plastered and painted concrete	61.61	0.02	0.02	0.03	0.03	0.05	0.05
Floor	Linoleum on floor podium	76.14	0.02	0.02	0.03	0.04	0.05	0.05
White Board	White board directly mounted on the wall	5.9	0.02	0.03	0.03	0.03	0.04	0.05
Door	Wooden door	3.15	0.14	0.10	0.06	0.08	0.10	0.10
Glass	Window glass	0.95	0.02	0.06	0.03	0.03	0.02	0.02

4.5.6. Simulation Results of the Scenarios

The mean Absorption for each scenario is shown in Figure 4.38 below. The EX scenario, representing the existing room, has the minimum absorption for each octave band. This is followed by the early reflection-oriented room acoustics design scenario ER. The ABS-CW scenario has the highest absorption, and ABS-C is the second-highest scenario in terms of absorption.

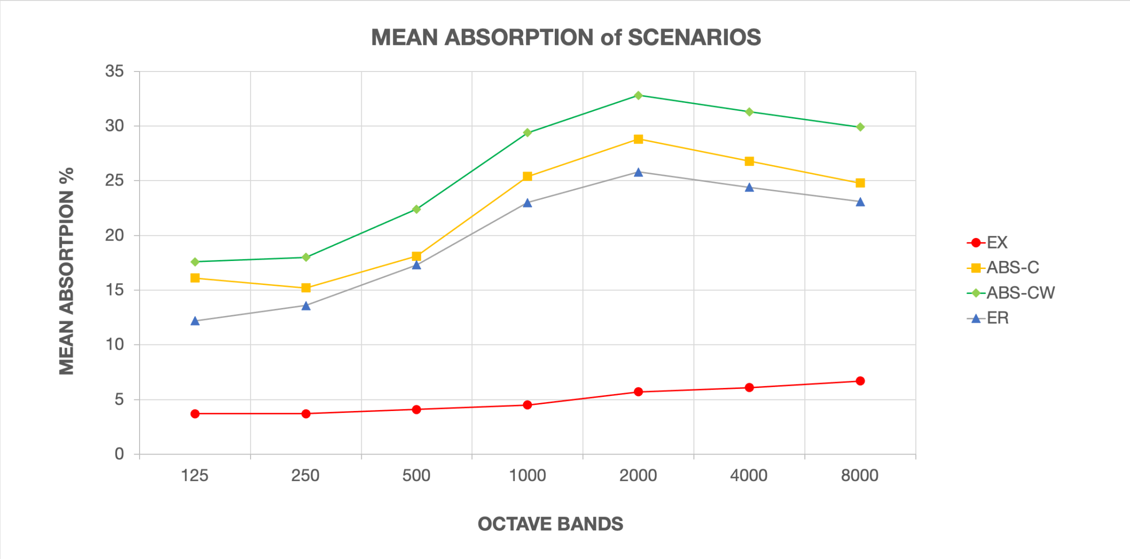


Figure 4.38. Mean Absorption of the Room Acoustics Design Scenarios

Reverberation Time results are displayed in Figure 4.39 below. The graph illustrates the average reverberation time for octave bands from 500Hz to 4kHz octave bands for each receiver.

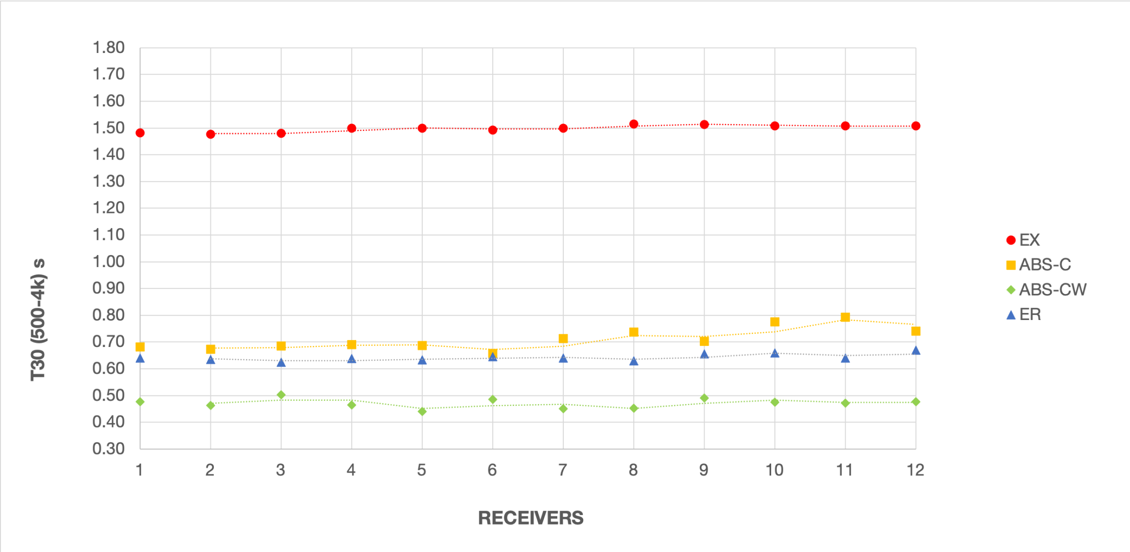


Figure 4.39. Reverberation Time (T_{30}) 500Hz-4kHz Average per Receiver

Figure 4.39 shows the reverberation time per receiver for each scenario. Except for the existing room scenario EX, all three scenarios significantly reduced the reverberation time. The lowest reverberation time values are observed in the ABS-CW scenario, where the maximum amount of sound-absorbing materials is used on walls and ceilings. Although the ABS-C scenario, which represents the conventional ceiling treatment, has a higher mean absorption than the ER scenario, it still has higher reverberation time values than the ER scenario.

Figure 4.40 displays the average relative sound level for octave bands from 500Hz to 4kHz for each receiver according to the room acoustics design scenarios. G_{50} values are in line with the mean absorption data computed for each scenario, except the ER scenario. According to Figure 4.38, it can be seen that the G_{50} values decrease as the mean absorption increases. However, the pattern is not followed in the ER scenario. In the ER scenario, the placement of sound absorbers on early-reflecting surfaces was avoided, and the reflections from these surfaces were retained. According to Figure 4.40, ER maximises the G_{50} while controlling the reverberation time compared to the other scenarios. G_{50} values of the back receivers (10-12) are significantly lower for ABS-C and ABS-CW scenarios.

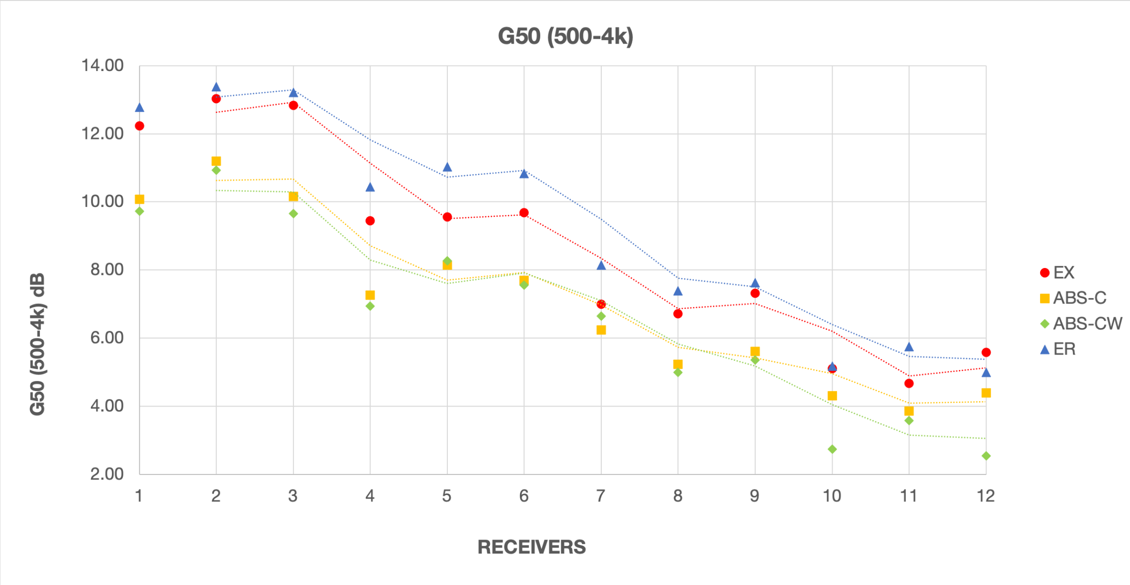


Figure 4.40. Relative Sound Level (G_{50}) 500Hz-4kHz Average per Receiver

Figure 4.41 shows STI versus G_{50} values of the scenarios for unoccupied classroom background noise, $L_{n,u}$. Each data point represents a receiver position, as illustrated in Figure 4.10. The first three data dots at the beginning of the series belong to the back receiver positions. The coefficient of determination shows a good fit for the linear trendline in EX, ABS-C and ABS-CW scenarios. The trendline of the ER scenario is significantly flat. This indicates that the STI values of the back receiver positions got closer to those of the front receiver positions due to early reflections. This is also seen in Figure 4.42, which displays the STI values for each receiver and the scenarios.

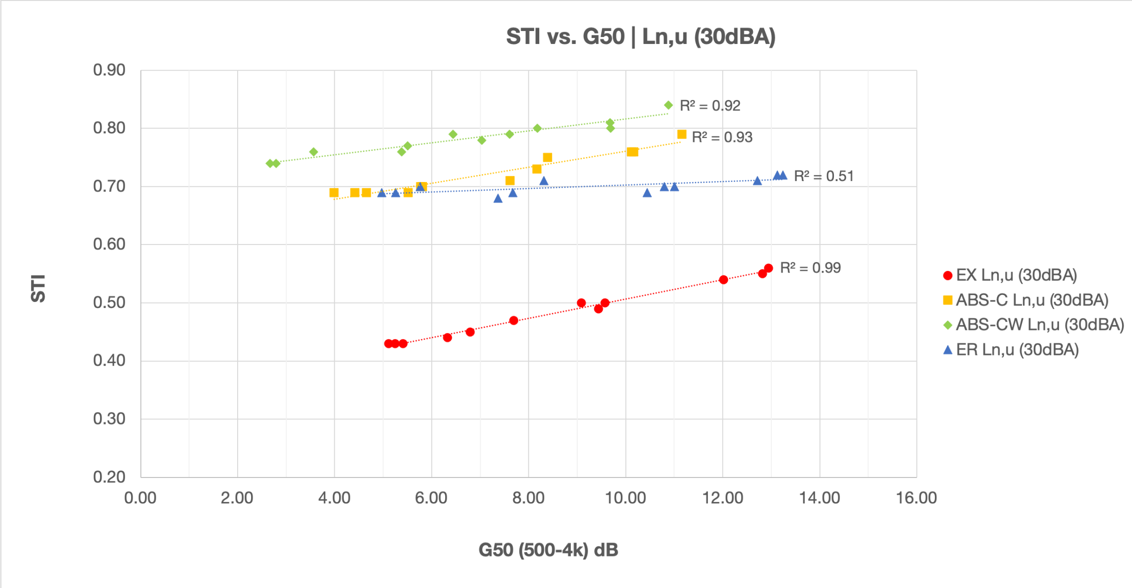


Figure 4.41. STI vs. G_{50} | $L_{n,u}$

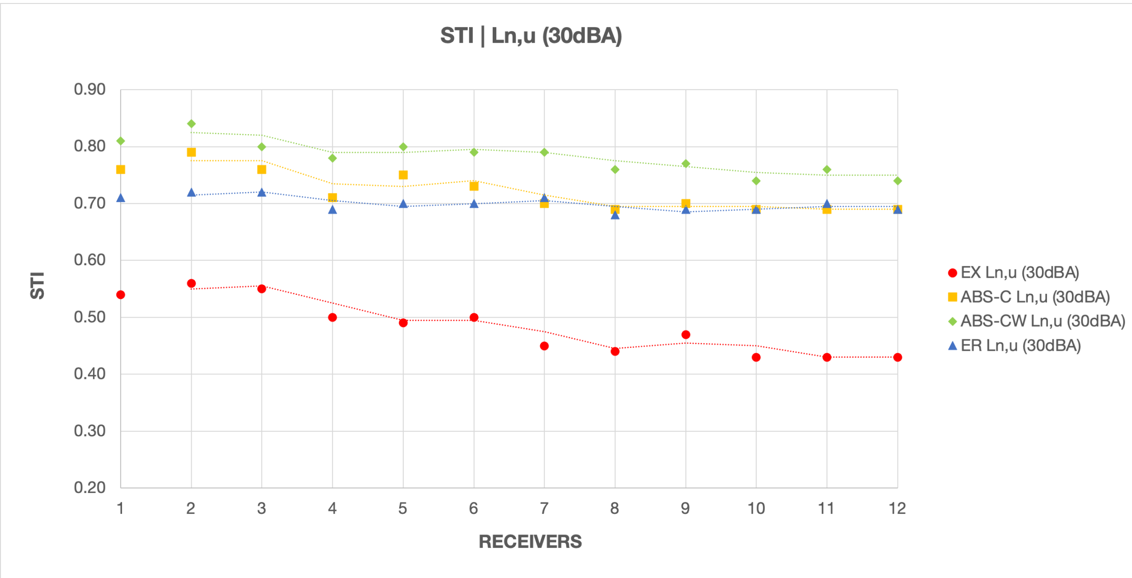


Figure 4.42. STI per Receiver | $L_{n,u}$

Figure 4.43 shows U_{50} versus G_{50} values of the scenarios for unoccupied classroom background noise, $L_{n,u}$. The values and the trendlines are similar to STI versus G_{50}, displayed in Figure 4.41.

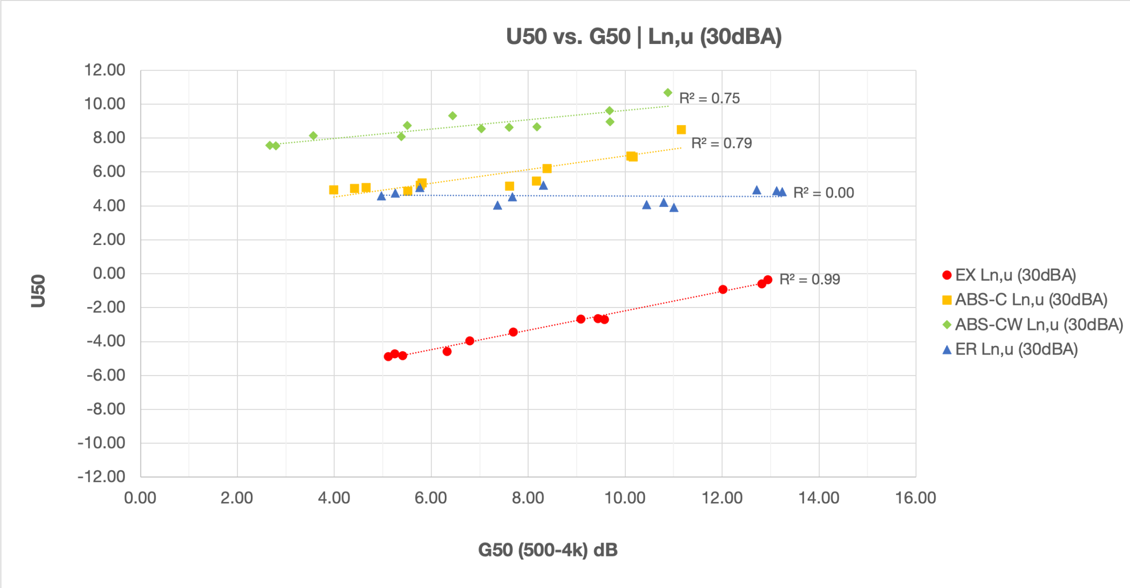


Figure 4.43. U_{50} vs. G_{50} | $L_{n,u}$

Figure 4.44 displays the average U_{50} for octave bands from 500Hz to 4kHz for each receiver according to the room acoustics design scenarios with the unoccupied classroom background noise level.

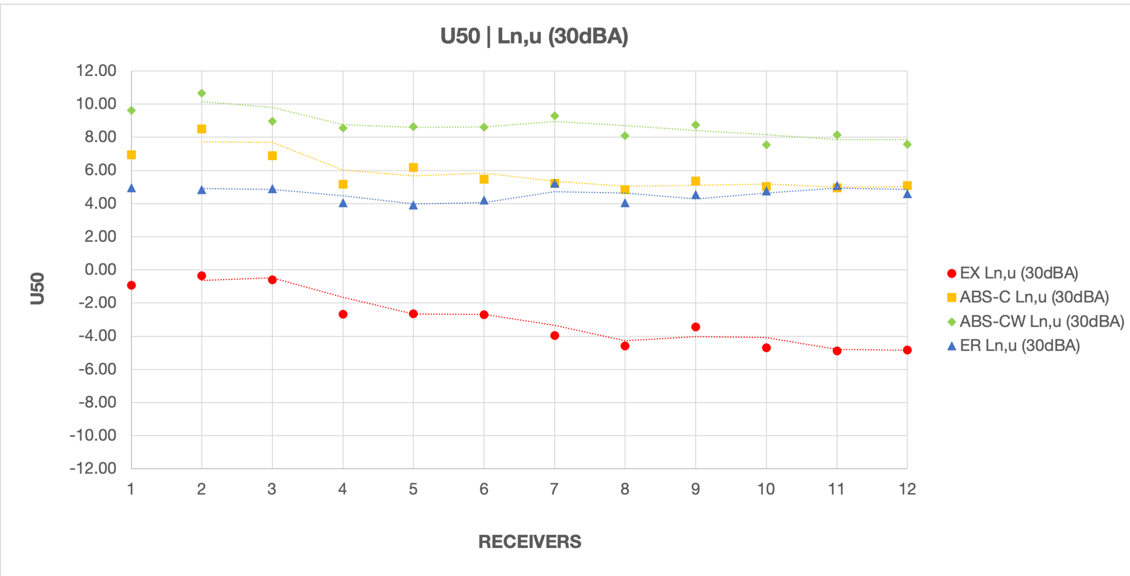


Figure 4.44. U_{50} per Receiver | $L_{n,u}$

Figure 4.45 shows STI versus G_{50} values of the scenarios for active classroom background noise, $L_{n,a}$. All trendlines yield a high coefficient of determination with the increased background noise level. With the increase in background noise, ER provided similar or better STI values for the back receiver positions compared to ABS-C and ABS-CW, and there was a greater reduction in the STI values of ABS-C and ABS-CW.

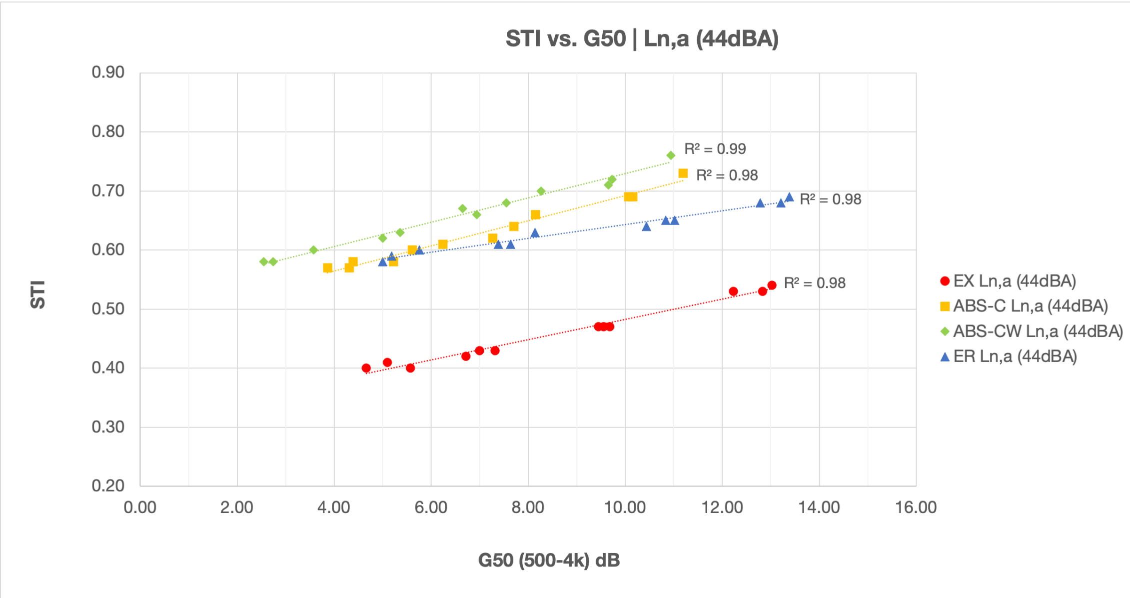


Figure 4.45. STI vs. G_{50} | $L_{n,a}$

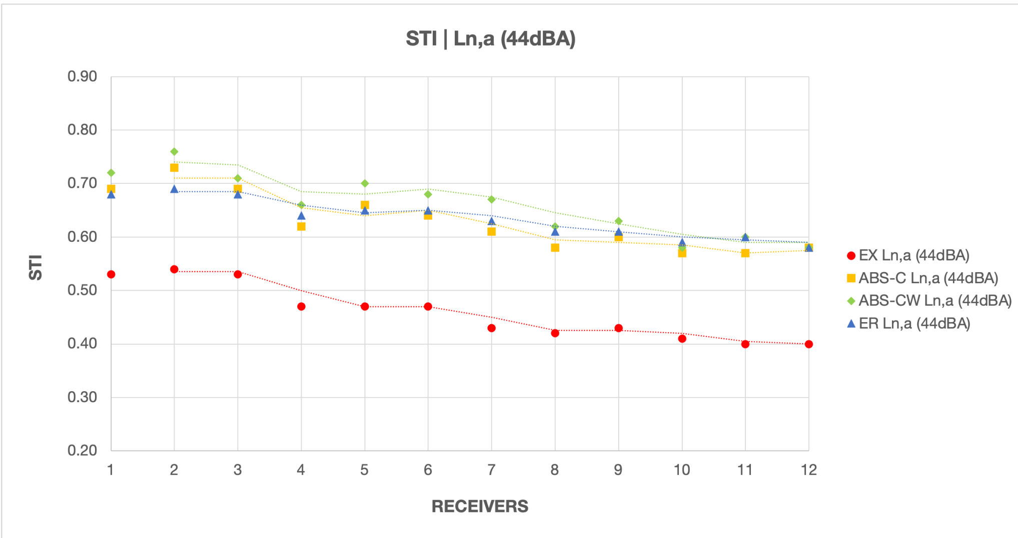


Figure 4.46. STI per Receiver | $L_{n,a}$

Figure 4.46 displays STI values for each receiver. Figure 4.47 illustrates U_{50} versus G_{50} values of the scenarios for active classroom background noise, $L_{n,a}$. The values and the trendlines agree with the STI versus G_{50}, given in Figure 4.46.

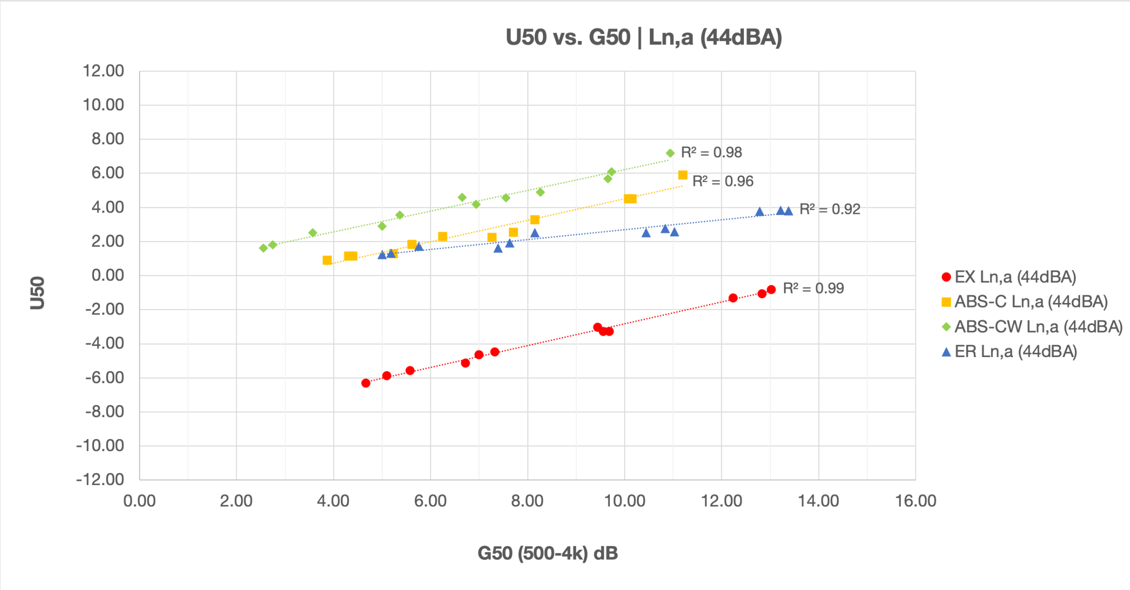


Figure 4.47. U_{50} vs. G_{50} | $L_{n,a}$

Figure 4.48 shows average U_{50} values for octave bands from 500Hz to 4kHz for each receiver according to the room acoustics design scenarios with the active classroom background noise level.

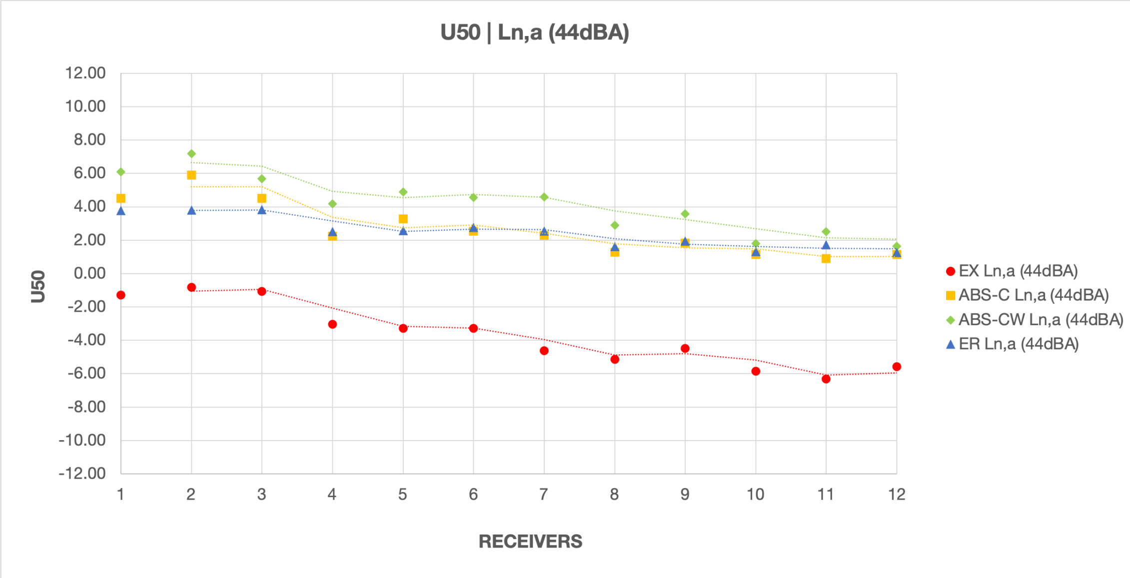


Figure 4.48. U_{50} per Receiver | $L_{n,a}$

Figure 4.49Figure 4.45 displays STI versus G_{50} values of the scenarios for active classroom background noise variation-1, $L_{n,a\text{-}v1}$, which is increased to 50 dBA. As the background noise level increases, all trendlines yield a higher coefficient of determination. ER came forward with the highest STI values starting from the third receiver position, as seen in Figure 4.50.

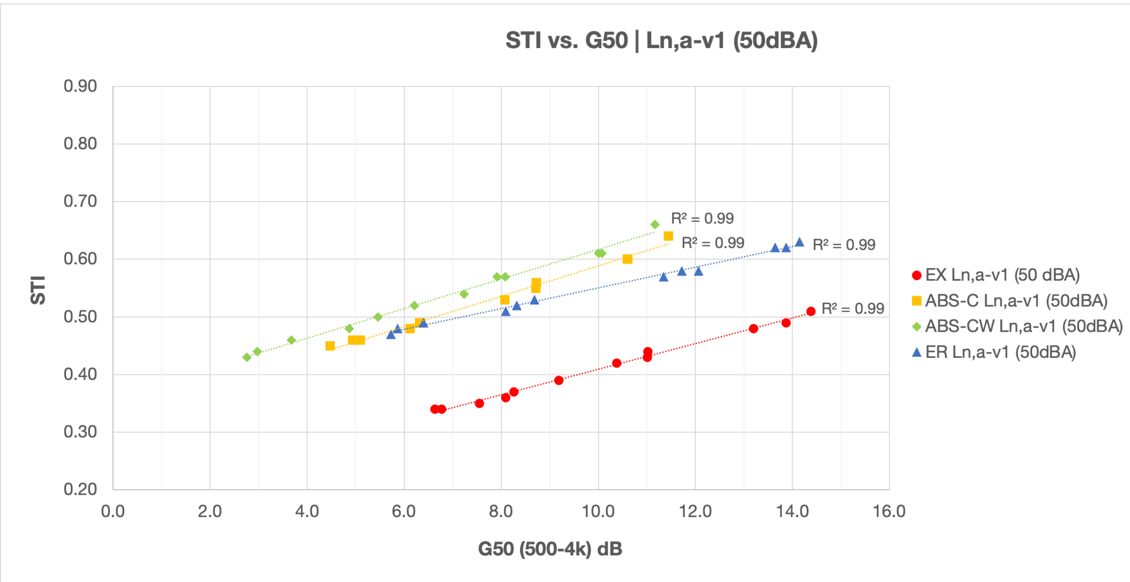


Figure 4.49. STI vs. G_{50} | $L_{n,a\text{-}v1}$

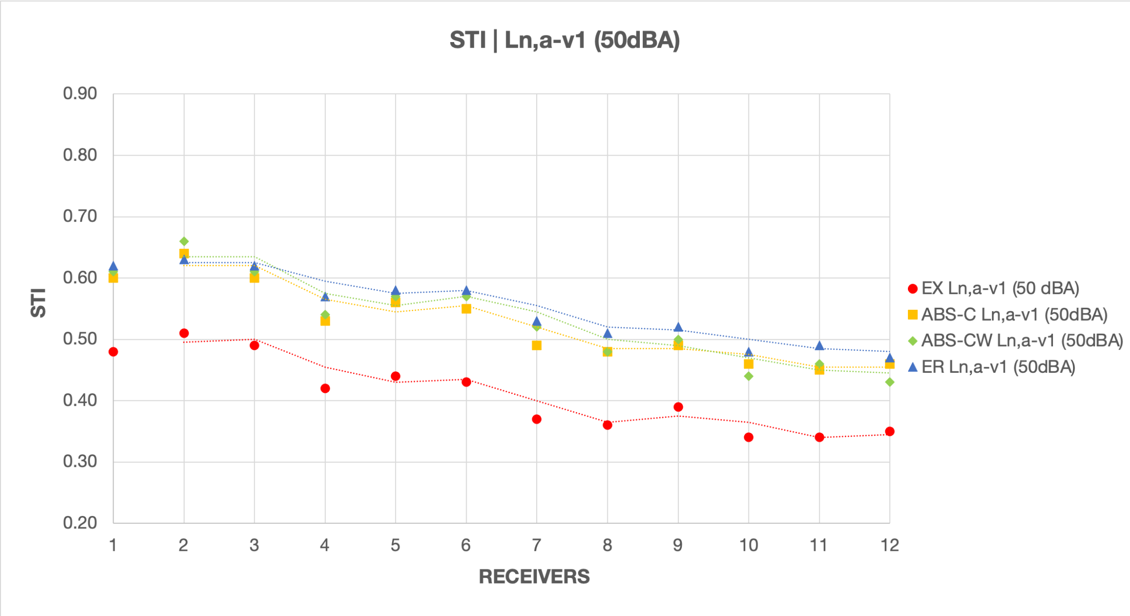


Figure 4.50. STI per Receiver | $L_{n,a\text{-}v1}$

Figure 4.51 and Figure 4.52 display U_{50} versus G_{50} graphs and U_{50} values per receiver, respectively. Both figures agree with the data obtained for STI, as shown in the previous charts, with the difference being that ER provides the highest U_{50} starting from receiver eight instead of the third receiver.

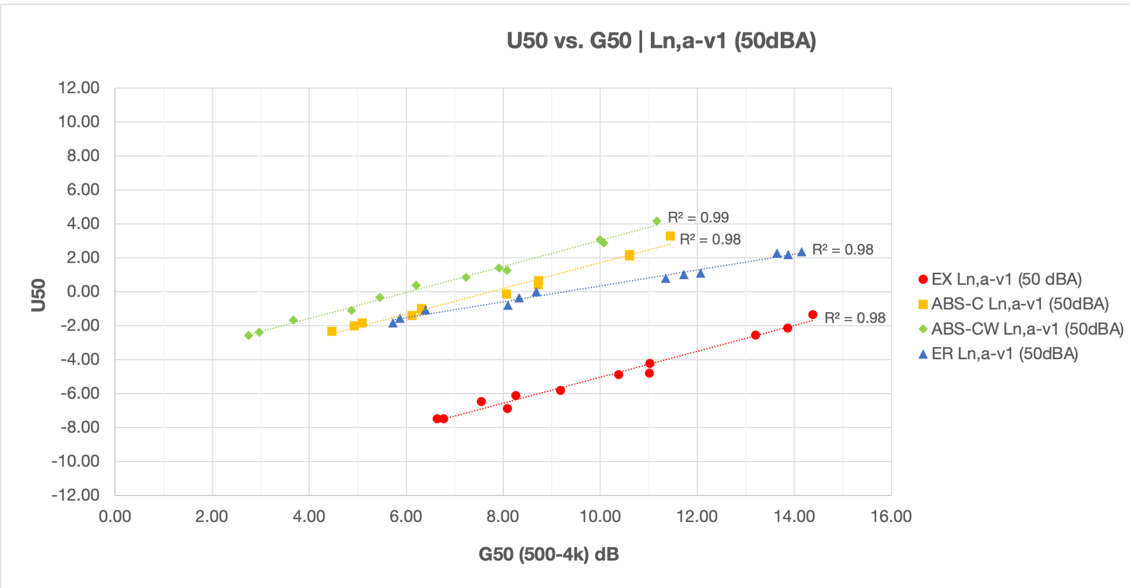


Figure 4.51. U_{50} vs. G_{50} | $L_{n,a\text{-}v1}$

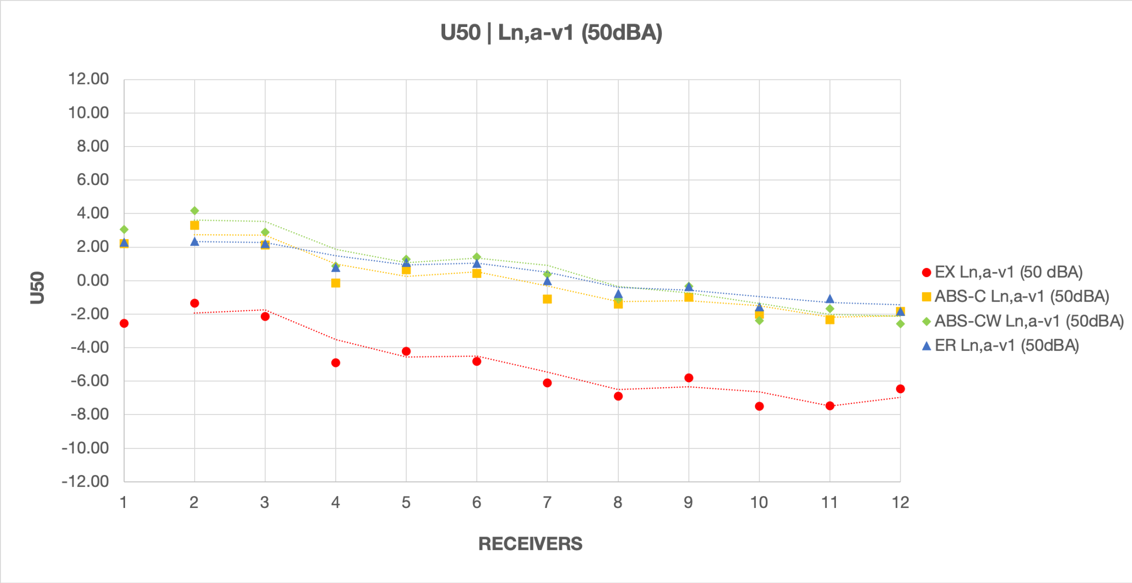


Figure 4.52. U_{50} per Receiver | $L_{n,a\text{-}v1}$

Figure 4.53 displays STI versus G_{50} values of the scenarios for active classroom background noise variation-2, $L_{n,a\text{-}v2}$, which is increased to 55 dBA. Among the other scenarios, ER provides the best STI values for all receiver positions at this background noise level, as seen in Figure 4.54. The coefficient of determination for the trends indicates a strong linear correlation between STI and G_{50} values.

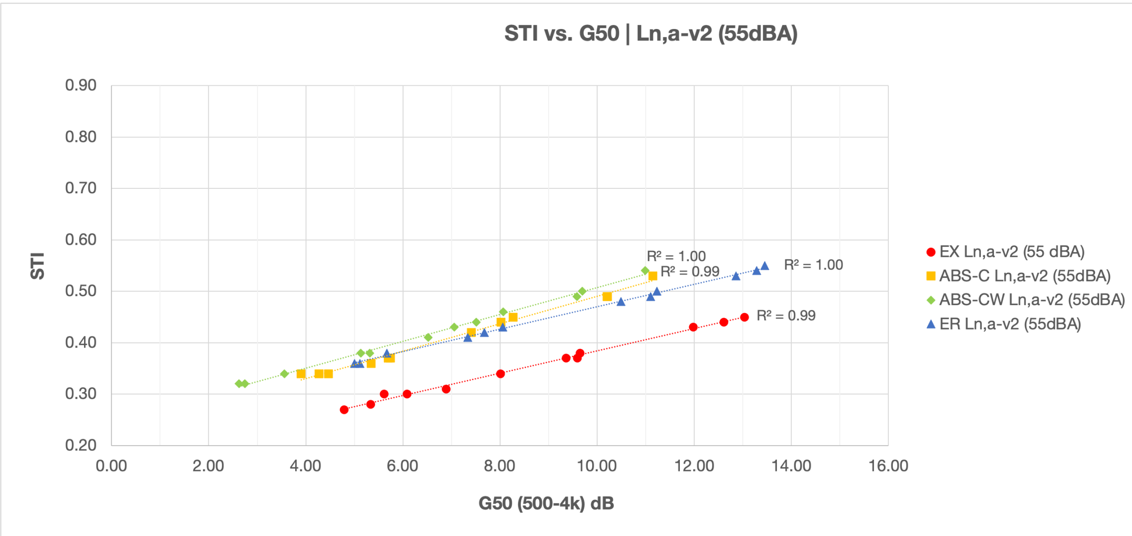


Figure 4.53. STI vs. G_{50} | $L_{n,a\text{-}v2}$

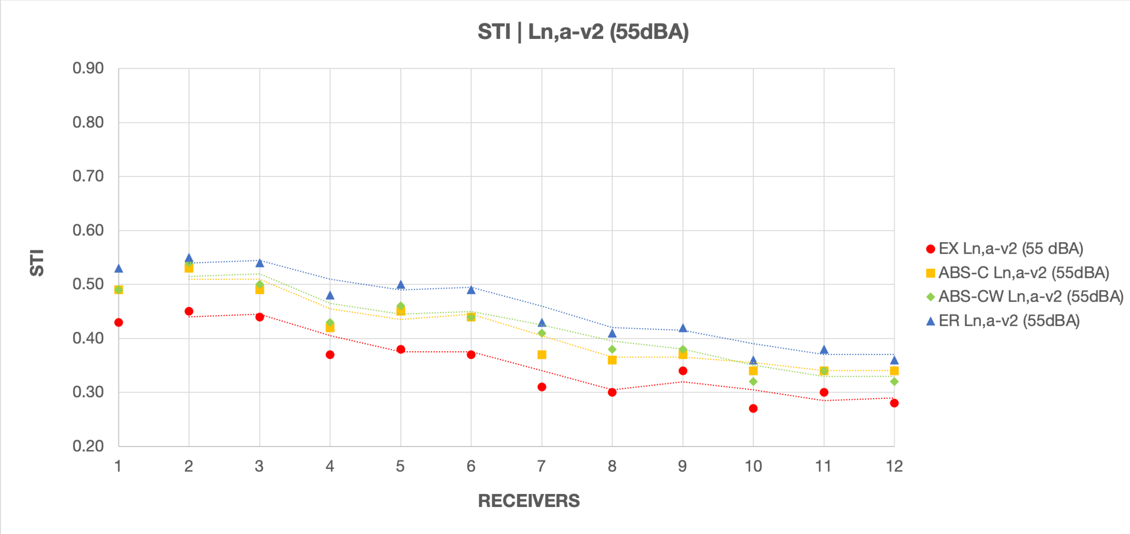


Figure 4.54. STI per Receiver | $L_{n,a\text{-}v2}$

Figure 4.55 displays U_{50} versus G_{50} values of the scenarios for active classroom background noise variation-2, $L_{n,a\text{-}v2}$. The chart shows a strong linear correlation between U_{50} and G_{50} and agrees with the data displayed in Figure 4.53.

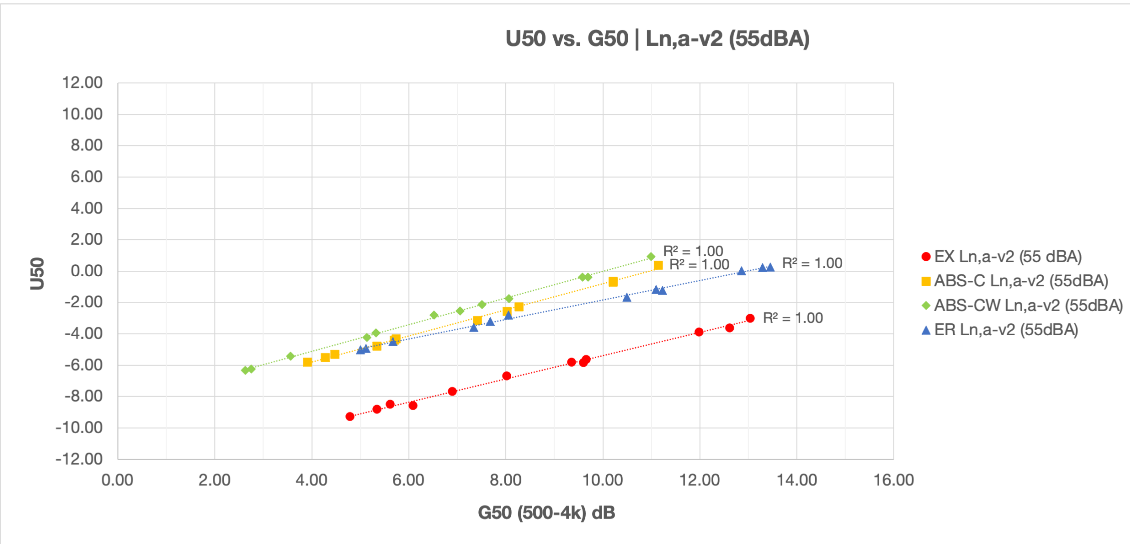


Figure 4.55. U_{50} vs. G_{50} | $L_{n,a\text{-}v2}$

ER provides the best U_{50} values starting from the third receiver, according to Figure 4.56 below.

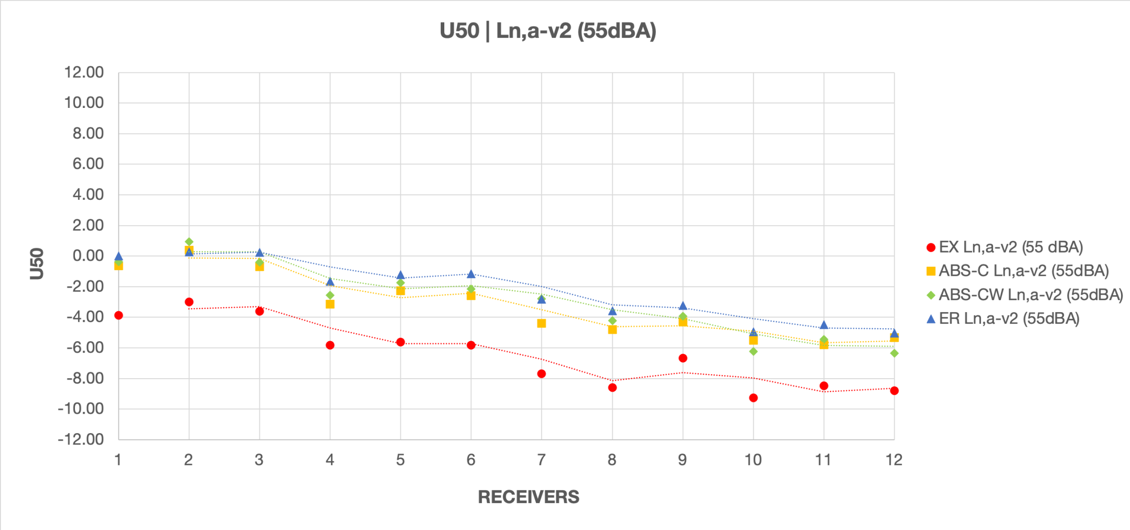


Figure 4.56. U_{50} per Receiver | $L_{n,a\text{-}v2}$

4.6. Listening Tests

Listening tests were conducted with ninety-six volunteers to investigate whether objective data sets obtained from simulated room acoustics design scenarios are subjectively meaningful.

4.6.1. Turkish Monosyllabic Word Recognition Test

For the listening tests, a list of monosyllabic Turkish words was used. The word list and their anechoic audio recordings were specifically developed for the "Turkish Monosyllabic Word Recognition Test, TMWRT" study (Mungan 2010). The list contains monosyllabic Turkish words with a consonant-vowel-consonant (CVC) structure, the most common structure among monosyllabic words in Turkish. The words were selected from a corpus of eight million words based on factors such as frequency of use in everyday language, recognition rates for listeners from diverse cultural backgrounds, phonemic balance, and homogeneity in distinctiveness. According to the related study, lists A, B, and C, each consisting of fifty different words, achieved a one hundred per cent recognition rate (Mungan Durankaya et al. 2014).

The anechoic recordings of that study were borrowed to be used in this study. The RMS level of each recorded word was checked and normalised to -20 dBFS using Audacity 3.0.2 digital audio editor before using them for the auralisation, as seen in Figure 4.57.

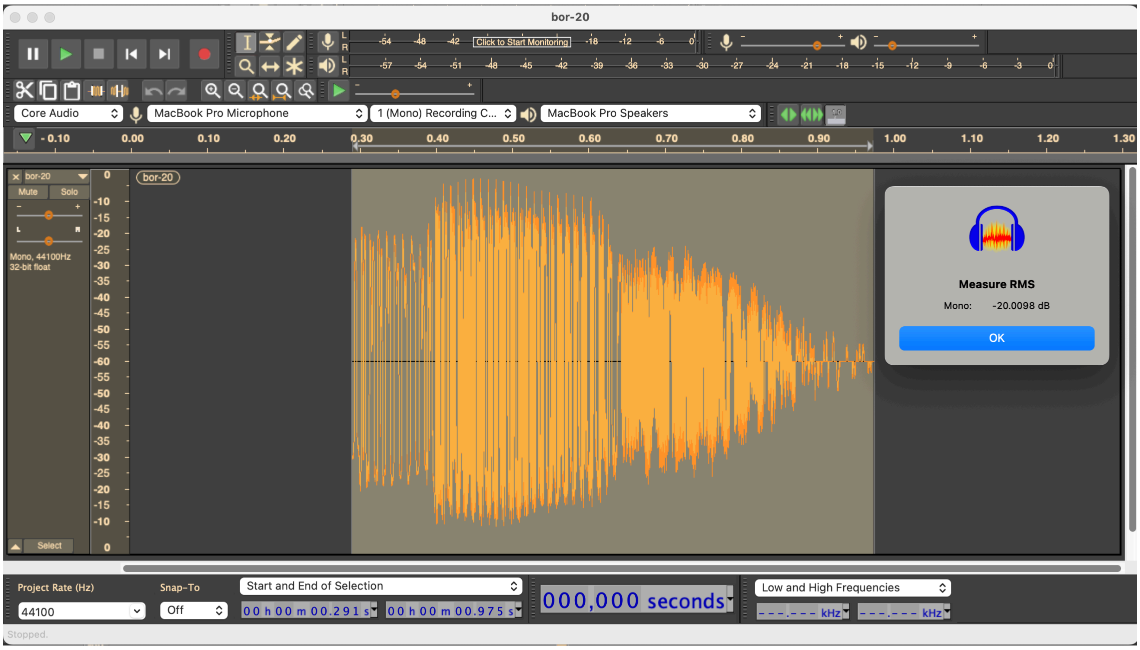


Figure 4.57. Verification of the Normalised RMS Level of a Word from TMWRT

4.6.2. Auralisation Process

The anechoic recordings were auralised using CATT GratisVolver Pro v2.0d with the impulse responses obtained from simulation scenarios described in section 4.5. Before auralisation, each list was sorted randomly to prevent anticipation through recognition of the word order. The impulse responses selected for the auralisation belong to receivers R10, R11, and R12, representing the students at the back of the classroom. These positions are disadvantaged regarding speech intelligibility because of the low SNR. If the speech intelligibility in these positions is improved satisfactorily, it will ensure improved speech intelligibility across the rest of the classroom. Figure 4.58 shows the position of the receivers in the classroom.

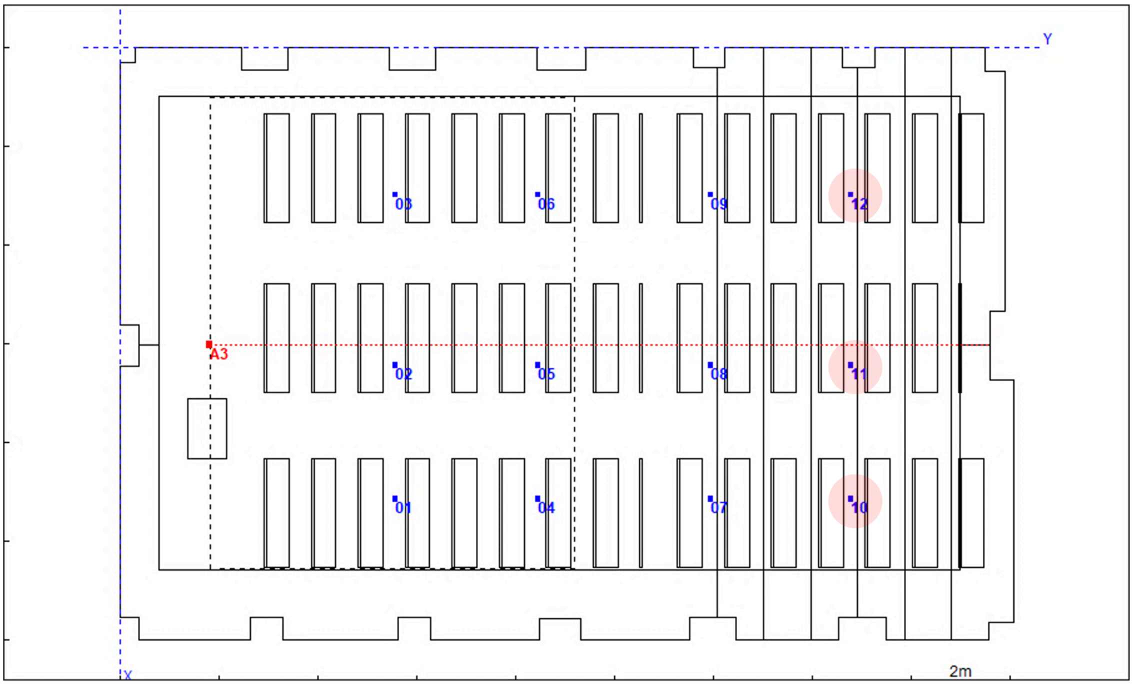


Figure 4.58. Receiver points R10, R11 and R12 in the back group

For auralisation, the impulse response for each receiver point must be exported as a calibrated WAV file to reflect the relative level at the receiver location. Each impulse response was exported in 32-bit PCM WAV format using CATT TUCT v2.0g to achieve this. The impulse response exported as 32-bit WAV files includes the relative calibration information. To have the level dependent on the receivers' location in the auralisation process, calibration was applied based on the auralisation level at the nearest receiver point. The first step was to carry out the auralisation process for location R02, closest to the speaker. This level was used as a reference for calibrating the auralisation of other receivers: R10, R11, and R12. This ensured that the auralised levels of the back receivers were calibrated according to the level of the receiver location in the front of the classroom.

Auralised audio files were created for the receiver points R10, R11, and R12 for the EX, ABS-C, ABS-CW, and ER scenarios using lists A, B, and C of the Turkish Monosyllabic Word Recognition Test.

Thirty-six audio files were generated at the end of the auralisation process. Furthermore, seventy-two combinations were obtained using two background noise levels representing unoccupied ($L_{n,u}$) and active ($L_{n,a}$) classrooms. The diagram in Figure 4.59 shows the procedure for generating the listening test audio material.

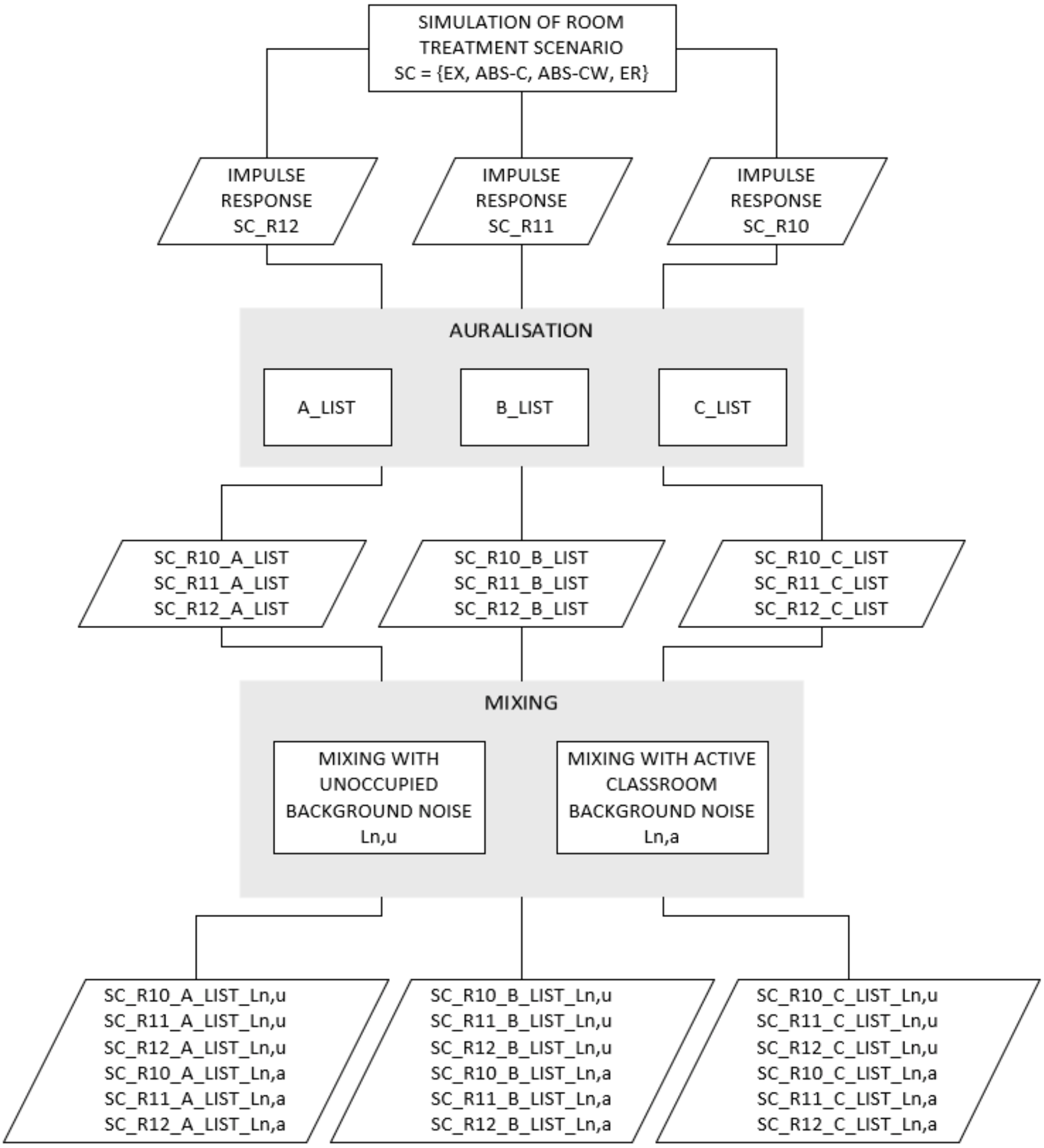


Figure 4.59. The Procedure of Generating the Listening Test Audio

4.6.3. Mixing Background Noise with Auralised Word Lists

During binaural listening tests, pink noise was utilised to simulate background noise and to achieve varying signal-to-noise ratios. Initially, pink noise was shaped spectrally based on the frequency range of the ambient noise measured in the active classrooms, given in Table 4.13.

A specific procedure was devised to shape the pink noise according to the activity noise spectrum. Initially, the pink noise signal was imported into Audacity. It was then divided into one-octave bands, with each octave band being assigned to a separate track. Any bands that did not fall within the 125Hz-4000Hz octave bands were removed, as illustrated in Figure 4.60. In the last step, the RMS level of each octave band was adjusted based on the active classroom's background noise displayed in Table 4.13.

Table 4.19 shows the relative levels obtained by normalising the spectrum according to Table 4.13 to produce an A-weighted level of 0.0 dB. The RMS level of each octave band of the pink noise signal was adjusted according to Table 4.19, and the signal was mixed down.

Table 4.19. Active classroom background noise spectrum

f (Hz)	125	250	500	1000	2000	4000	A-weighted
La,n Ref. Level	1.2	-1.2	-3.9	-7.2	-9.4	-5.8	0.0

Figure 4.60 illustrates modified pink noise representing active classroom background noise.

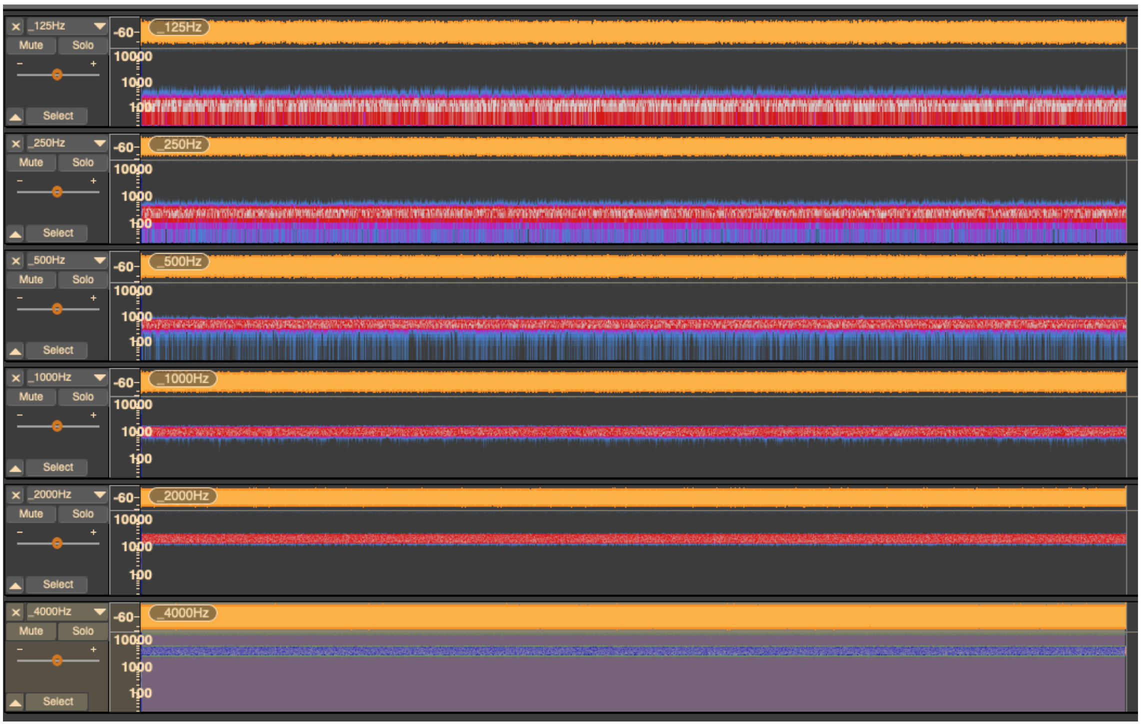


Figure 4.60. Decomposed and shaped pink noise

The auralised word recordings were placed as separate audio tracks in the digital editor for the listening tests. Two tracks for $L_{n,u}$ (unoccupied background noise) and $L_{n,a}$ (occupied background noise) were added below the auralised word tracks. At this stage, checking the RMS levels of auralised word lists and the background noise is essential since the auralisation process changed the RMS levels initially adjusted for the anechoic recordings. The goal is to maintain the level difference between the speech signal and the background noise level. The levels of two background noises, Ln,u and Ln,a, are known. The speech signal level for the receivers R10, R11 and R12 was obtained from the simulations of the respective scenarios. The table displays the resulting speech levels for the R10, R11 and R12 locations for a speaking level of 70dBA level 1 meter away from the speaker according to Annex J.3 of IEC 60268-16 2011.

Table 4.20. Speech Levels at the Receivers R10, R11 and R12

SCENARIO	RECEIVERS	SPEECH LEVEL SPL dBA	SCENARIO AVERAGE SPL dBA	SPL - $L_{n,u}$ dBA	SPL - $L_{n,a}$ dBA
EX	R10	64	64	34	20
	R11	64			
	R12	64			
ABS-C	R10	58	58	28	15
	R11	58			
	R12	59			
ABS-CW	R10	56	56	26	13
	R11	57			
	R12	56			
ER	R10	59	59	29	15
	R11	59			
	R12	59			

The two left columns indicate the level difference between speech signal and background noise for each scenario. This level difference (SNR) was achieved by digitally manipulating the RMS level of the speech and noise signals, respectively. The RMS levels of two signals, speech as foreground and noise as background, were measured and modified using the "Contrast Analysis" function to produce the level difference. The upper track in Figure 4.61 contains the auralised word recording, while the lower track contains the modified pink noise as background noise. The SNR was digitally adjusted via the RMS levels of the background noise with respect to the foreground signal level, as shown in Figure 4.61.

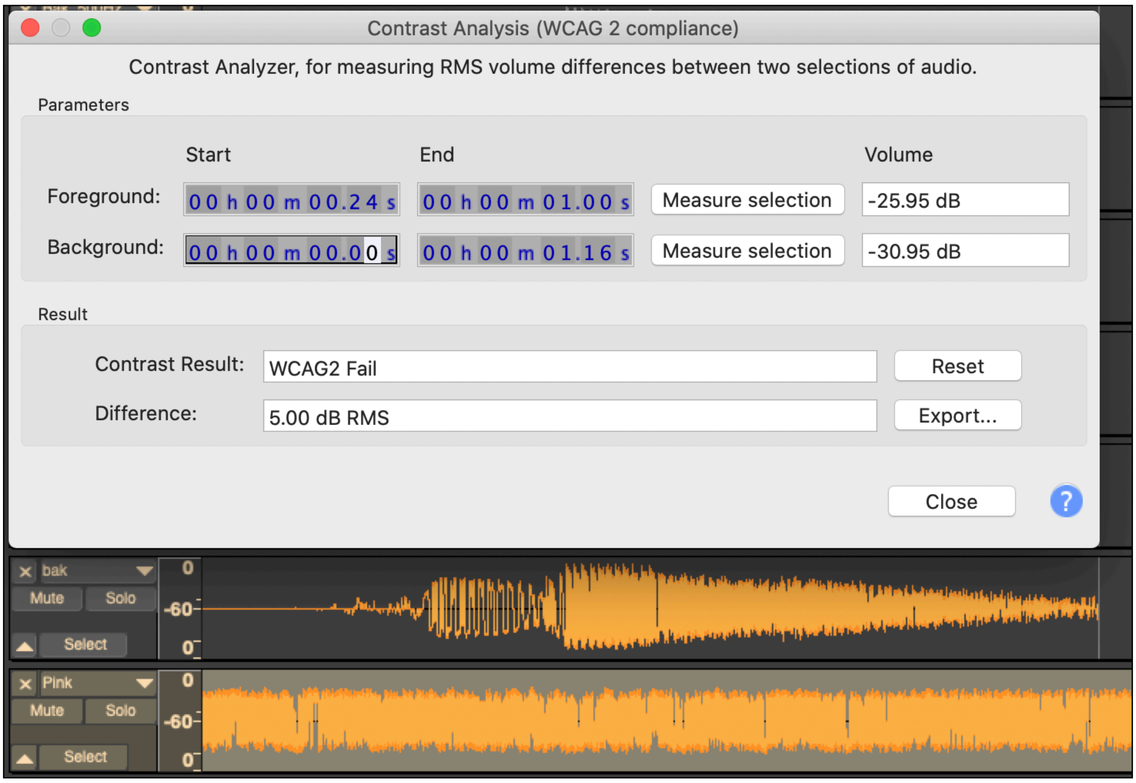


Figure 4.61. Adjustment of SNR via RMS level of the background noise

The process was repeated for each room acoustics design scenario and each A, B, and C-word list, resulting in 12 sets. The figure below presents the set for the ABS-C scenario.

Table 4.21 displays the list of the listening test audio material produced by the mixing process following the auralisation, as illustrated in Figure 4.59.

Table 4.21 The List of Generated Audio for the Listening Tests

SCENARIO	REC.	TMWRT LIST	AURALISED AUDIO FILE	BG. NOISE	LISTENING TEST COMBINATION	# OF COMB.
EX	R10	A_LIST	EX_R10_A_LIST	$L_{n,u}$	EX_R10_A_LIST_Ln,u	1
				$L_{n,a}$	EX_R10_A_LIST_Ln,a	2
		B_LIST	EX_R10_B_LIST	$L_{n,u}$	EX_R10_B_LIST_Ln,u	3
				$L_{n,a}$	EX_R10_B_LIST_Ln,a	4
		C_LIST	EX_R10_C_LIST	$L_{n,u}$	EX_R10_C_LIST_Ln,u	5
				$L_{n,a}$	EX_R10_C_LIST_Ln,a	6
	R11	A_LIST	EX_R11_A_LIST	$L_{n,u}$	EX_R11_A_LIST_Ln,u	7
				$L_{n,a}$	EX_R11_A_LIST_Ln,a	8
		B_LIST	EX_R11_B_LIST	$L_{n,u}$	EX_R11_B_LIST_Ln,u	9
				$L_{n,a}$	EX_R11_B_LIST_Ln,a	10
		C_LIST	EX_R11_C_LIST	$L_{n,u}$	EX_R11_C_LIST_Ln,u	11
				$L_{n,a}$	EX_R11_C_LIST_Ln,a	12
	R12	A_LIST	EX_R12_A_LIST	$L_{n,u}$	EX_R12_A_LIST_Ln,u	13
				$L_{n,a}$	EX_R12_A_LIST_Ln,a	14
		B_LIST	EX_R12_B_LIST	$L_{n,u}$	EX_R12_B_LIST_Ln,u	15
				$L_{n,a}$	EX_R12_B_LIST_Ln,a	16
		C_LIST	EX_R12_C_LIST	$L_{n,u}$	EX_R12_C_LIST_Ln,u	17
				$L_{n,a}$	EX_R12_C_LIST_Ln,a	18
ABS-C	R10	A_LIST	ABS-C_R10_A_LIST	$L_{n,u}$	ABS-C_R10_A_LIST_Ln,u	19
				$L_{n,a}$	ABS-C_R10_A_LIST_Ln,a	20
		B_LIST	ABS-C_R10_B_LIST	$L_{n,u}$	ABS-C_R10_B_LIST_Ln,u	21
				$L_{n,a}$	ABS-C_R10_B_LIST_Ln,a	22
		C_LIST	ABS-C_R10_C_LIST	$L_{n,u}$	ABS-C_R10_C_LIST_Ln,u	23
				$L_{n,a}$	ABS-C_R10_C_LIST_Ln,a	24
	R11	A_LIST	ABS-C_R11_A_LIST	$L_{n,u}$	ABS-C_R11_A_LIST_Ln,u	25
				$L_{n,a}$	ABS-C_R11_A_LIST_Ln,a	26
		B_LIST	ABS-C_R11_B_LIST	$L_{n,u}$	ABS-C_R11_B_LIST_Ln,u	27
				$L_{n,a}$	ABS-C_R11_B_LIST_Ln,a	28
		C_LIST	ABS-C_R11_C_LIST	$L_{n,u}$	ABS-C_R11_C_LIST_Ln,u	29
				$L_{n,a}$	ABS-C_R11_C_LIST_Ln,a	30
	R12	A_LIST	ABS-C_R12_A_LIST	$L_{n,u}$	ABS-C_R12_A_LIST_Ln,u	31
				$L_{n,a}$	ABS-C_R12_A_LIST_Ln,a	32
		B_LIST	ABS-C_R12_B_LIST	$L_{n,u}$	ABS-C_R12_B_LIST_Ln,u	33
				$L_{n,a}$	ABS-C_R12_B_LIST_Ln,a	34
		C_LIST	ABS-C_R12_C_LIST	$L_{n,u}$	ABS-C_R12_C_LIST_Ln,u	35
				$L_{n,a}$	ABS-C_R12_C_LIST_Ln,a	36

(cont. on next page)

Table 4.21 (cont.)

SCENARIO	REC.	TMWRT LIST	AURALISED AUDIO FILE	BG. NOISE	LISTENING TEST COMBINATION	# OF COMB.
ABS-CW	R10	A_LIST	ABS-CW_R10_A_LIST	$L_{n,u}$	ABS-CW_R10_A_LIST_Ln,u	37
				$L_{n,a}$	ABS-CW_R10_A_LIST_Ln,a	38
		B_LIST	ABS-CW_R10_B_LIST	$L_{n,u}$	ABS-CW_R10_B_LIST_Ln,u	39
				$L_{n,a}$	ABS-CW_R10_B_LIST_Ln,a	40
		C_LIST	ABS-CW_R10_C_LIST	$L_{n,u}$	ABS-CW_R10_C_LIST_Ln,u	41
				$L_{n,a}$	ABS-CW_R10_C_LIST_Ln,a	42
	R11	A_LIST	ABS-CW_R11_A_LIST	$L_{n,u}$	ABS-CW_R11_A_LIST_Ln,u	43
				$L_{n,a}$	ABS-CW_R11_A_LIST_Ln,a	44
		B_LIST	ABS-CW_R11_B_LIST	$L_{n,u}$	ABS-CW_R11_B_LIST_Ln,u	45
				$L_{n,a}$	ABS-CW_R11_B_LIST_Ln,a	46
		C_LIST	ABS-CW_R11_C_LIST	$L_{n,u}$	ABS-CW_R11_C_LIST_Ln,u	47
				$L_{n,a}$	ABS-CW_R11_C_LIST_Ln,a	48
	R12	A_LIST	ABS-CW_R12_A_LIST	$L_{n,u}$	ABS-CW_R12_A_LIST_Ln,u	49
				$L_{n,a}$	ABS-CW_R12_A_LIST_Ln,a	50
		B_LIST	ABS-CW_R12_B_LIST	$L_{n,u}$	ABS-CW_R12_B_LIST_Ln,u	51
				$L_{n,a}$	ABS-CW_R12_B_LIST_Ln,a	52
		C_LIST	ABS-CW_R12_C_LIST	$L_{n,u}$	ABS-CW_R12_C_LIST_Ln,u	53
				$L_{n,a}$	ABS-CW_R12_C_LIST_Ln,a	54
ER	R10	A_LIST	ER_R10_A_LIST	$L_{n,u}$	ER_R10_A_LIST_Ln,u	55
				$L_{n,a}$	ER_R10_A_LIST_Ln,a	56
		B_LIST	ER_R10_B_LIST	$L_{n,u}$	ER_R10_B_LIST_Ln,u	57
				$L_{n,a}$	ER_R10_B_LIST_Ln,a	58
		C_LIST	ER_R10_C_LIST	$L_{n,u}$	ER_R10_C_LIST_Ln,u	59
				$L_{n,a}$	ER_R10_C_LIST_Ln,a	60
	R11	A_LIST	ER_R11_A_LIST	$L_{n,u}$	ER_R11_A_LIST_Ln,u	61
				$L_{n,a}$	ER_R11_A_LIST_Ln,a	62
		B_LIST	ER_R11_B_LIST	$L_{n,u}$	ER_R11_B_LIST_Ln,u	63
				$L_{n,a}$	ER_R11_B_LIST_Ln,a	64
		C_LIST	ER_R11_C_LIST	$L_{n,u}$	ER_R11_C_LIST_Ln,u	65
				$L_{n,a}$	ER_R11_C_LIST_Ln,a	66
	R12	A_LIST	ER_R12_A_LIST	$L_{n,u}$	ER_R12_A_LIST_Ln,u	67
				$L_{n,a}$	ER_R12_A_LIST_Ln,a	68
		B_LIST	ER_R12_B_LIST	$L_{n,u}$	ER_R12_B_LIST_Ln,u	69
				$L_{n,a}$	ER_R12_B_LIST_Ln,a	70
		C_LIST	ER_R12_C_LIST	$L_{n,u}$	ER_R12_C_LIST_Ln,u	71
				Ln,a	ER_R12_C_LIST_Ln,a	72

Figure 4.62 shows the listening test set order for the ABS-C scenario in Audacity 3.0.2. The list and receiver combination is represented by tracks arranged from the top as A_ListxR10, B_ListxR11, and C_ListxR12. The last two tracks at the bottom

are for noise, which includes unoccupied noise (Ln,u) and active class noise (Ln,a). This is the order for the first round. Each track can be turned on and off independently, allowing the playing of specific lists and background noise combinations.

For the second round, the order is B_ListxR10, C_ListxR11, and A_ListxR12. For the third round, the order is C_ListxR10, A_ListxR11, and B_ListxR12. The orders for the first, second and third rounds were repeated for each room acoustics design scenario.

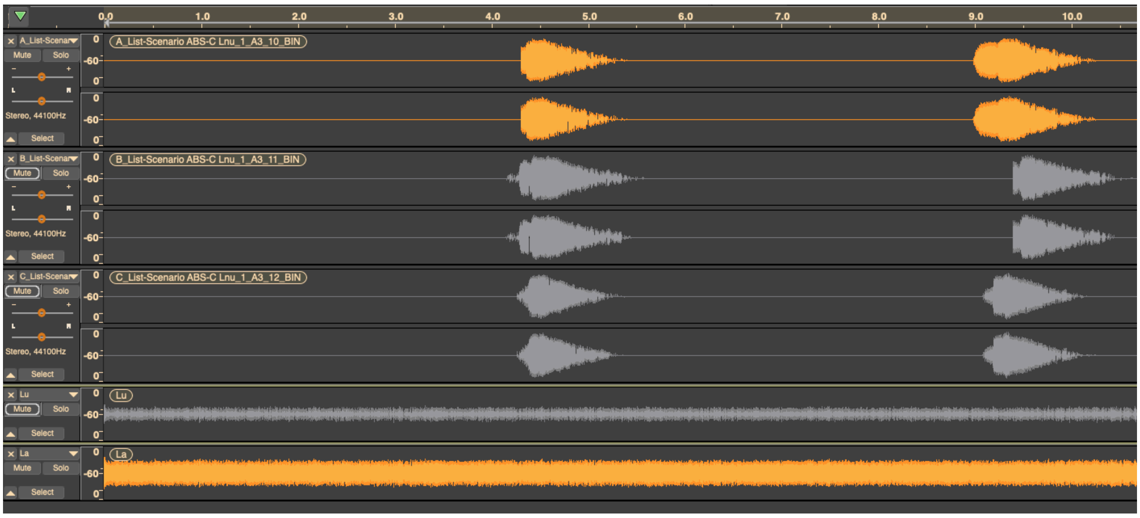


Figure 4.62 Listening Test Set for Scenario ABS-C Round-1

4.6.4. Listening Test Procedure

Each volunteer was asked to listen to the auralisation of a single scenario combined with one background noise. This means every listener had to listen to three receiver positions: R10, R11, and R12. This test flow is the equivalent of the listener entering the classroom and sitting in positions R10, R11 and R12 successively. In this flow, where the same listener evaluates different listening positions in the same room scenario, another word list was assigned to each of the three listener locations to assess the listener locations with different non-repeating words. Furthermore, each volunteer participated in a specific listening session only once. No volunteer participated in any listening session for a second time. In each round, all room scenarios in combination with two background noise levels were covered. In order to avoid the speech recognition scores being biased by a specific word list, the word lists were rotated between the receiver locations in each round to provide all possible combinations. The diagram in Figure 4.63 shows the listening test procedure for three rounds of listening tests.

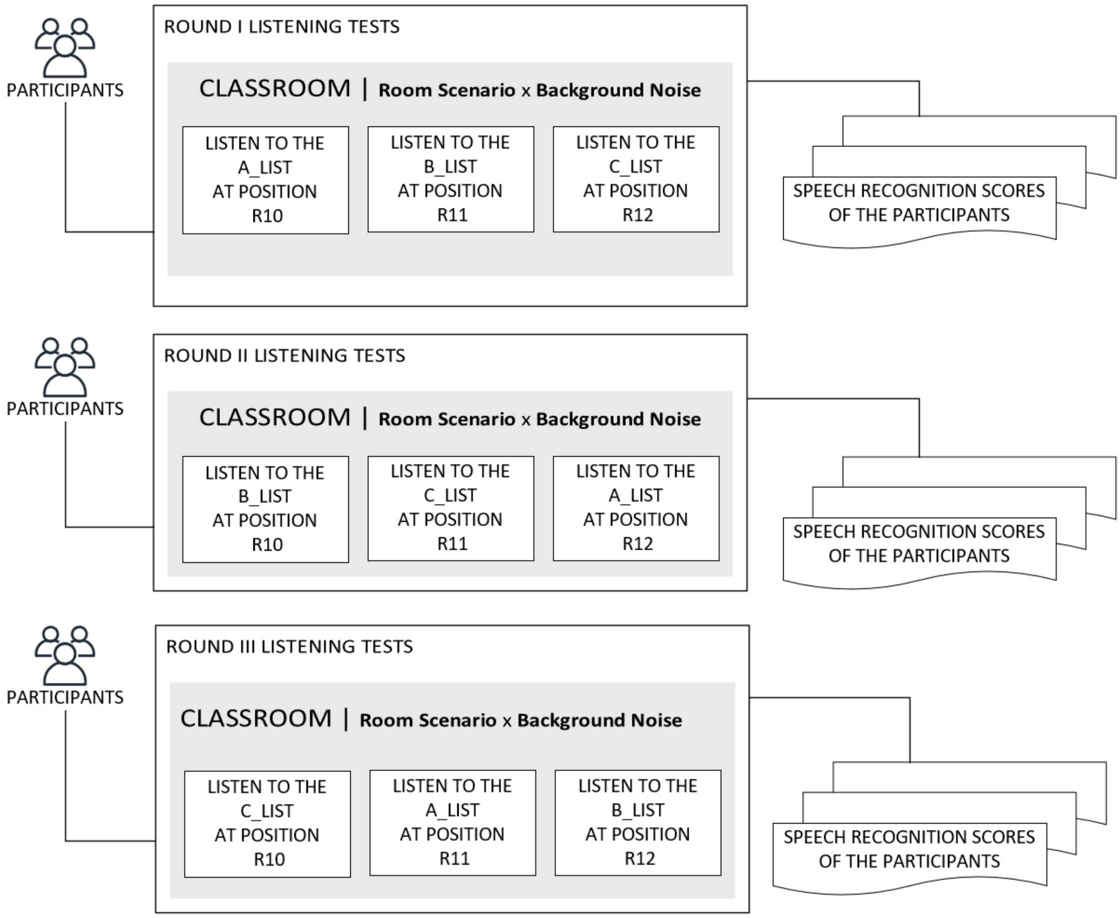


Figure 4.63. Test Procedure Diagram

The table below shows the listening session sets. Each set contains a specific room scenario, word list, receiver location and background noise combination. Every set was presented to four participants in each round. At the end of the third round, every set was listened to by twelve participants, including all possible receiver location and word list combinations.

Table 4.22. Listening Test Combinations

ROUND I LISTENING TEST COMBINATION	ROUND II LISTENING TEST COMBINATION	ROUND III LISTENING TEST COMBINATION
EX_R10_A_LIST_Ln,u EX_R11_B_LIST_Ln,u EX_R12_C_LIST_Ln,u	EX_R10_B_LIST_Ln,u EX_R11_C_LIST_Ln,u EX_R12_A_LIST_Ln,u	EX_R10_C_LIST_Ln,u EX_R11_A_LIST_Ln,u EX_R12_B_LIST_Ln,u
EX_R10_A_LIST_Ln,a EX_R11_B_LIST_Ln,a EX_R12_C_LIST_Ln,a	EX_R10_B_LIST_Ln,a EX_R11_C_LIST_Ln,a EX_R12_A_LIST_Ln,a	EX_R10_C_LIST_Ln,a EX_R11_A_LIST_Ln,a EX_R12_B_LIST_Ln,a
ABS-C_R10_A_LIST_Ln,u ABS-C_R11_B_LIST_Ln,u ABS-C_R12_C_LIST_Ln,u	ABS-C_R10_B_LIST_Ln,u ABS-C_R11_C_LIST_Ln,u ABS-C_R12_A_LIST_Ln,u	ABS-C_R10_C_LIST_Ln,u ABS-C_R11_A_LIST_Ln,u ABS-C_R12_B_LIST_Ln,u
ABS-C_R10_A_LIST_Ln,a ABS-C_R11_B_LIST_Ln,a ABS-C_R12_C_LIST_Ln,a	ABS-C_R10_B_LIST_Ln,a ABS-C_R11_C_LIST_Ln,a ABS-C_R12_A_LIST_Ln,a	ABS-C_R10_C_LIST_Ln,a ABS-C_R11_A_LIST_Ln,a ABS-C_R12_B_LIST_Ln,a
ABS-CW_R10_A_LIST_Ln,u ABS-CW_R11_B_LIST_Ln,u ABS-CW_R12_C_LIST_Ln,u	ABS-CW_R10_B_LIST_Ln,u ABS-CW_R11_C_LIST_Ln,u ABS-CW_R12_A_LIST_Ln,u	ABS-CW_R10_C_LIST_Ln,u ABS-CW_R11_A_LIST_Ln,u ABS-CW_R12_B_LIST_Ln,u
ABS-CW_R10_A_LIST_Ln,a ABS-CW_R11_B_LIST_Ln,a ABS-CW_R12_C_LIST_Ln,a	ABS-CW_R10_B_LIST_Ln,a ABS-CW_R11_C_LIST_Ln,a ABS-CW_R12_A_LIST_Ln,a	ABS-CW_R10_C_LIST_Ln,a ABS-CW_R11_A_LIST_Ln,a ABS-CW_R12_B_LIST_Ln,a
ER_R10_A_LIST_Ln,u ER_R11_B_LIST_Ln,u ER_R12_C_LIST_Ln,u	ER_R10_B_LIST_Ln,u ER_R11_C_LIST_Ln,u ER_R12_A_LIST_Ln,u	ER_R10_C_LIST_Ln,u ER_R11_A_LIST_Ln,u ER_R12_B_LIST_Ln,u
ER_R10_A_LIST_Ln,a ER_R11_B_LIST_Ln,a ER_R12_C_LIST_Ln,a	ER_R10_B_LIST_Ln,a ER_R11_C_LIST_Ln,a ER_R12_A_LIST_Ln,a	ER_R10_C_LIST_Ln,a ER_R11_A_LIST_Ln,a ER_R12_B_LIST_Ln,a

For a specific scenario combined with a particular background noise level, a volunteer listened to R10xA_List, R11xB_List, and R12xC_List in the first round of listening tests. In the second round, the same volunteer listened to R10xB_List, R11xC_List, and R12xA_List for the same scenario and background noise combination. In the third round, keeping the same scenario and background noise combination, each volunteer listened to R10xC_List, R11xA_List, and R12xB_List.

4.6.5. Listening Test Setup

Three receiver positions, R10, R11, and R12, representing the group of students sitting in the back of the classroom, were chosen. Audio files were obtained by auralisation of TMWRT words using three impulse responses for each location from the scenarios described in section 4.5. A second set of audio files was obtained by mixing the audio files with background noise representing the noise in the active classrooms. Each file was used in listening tests for speech recognition and was scored by the participants. The audio files were played via the digital audio editor Audacity running on a PC. The participants listened to the audio using AKG K72 closed-back headphones. To check the hearing level of the participants, a pure tone audio having an RMS level of -10 dB lower than the listening test audio was played to the participants at the beginning of the test. The participants who did not pass hearing all the test signals were excluded. The listening tests were conducted in the Building Physics Laboratory at the Department of Architecture at Izmir Institute of Technology.

Figure 4.64. A Photograph from a Binaural Listening Test Session

4.6.6. Collection Of The Listening Test Data

A spreadsheet was used to collect data during the test sessions. The participants repeated what they heard during the binaural listening while the researcher entered their replies as the test progressed. The figure shows a sample speech recognition test sheet.

Table 4.23. Speech Recognition Test Sheet

SPEECH RECOGNITION TEST SHEET	TEST SCENARIO	ER Ln,a	HEARING TEST	
"Turkish Monosyllabic Word Recognition Test"	TEST ROUND	3	250	PASS
	TEST DATE	29.11.2023	500	PASS
	TEST TIME	21:00	1000	PASS
	PARTICIPANT'S NAME	E***M	2000	PASS
	AGE	20	4000	PASS
	HEARING TEST	NORMAL	8000	PASS

TMWRT A_LIST			R11	TMWRT B_LIST			R12	TMWRT C_LIST			R10
#	WORD	ANS.	SCORE	#	WORD	ANS.	SCORE	#	WORD	ANS.	SCORE
1	**tan**	tan	TRUE	1	**boy**	boy	TRUE	1	**hep**	hep	TRUE
2	**sel**	sel	TRUE	2	**tur**	tur	TRUE	2	**hız**	hız	TRUE
3	**çam**	çam	TRUE	3	**han**	han	TRUE	3	**kek**	kek	TRUE
4	**dik**	dik	TRUE	4	**kap**	kap	TRUE	4	**yel**	yer	FALSE
5	**göç**	göç	TRUE	5	**sat**	sat	TRUE	5	**del**	del	TRUE
6	**şah**	şah	TRUE	6	**mil**	mil	TRUE	6	**gör**	gör	TRUE
7	**nar**	nar	TRUE	7	**gök**	gök	TRUE	7	**fay**	fay	TRUE
8	**buz**	buz	TRUE	8	**bez**	bez	TRUE	8	**nem**	nem	TRUE
9	**ver**	ver	TRUE	9	**nur**	nur	TRUE	9	**kar**	kar	TRUE
10	**yer**	yer	TRUE	10	**yat**	yat	TRUE	10	**beş**	beş	TRUE
11	**set**	set	TRUE	11	**dam**	dam	TRUE	11	**dur**	dur	TRUE
12	**baş**	baş	TRUE	12	**kin**	kin	TRUE	12	**sap**	sap	TRUE
13	**yay**	yay	TRUE	13	**diz**	diz	TRUE	13	**ray**	ray	TRUE
14	**kır**	kır	TRUE	14	**kat**	kat	TRUE	14	**gel**	gel	TRUE
15	**bal**	bal	TRUE	15	**bir**	bir	TRUE	15	**bar**	bar	TRUE
16	**tel**	tel	TRUE	16	**gez**	gez	TRUE	16	**bay**	bay	TRUE
17	**bor**	bor	TRUE	17	**tek**	tek	TRUE	17	**dök**	dök	TRUE
18	**kum**	kum	TRUE	18	**pes**	tez	FALSE	18	**sun**	sun	TRUE
19	**mum**	mu	TRUE	19	**ben**	ben	TRUE	19	**bin**	bin	TRUE
20	**mal**	mal	TRUE	20	**dön**	dön	TRUE	20	**yan**	yan	TRUE
21	**bak**	bak	TRUE	21	**kül**	kül	TRUE	21	**sağ**	sar	FALSE
22	**sor**	sor	TRUE	22	**bağ**	bağ	TRUE	22	**yok**	yok	TRUE
23	**giy**	giy	TRUE	23	**fes**	fes	TRUE	23	**vah**	vah	TRUE
24	**dağ**	dar	FALSE	24	**hür**	hür	TRUE	24	**bol**	bol	TRUE
25	**bit**	bit	TRUE	25	**kem**	kem	TRUE	25	**ten**	ten	TRUE
26	**biz**	biz	TRUE	26	**çay**	çay	TRUE	26	**mis**	mis	TRUE
27	**küp**	küp	TRUE	27	**geç**	geç	TRUE	27	**şov**	şov	TRUE
28	**rey**	rey	TRUE	28	**boş**	boş	TRUE	28	**kes**	kes	TRUE
29	**zor**	zor	TRUE	29	**ruh**	ruh	TRUE	29	**küt**	küt	TRUE
30	**pis**	pis	TRUE	30	**sev**	sev	TRUE	30	**çat**	çat	TRUE
31	**kas**	kas	TRUE	31	**bey**	bey	TRUE	31	**gir**	gir	TRUE
32	**her**	her	TRUE	32	**dar**	dar	TRUE	32	**tas**	tas	TRUE
33	**çek**	çek	TRUE	33	**vur**	vur	TRUE	33	**güç**	güç	TRUE
34	**doz**	doz	TRUE	34	**can**	can	TRUE	34	**baz**	baz	TRUE
35	**gün**	gün	TRUE	35	**yap**	yap	TRUE	35	**dış**	dış	TRUE
36	**far**	far	TRUE	36	**sar**	sar	TRUE	36	**dem**	dem	TRUE
37	**sır**	sır	TRUE	37	**yem**	yem	TRUE	37	**kir**	kir	TRUE
38	**his**	his	TRUE	38	**diş**	diş	TRUE	38	**sür**	sür	TRUE
39	**yön**	yön	TRUE	39	**zil**	zil	TRUE	39	**yak**	yak	TRUE

(cont. on next page)

Table 4.23 (cont.)

TMWRT A_LIST			R11
#	WORD	ANS.	SCORE
40	**yün**	yün	TRUE
41	**dev**	dev	TRUE
42	**cep**	cep	TRUE
43	**hat**	hat	TRUE
44	**kul**	kul	TRUE
45	**bel**	bel	TRUE
46	**din**	din	TRUE
47	**tak**	tak	TRUE
48	**düş**	düş	TRUE
49	**kan**	kan	TRUE
50	**ger**	ger	TRUE
CUMULATIVE SCORE			49

TMWRT B_LIST			R12
#	WORD	ANS.	SCORE
40	**sık**	sık	TRUE
41	**çık**	çık	TRUE
42	**bil**	bil	TRUE
43	**yar**	yar	TRUE
44	**dal**	dal	TRUE
45	**şen**	şen	TRUE
46	**tür**	tür	TRUE
47	**mor**	mor	TRUE
48	**gül**	gür	FALSE
49	**has**	has	TRUE
50	**kor**	kor	TRUE
CUMULATIVE SCORE			48

TMWRT C_LIST			R10
#	WORD	ANS.	SCORE
40	**ter**	ter	TRUE
41	**çal**	çal	TRUE
42	**hem**	hem	TRUE
43	**boz**	boz	TRUE
44	**pir**	pir	TRUE
45	**cin**	cin	TRUE
46	**bul**	bul	TRUE
47	**zar**	zar	TRUE
48	**mit**	mit	TRUE
49	**dün**	dün	TRUE
50	**kur**	kur	TRUE
CUMULATIVE SCORE			48

4.6.7. Listening Test Results

The results of speech recognition tests (SRT) for each scenario with an unoccupied classroom background noise level ($L_{n,u}$) and active classroom background noise level ($L_{n,a}$) are presented in Figure 4.65. The columns in the graph represent the average scores obtained in three test rounds using three-word lists (A, B, C).

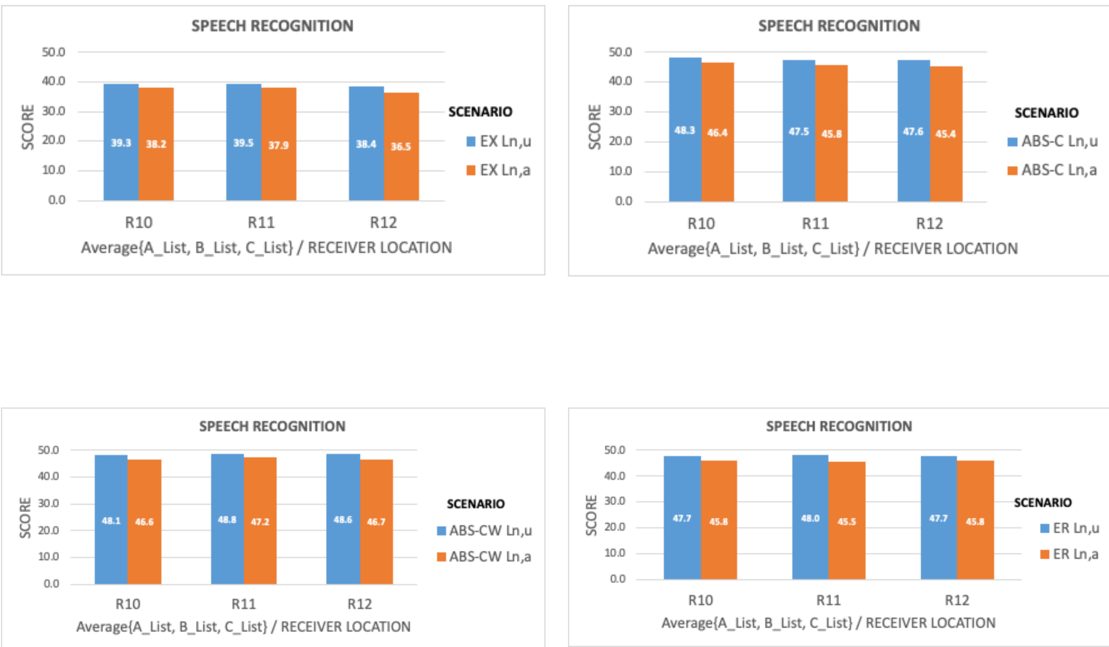
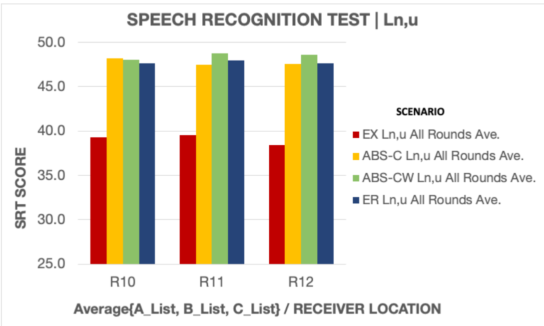


Figure 4.65. SRT Results for Each Scenario

In Figure 4.65, the blue columns on the left show the results of the scenarios with the unoccupied classroom background noise level ($L_{n,u}$), while the red columns on the right show the results with the active classroom background noise level ($L_{n,a}$).

Figure 4.66 displays the speech recognition test (SRT) scores for each scenario per receiver position. The chart on the left shows the SRT scores with unoccupied background noise; the chart on the right shows the scores for the scenarios with active classroom background noise. The columns in the charts represent the average scores obtained in three test rounds using three-word lists (A, B, C). The SRT results indicate that all room acoustics design scenarios have significantly improved speech intelligibility, as the simulation results show. In contrast to the significant difference in the values of speech intelligibility metrics STI and U_{50} obtained from the simulation scenarios, the difference in the SRT scores is closer than the simulated results.



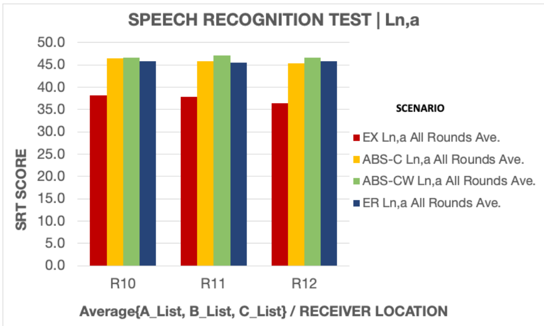


Figure 4.66. SRT Scores according to Background Noise Levels $L_{n,u}$ and $L_{n,a}$

CHAPTER 5

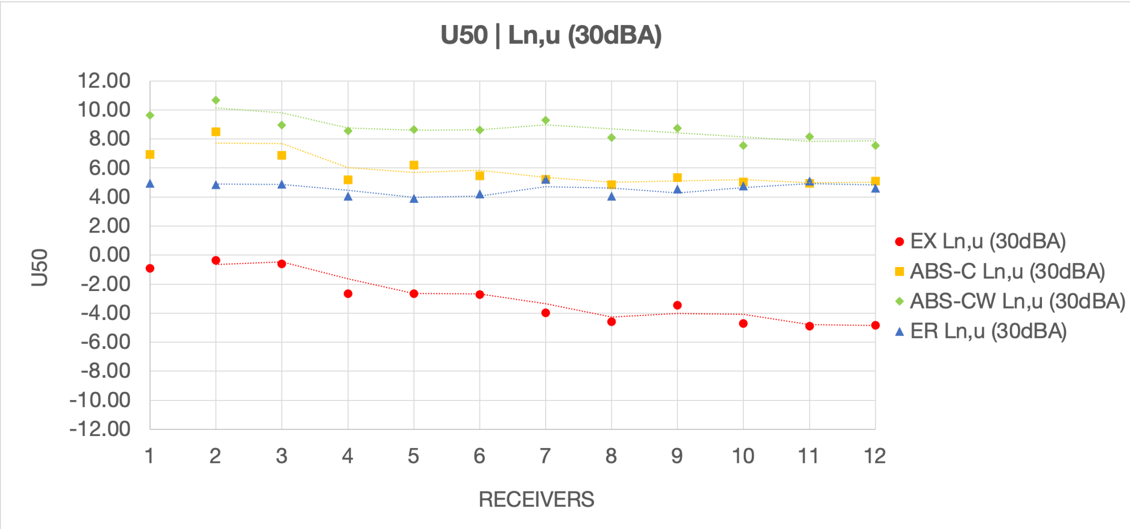
DISCUSSION

The study analysed four different room acoustics design scenarios. The first scenario, EX, represented the existing room without additional treatment. The second scenario, ABS-C, used the entire ceiling area but only treated the ceiling. This scenario represents the conventional room acoustics design of the classrooms. The third scenario, ABS-CW, an extension of the conventional room acoustics treatment, used the whole ceiling, side, and back wall areas to achieve the possible minimum reverberation time. Finally, the fourth scenario, ER, represented an early reflection-oriented room acoustics design with a partial treatment on the ceiling and walls while preserving the early reflection zones.

The study quantifies the contribution of early reflections by the relative sound level of direct and early reflections, known as G_{50}, within the frequency range of 500Hz to 4kHz and observes their effect on speech intelligibility by STI and U_{50} parameters.

The main factor in determining the optimal room acoustics design scenario is to attain the highest possible speech intelligibility while dealing with the active classroom background noise. The feasibility and cost of the room acoustics design should also be considered.

One of the prominent elements in the study is the consideration of the active classroom background noise levels. The scenarios were tested with four different background noise levels. $L_{n,u}$ represents the unoccupied classroom background noise level at 30.5 dBA, measured in the sample classroom. $L_{n,a}$ is the active classroom background noise level at 44 dBA taken from the recent literature on university classrooms. $L_{n,a\text{-}v1}$ and $L_{n,a\text{-}v2}$ are the variations of $L_{n,a}$ by shifting the spectrum to obtain 50 dBA and 55 dBA noise levels, respectively. Active classroom background noise level is the point that the ER, early-reflection-oriented room acoustics design scenario, starts to come forward regarding speech intelligibility. The charts in Figure 5.1 and Figure 5.2 below compare speech intelligibility results for two background noise levels: unoccupied classroom background noise level, $L_{n,u}$, and active classroom background noise level variation-1, $L_{n,a\text{-}v1}$. The ER scenario ranks third in speech intelligibility at background noise level, $L_{n,u}$. However, it ranks first when the background noise level rises to $L_{n,a\text{-}v1}$. At 50 dBA background noise level, U_{50} and STI values indicate that, among other scenarios, positions further away from the speaker have better speech intelligibility in the ER scenario, as displayed by the bottom charts in Figure 5.1 and Figure 5.2.



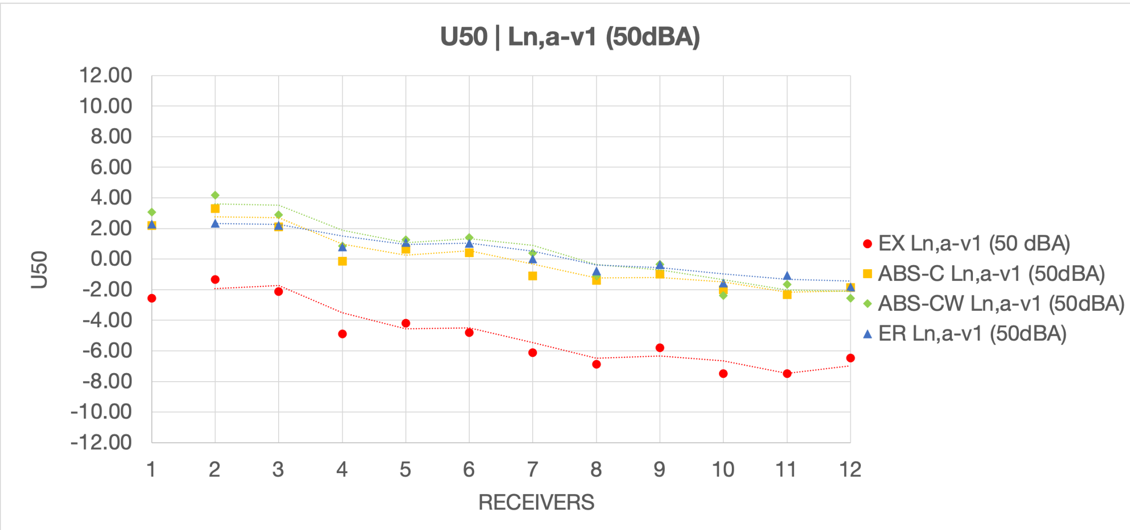
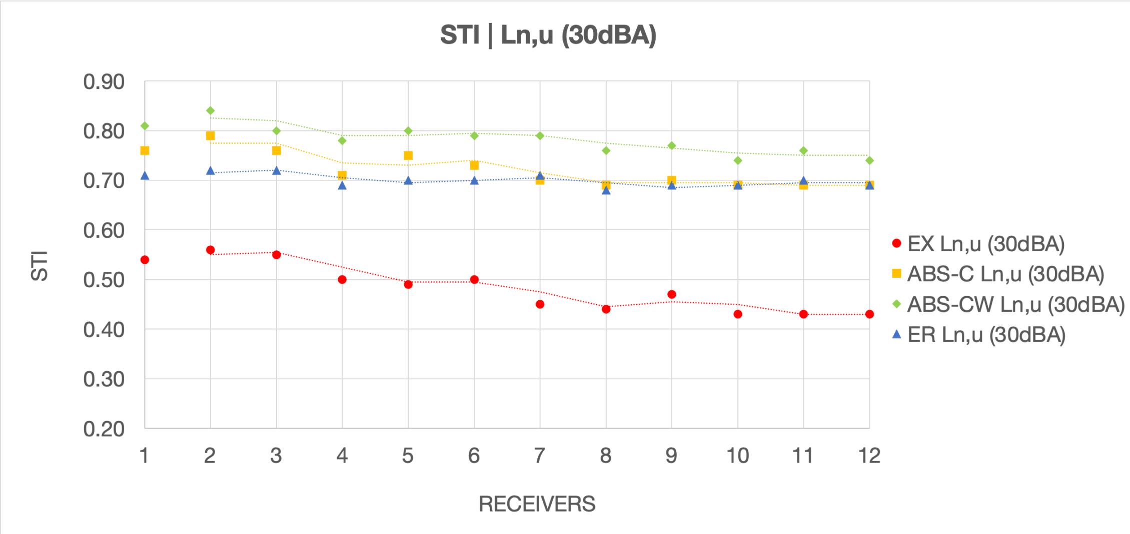


Figure 5.1. Comparison of scenarios for U_{50} with two background noise levels



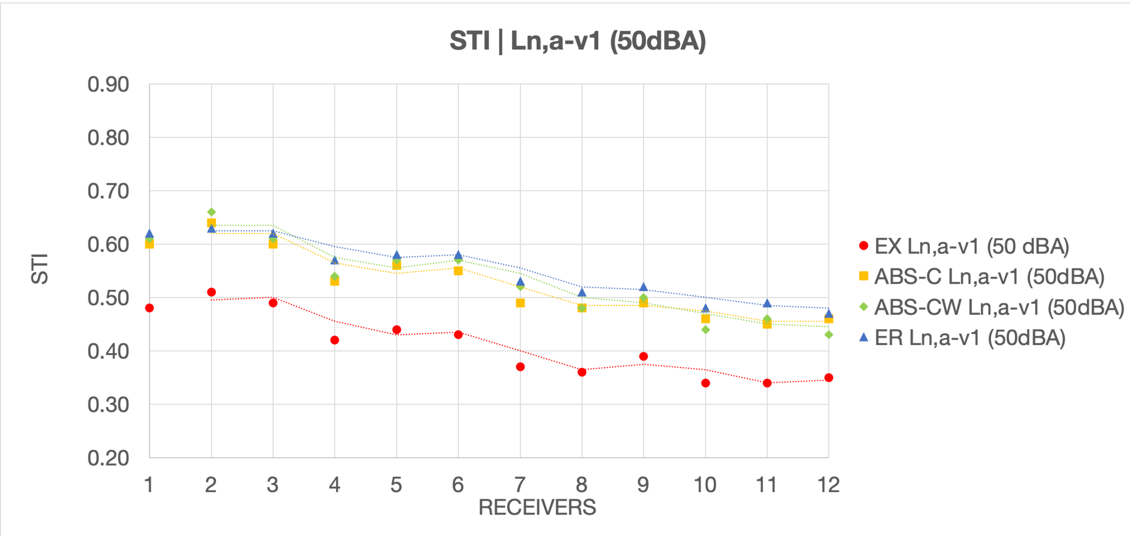
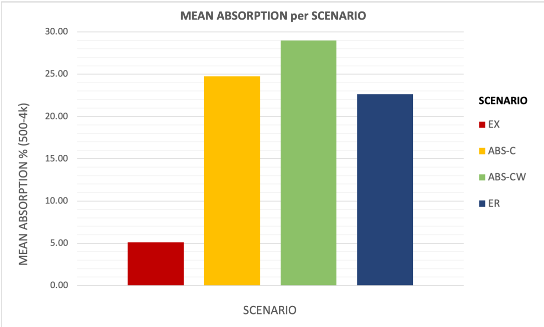


Figure 5.2. Comparison of scenarios for STI with two background noise levels

Figure 5.3 and Figure 5.4 display mean absorption and reverberation time, respectively, for each scenario.



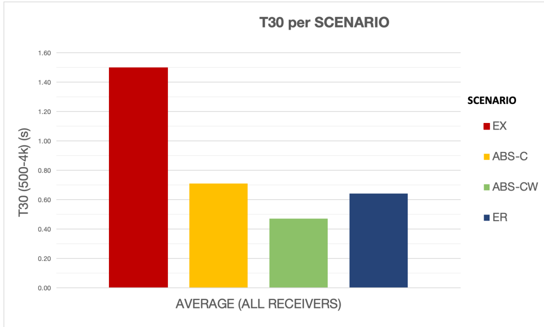


Figure 5.3. Mean Absorption per Scenario

Figure 5.4. Average T_{30} per Scenario

A summary of scenario results for the back receiver locations is provided in Table 5.1 with the values representing the average of R10, R11, and R12 receiver positions.

Table 5.1. Summary of Scenario Results for the Back Receiver Locations

		AVERAGE OF THE RECEIVERS 10-11-12									
				[Ln,u]		[Ln,a] (44 dBA)		[Ln,a-v1] (50 dBA)		[Ln,a-v2] (55 dBA)	
SCENARIO	MEAN ABS. (500-4k) (%)	T30 (500-4k) (s)	G50 (500-4k) (dB)	STI	U50 (500-4k) (dB)	STI	U50 (500-4k) (dB)	STI	U50 (500-4k) (dB)	STI	U50 (500-4k) (dB)
EX	5.10	1.51	5.11	0.43	-4.81	0.40	-5.92	0.34	-7.14	0.28	-8.85
ABS-C	24.78	0.77	4.19	0.69	5.02	0.57	1.06	0.46	-2.06	0.34	-5.54
ABS-CW	28.98	0.48	2.95	0.75	7.75	0.59	1.98	0.44	-2.20	0.33	-6.00
ER	22.63	0.66	5.31	0.69	4.82	0.59	1.43	0.48	-1.48	0.37	-4.81

Table 5.1 highlights the significance of the ER scenario, where early reflections were retained, and absorption was applied on surfaces not reflecting the early sound to the audience area. Although the ER scenario has the third lowest mean absorption, it becomes the best option in terms of speech intelligibility (STI and U_{50}) as the background noise level rises from 30 dBA to 55 dBA. The factor making the ER the best option is G_{50}. The ER scenario provides the highest G_{50} values for the back receiver locations, as seen in Figure 5.5 below.

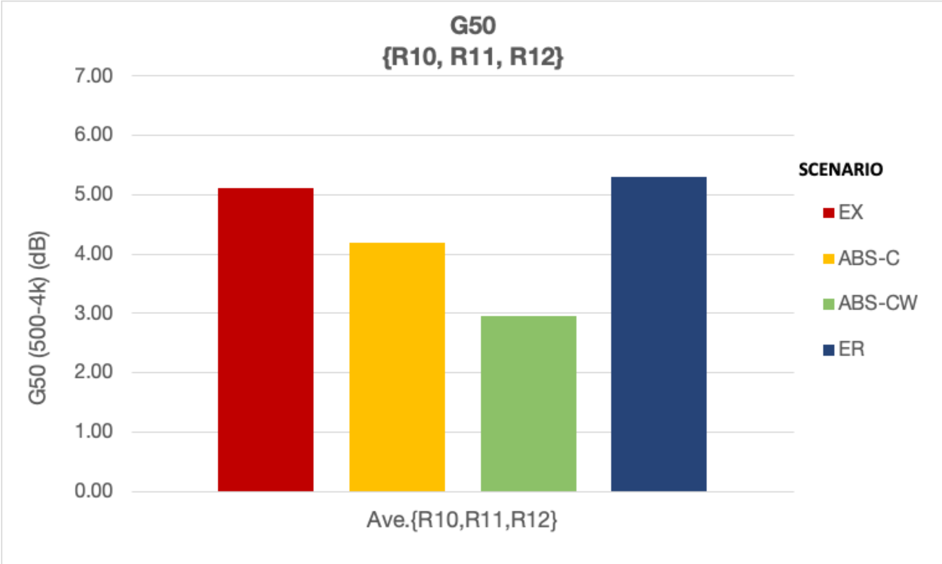


Figure 5.5. The average G_{50} values for the back receivers

Although the EX scenario has the second highest G_{50} value, its intelligibility values are the lowest among the four scenarios. Neither minimising the reverberation time (T_{30}) nor maximising the relative level of the direct sound and early reflections (G_{50}) achieves the best speech intelligibility alone. This finding is consistent with the literature on early reflections, prioritising maximising the energy of the direct speech sound and early reflections before considering reverberation time.

The reverberation time of the ER scenario was expected to be higher than the ABS-C scenario, referring to mean absorption for each scenario, as displayed in Figure 5.3. Surprisingly, the ER scenario exhibited lower reverberation times than the ABS-C scenario at all receiver points, as illustrated in Figure 5.6. This may be due to the fact that the ER scenario supports early reflections while selectively targeting late-part sound energy via the absorbers placed on surfaces not related to early sound. This supports the priority of early reflection consideration before addressing the controlling late reflections, i.e., the reverberation time.

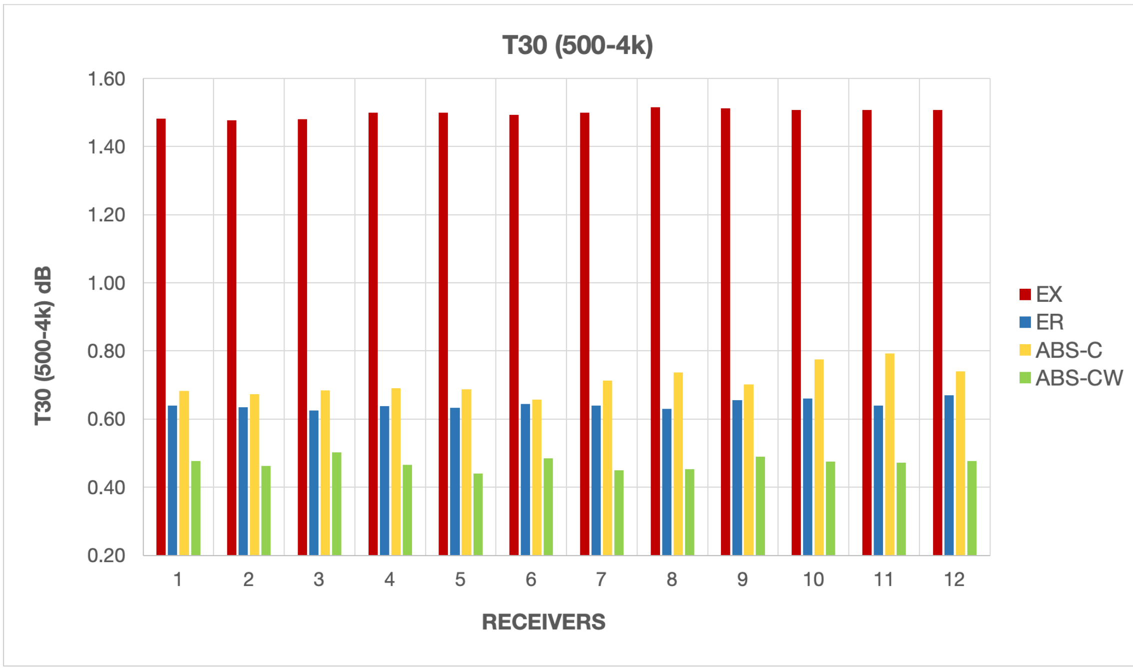


Figure 5.6. Reverberation Time (T_{30}) for each receiver

The role of G_{50} is also evident when comparing ABS-C and ABS-CW at an activity noise level of 44 dBA and higher: ABS-C has a higher G_{50} than ABS-CW due to lower mean absorption. ABS-CW has the lowest reverberation time with absorbing side walls and ceiling, including the areas reflecting the early sound energy leading to the lowest G_{50}. ABS-CW has the highest speech intelligibility when the background noise is low. But as the background noise rises, as in the case of active classrooms, ABS-CW drops down in speech intelligibility ranking. The ER scenario becomes the best option, and the ABS-CW scenario becomes the least favourable.

The relative sound level of early and direct sound for each receiver in room acoustics scenarios is shown in Figure 5.7.

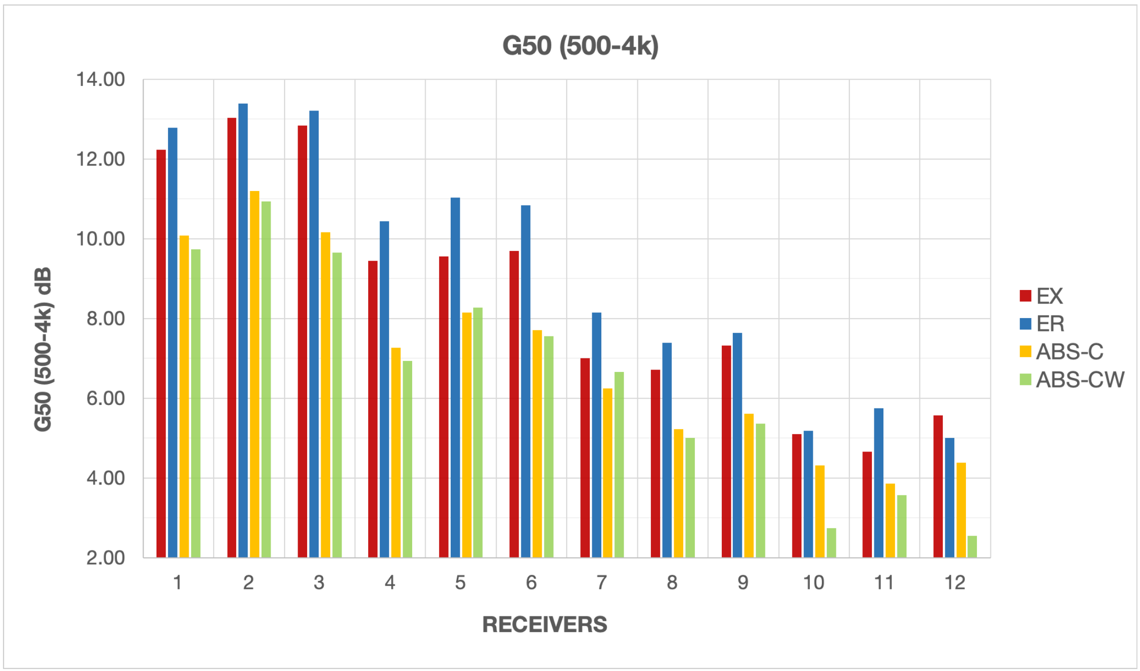


Figure 5.7. Relative Sound Level G_{50} (Direct and Early Sound) for each receiver

In addition to the evaluation for the back audience positions, the highest relative sound level for direct sound and early reflections (G_{50}) is observed in the ER scenario across the receiver positions. The existing room scenario also exhibits high G_{50} values. This is expected since the EX scenario has the lowest mean absorption, meaning that all reflections, including both useful and detrimental ones, are reflected off the room boundaries due to the lack of absorption. However, even though ER's mean absorption is higher than EX's mean absorption by 16%, ER provides the higher G_{50} for the majority of receiver positions, particularly for the audience positions further away from the speaker position, as a result of early reflection-oriented room acoustic design.

The early-reflection-oriented room acoustics design scenario used 35% less ceiling area for absorption than ABS-C and ABS-CW scenarios. ER used 20% less wall area than the ABS-CW scenario while achieving similar or better speech intelligibility. The ER scenario’s mean absorption is less than the mean absorption of the ABS-C scenario by 2.2%. However, the ER scenario’s reverberation time is lower than ABS-C’s by 11%. Half of the absorbing surface in the ABS-C scenario is on the area that provides first-order reflections from the ceiling to the audience area, meaning that the absorbers in the ABS-C scenario deal with absorbing early sound energy instead of controlling late reflections.

The ABS-CW scenario's mean absorption is higher than the ER scenario's by 6.35%. In turn, the average reverberation time of ABS-CW is lower than ER's by 27.3%. However, both scenarios provided the same degree of speech intelligibility for the back audience locations at 44 dBA background noise level. However, although the ER has lower mean absorption and higher reverberation time, it ranks first regarding speech intelligibility at background noise levels of 50 dBA to 55 dBA. The determinant is G_{50}, the relative sound level of direct and early reflections. According to the ABS-CW scenario, the ER scenario had a higher G_{50} by 2.15dB and a longer T_{30} by 0.21s.

STI – G_{50} and U_{50} – G_{50} charts on the following pages show a strong correlation between speech intelligibility metrics and the relative sound levels of direct sound and its early reflections. This is expected since it is known that the early reflections reinforce the direct sound and raise SNR in favour of the speech signal. One remarkable observation is that the regression lines obtained by the ER scenario, as displayed in Figure 5.14 and Figure 5.15, have a less steep slope than the lines in other scenarios. This indicates that early-reflection-oriented room acoustics design increases the signal level of the back audience positions and provides a more uniform speech intelligibility across the classroom.

The charts also show that the adverse impact of increasing background noise levels is more substantial for the lower G_{50}. This is evident in the vertical distance of the regression lines in the ABS-C and ABS-CW scenarios, exhibiting relatively low G_{50} towards back audience locations.

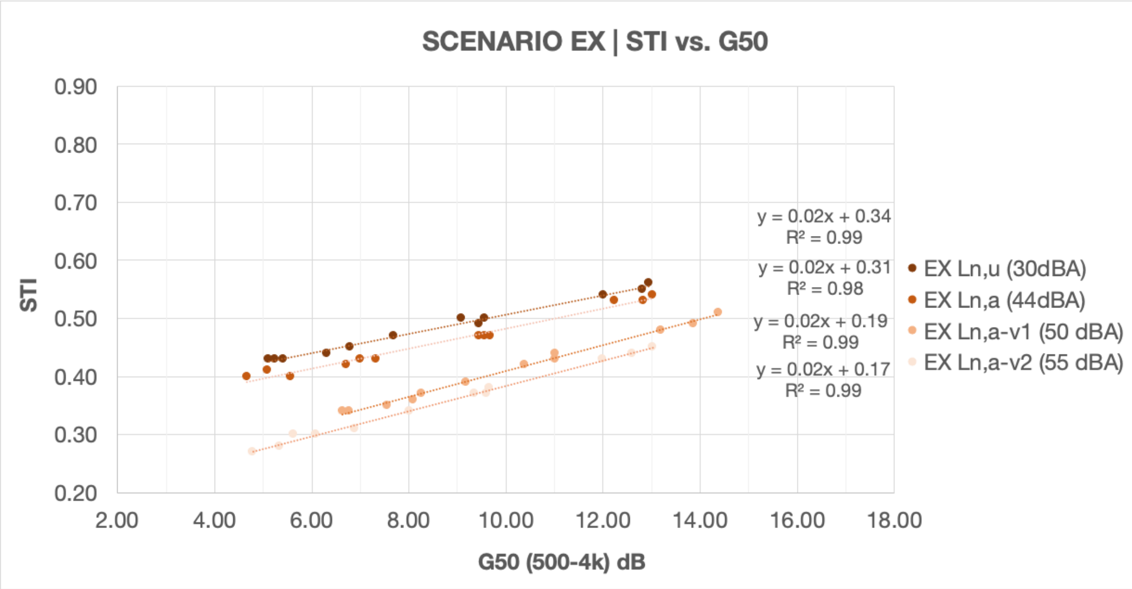


Figure 5.8. Scenario EX | STI vs. G_{50}

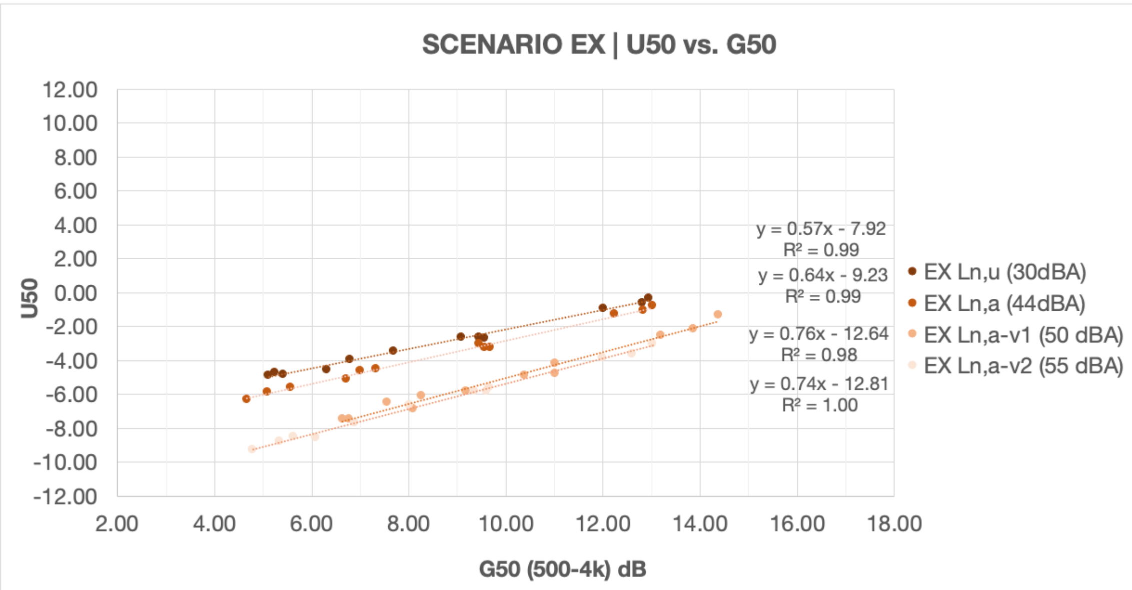


Figure 5.9. Scenario EX | U_{50} vs. G_{50}

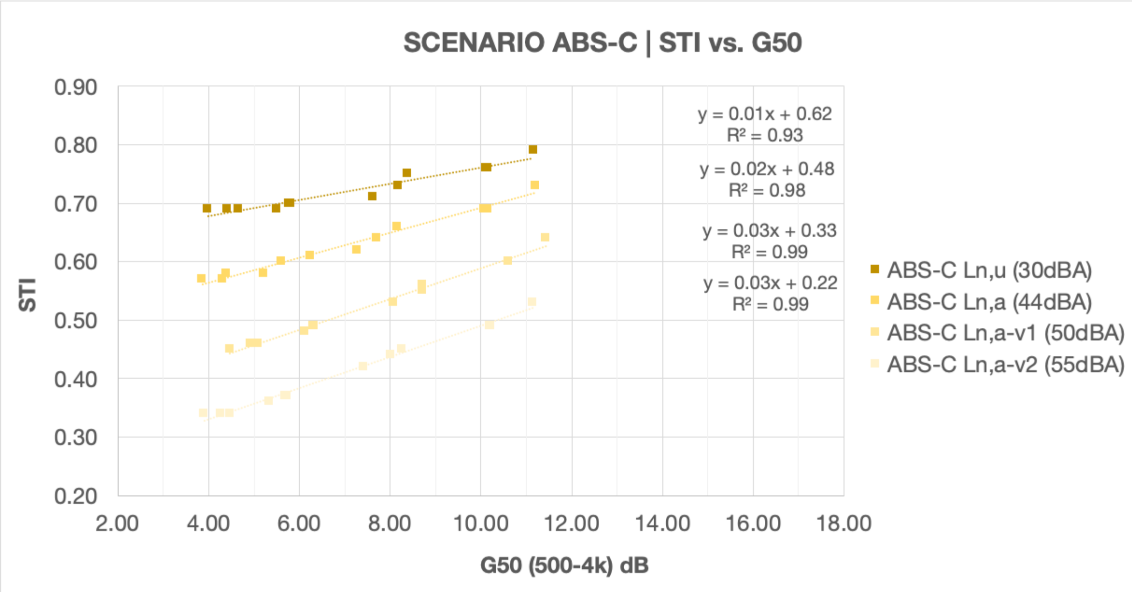


Figure 5.10. Scenario ABS-C | STI vs. G_{50}

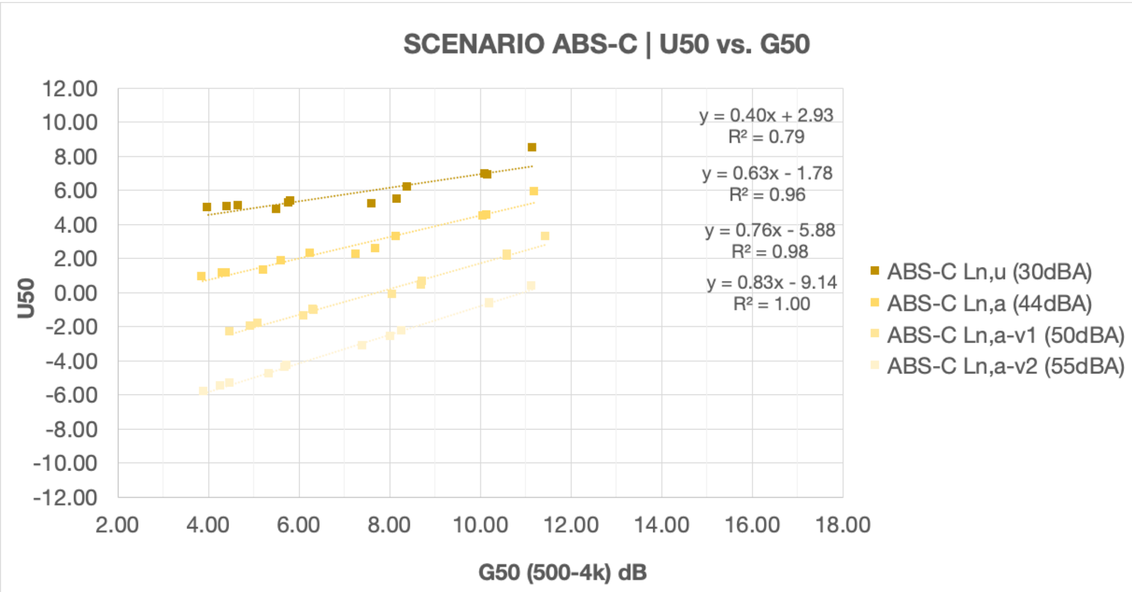


Figure 5.11. Scenario ABS-C | U_{50} vs. G_{50}

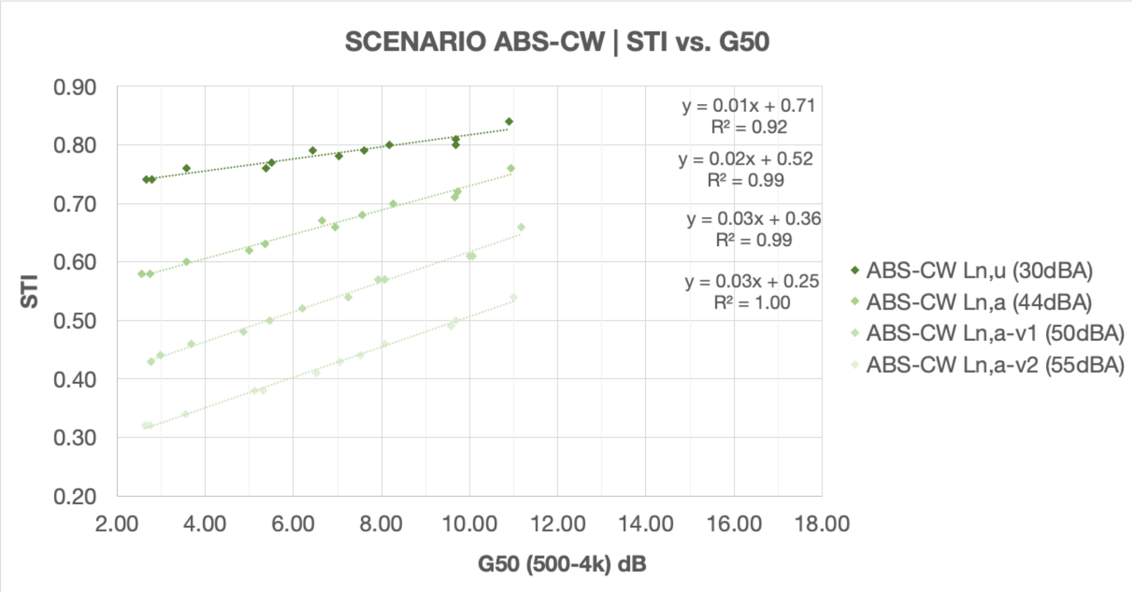


Figure 5.12. Scenario ABS-CW | STI vs. G_{50}

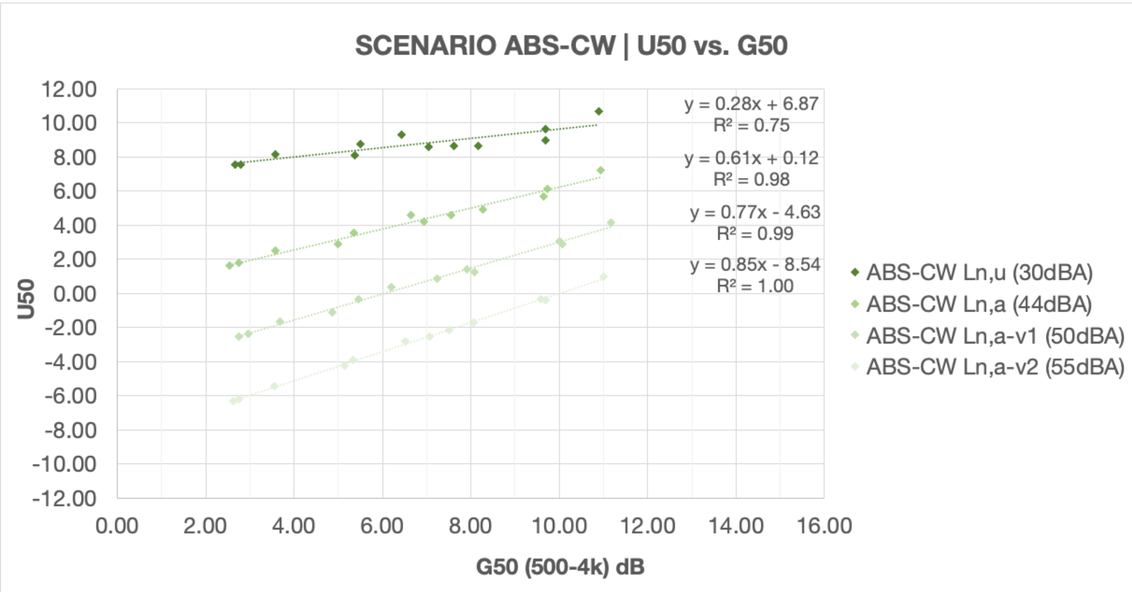


Figure 5.13. Scenario ABS-CW | U_{50} vs. G_{50}

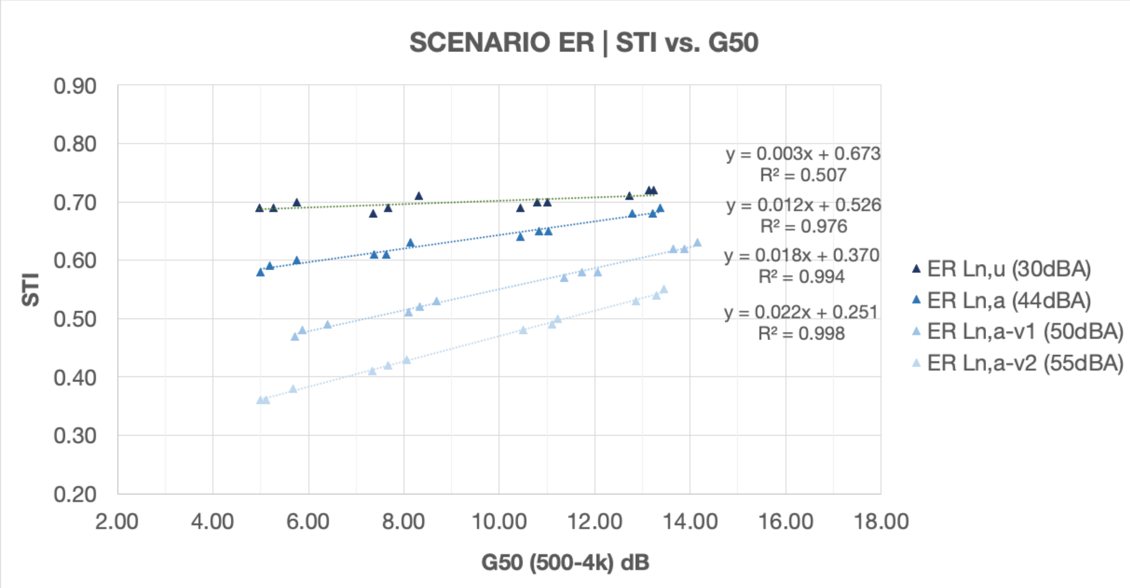


Figure 5.14. Scenario ER | STI vs. G_{50}

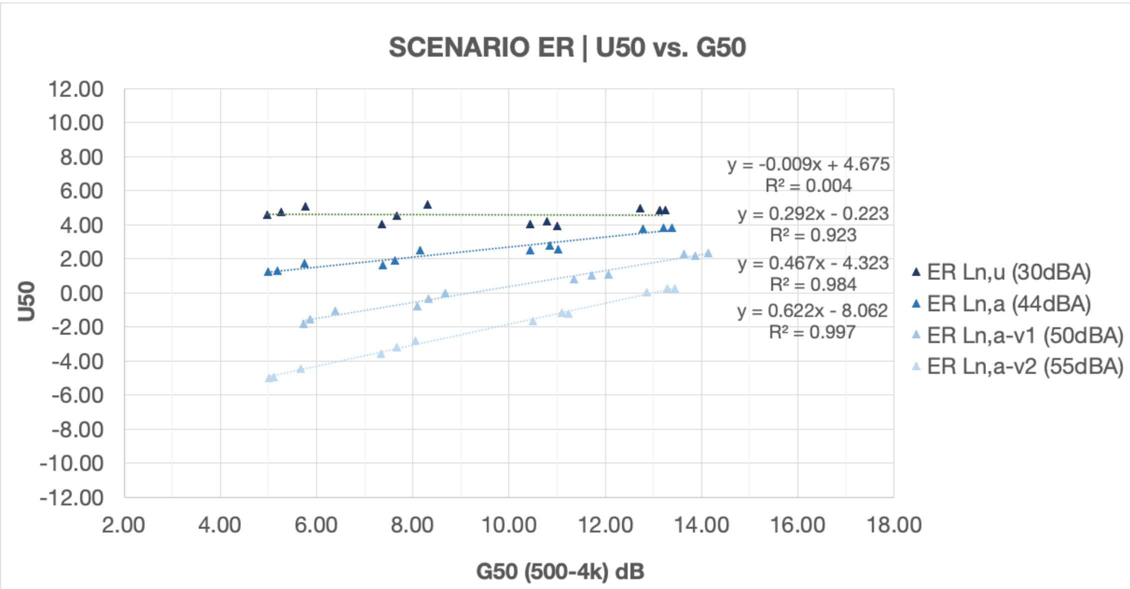


Figure 5.15. Scenario ER | U_{50} vs. G_{50}

Speech recognition tests were conducted with 96 participants. Overall, 288 data points were obtained by combining three TMWRT lists (A, B, C) and three receiver positions, namely R10, R11 and R12, representing the back audience locations. SRT scores obtained from binaural listening tests were compared to simulated STI and U_{50} values, as displayed in Figure 5.16 and Figure 5.17. The listening tests used two background noise levels, $L_{n,u}$ and $L_{n,a}$.

The trendlines yield high values for the coefficient of determination, indicating a strong correlation between simulated speech intelligibility metrics and SRT scores obtained from the listening tests. The SRT scores for the ABS-C, ABS-CW, and ER scenarios were closely clustered, with significantly higher scores than the EX scenario.

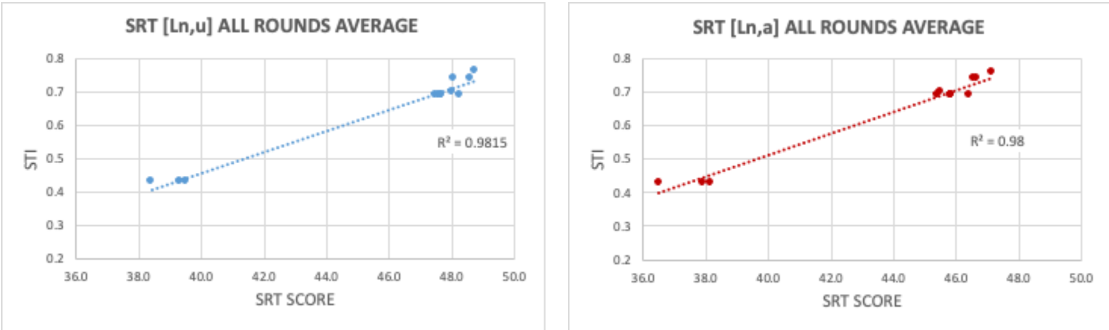


Figure 5.16. SRT vs. STI

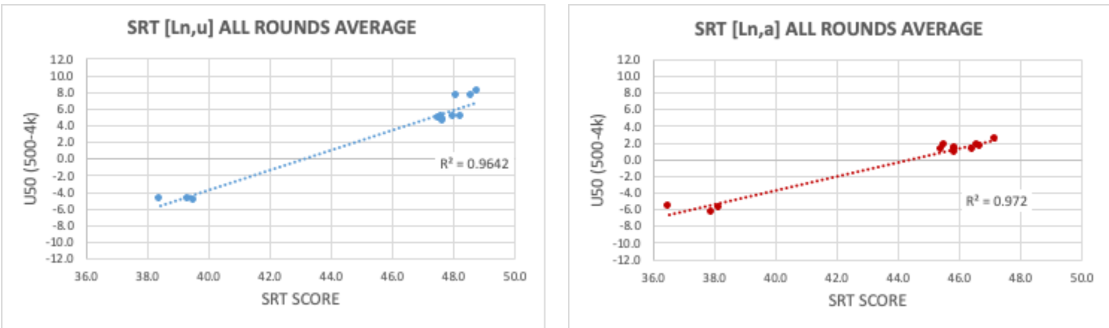
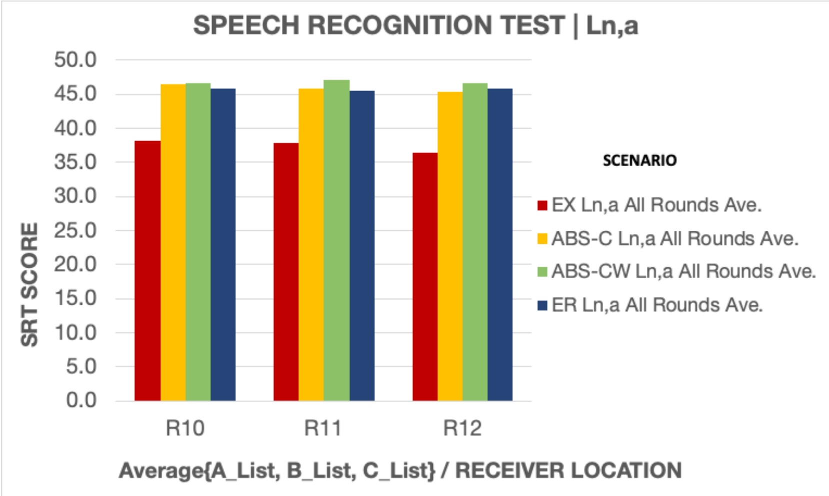
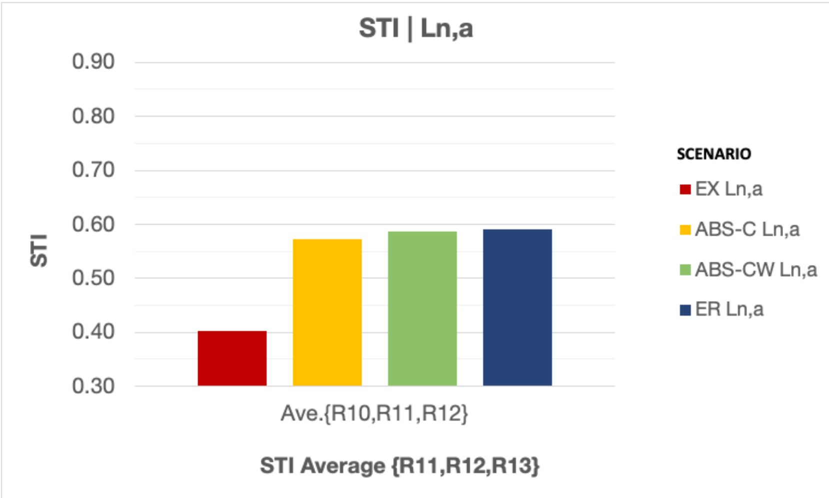


Figure 5.17. SRT vs. U_{50}

Figure 5.18 compares the SRT scores to speech intelligibility results from the room scenarios. The SRT results agree with the STI and U_{50} results overall. However, the ranking order of the room acoustic design scenarios varies slightly. The possible reasons could be the level or content of artificially added noise signals to simulate background noise during the binaural listening sessions or the participants' hearing adaptation to the steady background noise.





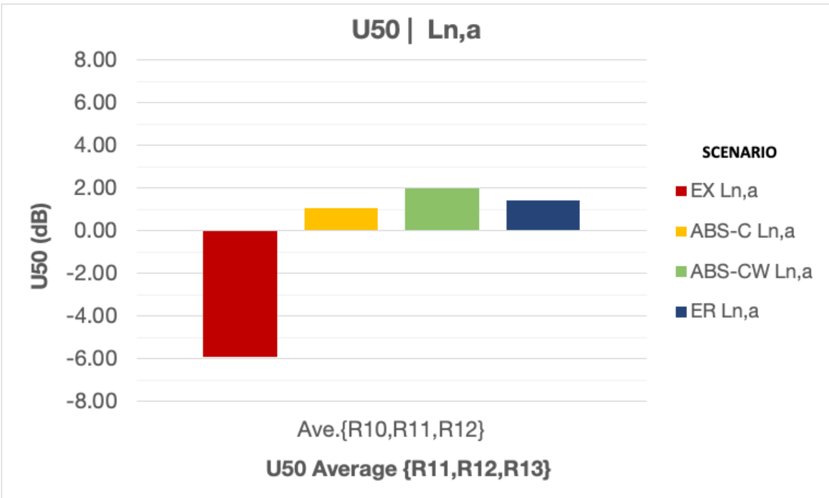


Figure 5.18. Comparison of SRT to STI and U_{50} at $L_{n,a}$

CHAPTER 6

CONCLUSION

The ultimate goal of the room acoustics design for rooms for speech is to provide satisfactory speech intelligibility for all audience locations, particularly those away from the lecturer. Since SNR is the most significant factor determining speech intelligibility, an optimal reverberation time regarding speech intelligibility can be determined only if varying levels of speech and background noise in active classrooms are considered. The study's results suggest that the relative sound level of speech's direct and early sound (G_{50}) can form a practical pair of criteria with reverberation time to reach that goal.

In order to improve speech intelligibility, it is necessary to optimise the solution in two interrelated domains: the time domain and the energy or pressure domain. Increasing the speech sound pressure level, i.e., the energy domain, enhances speech intelligibility by improving SNR. Time domain, on the other hand, refers to the temporal order of room reflections on the time axis and is quantified by reverberation time (T_{30}). Excessive reverberation time reduces speech intelligibility by causing speech articulations to overlap and mask each other. Improving speech intelligibility in the time domain is essential to prevent overlapping articulations but requires a trade-off between time and energy domains. The time domain side of the problem cannot be solved by a change in direct speech sound energy. The solution lies in controlling the energy of late reflections via sound-absorbing surfaces that reduce reverberation time and preserve early reflections to support the direct speech signal. Decreasing reverberation time via absorbing room surfaces may also reduce the sound pressure level of the total speech sound due to absorbed early reflections. An optimal reverberation time would mean a point that is sufficiently low to prevent temporal overlapping of successive syllables in speech and sufficiently high to reserve an adequate room for early reflections. Therefore, the value cannot be specific but rather a range determined by the given conditions, essentially by the active classroom noise and G_{50}. This is the reason why G_{50} gains priority over T_{30}. According to the results of this study, G_{50} plays a crucial role in determining the range of reverberation time that works for required speech intelligibility. The process should start with identifying the reflection patterns for a specific room geometry before referring to the numeric values of the room acoustics parameters. The material selection should be decided based on the function and geometry of the room, in contrast to the approach that tries to achieve the required performance by focusing solely on applying a calculated amount of acoustic treatments.

The study shows that early reflection-oriented room acoustics design (ERORAD) is an effective and efficient approach to improving speech intelligibility for distant audience positions in conventional classrooms. Findings exhibited that ERORAD is significant, particularly for the active classroom background levels.

ERORAD method offers a technique to identify surfaces that benefit from early reflections. G_{50} is found to be an excellent indicator to quantify the relative sound level of direct sound and its early reflections. The study shows that G_{50} is strongly correlated with speech intelligibility, particularly for higher background noise levels, as in the case of active classrooms. The ERORAD method prioritises G_{50} before considering the reverberation time, T_{30}.

6.1. Contributions

The ERORAD Method

Despite the substantial literature on the positive effect of early reflections on speech intelligibility, there appears to be a gap in the methodology to help designers develop room geometry based on these principles. This dissertation contributes to the gap in a practical method for architects and room acoustics designers to develop early-reflection-oriented room geometry to integrate acoustic function early in the design process.

The study showed that an early-reflection-oriented room acoustics design (ERORAD) methodology based on geometrical acoustics increases the relative level of direct and early speech sound at distant audience locations by categorising the room surfaces as functional surfaces (ERS) for early reflection of speech sound and appropriate surfaces for absorption (SfA) of the late reflections to control reverberation time. The method uses the image-source method (ISM) to identify the early reflection room surfaces. The ERORAD method is based on the following steps:

(1) Identify the early reflection surfaces (ERS) using the image-source method to maximise G_{50}. The audience locations should be considered concerning the lecturer's possible positions. The ERS should be hard-reflecting materials. The areas left outside ERS are designated as surfaces available for absorption (SfA) and can be used to control late reflections and the resulting reverberation time.

(2) Determine the size of the identified surfaces based on the wavelength of 350Hz to reflect the speech sound for the significantly contributing frequencies starting from the 500Hz octave band.

(3) Control the reverberation time by using appropriate absorbers on SfA.

(4) According to the research results, T_{30} (500-4k) < 0.9s with $G_{50} \geq 4$ dB provides satisfactory speech intelligibility at 44 dBA background noise level. Every 1 dB increase of the background noise should be balanced with the same amount of increase in G_{50} to keep the speech intelligibility satisfactory across the classroom.

Binaural Listening with Modifiable Background Noise

The study also presents a method for using auralised audio files for binaural listening tests with a background noise signal of which spectrum and level can be modified. The contribution of this method is that the auralised speech can be mixed with the desired background noise in a digital audio editor, and the signal and noise levels can be manipulated digitally via RMS levels. This way, varying SNR can be obtained for listening tests using the same auralised audio.

6.2. Limitations

One of the limitations of this study is that the background noise is regarded as uniform throughout the classroom. A steady background noise signal devised from the pink noise, according to the measured background noise spectrum in active classrooms, was used during the listening test to simulate the background noise. A steady noise may cause participants to adapt their hearing.

The room acoustics design scenarios were developed based on one real classroom at the Department of Architecture at IYTE. Although several scenarios were developed, the study's observation of changes with various room dimensions and geometries could have been more extensive.

The listening test was conducted with two background noise levels. Although the test scores strongly correlate to the results of the room acoustics design scenarios, it limited the observation of the higher level of background noise.

6.3. Future Work

The listening test method presented in this study provides an opportunity to conduct binaural listening tests with real noise audio recorded during active classroom sessions. The results of the binaural listening tests with real classroom noise can be used to calibrate and shape an artificial noise signal to standardise the test procedure.

The relationship between active classroom background noise, G_{50} and mean room absorption regarding speech intelligibility should be researched further. A ranking model can also be investigated to determine the weighting of the factors. For this purpose, the ERORAD model will be tested with various ERS and SfA configurations with varying room dimensions and geometries.

Additionally, it is necessary to research the significant octave bands for the intelligibility of Turkish words.

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APPENDIX A

SIMULATION DATA

Table A. 1. Scenario EX | Ln,u

EX Ln,u (30dBA)	RECEIVER	1	2	3	4	5	6	7	8	9	10	11	12
MEAN	U50 (500-4k)	-0.93	-0.35	-0.61	-2.67	-2.65	-2.71	-3.96	-4.59	-3.45	-4.71	-4.90	-4.82
	T30 (500-4k)	1.49	1.48	1.49	1.50	1.50	1.49	1.51	1.50	1.51	1.51	1.51	1.52
	G50 (500-4k)	12.02	12.94	12.82	9.08	9.44	9.57	6.80	6.32	7.69	5.24	5.12	5.41
T-30 (s)	T30(8k)	0.68	0.68	0.68	0.70	0.70	0.70	0.72	0.72	0.73	0.72	0.73	0.72
	T30(4k)	1.09	1.09	1.09	1.11	1.11	1.10	1.13	1.12	1.13	1.12	1.13	1.13
	T30(2k)	1.35	1.35	1.35	1.36	1.36	1.36	1.37	1.35	1.37	1.38	1.36	1.38
	T30(1k)	1.66	1.65	1.67	1.67	1.67	1.67	1.68	1.68	1.70	1.69	1.68	1.70
	T30(500)	1.84	1.82	1.84	1.85	1.86	1.84	1.85	1.86	1.85	1.86	1.85	1.86
	T30(250)	2.01	2.01	2.01	2.01	2.01	2.00	2.02	2.01	2.03	2.02	2.03	2.02
	T30(125)	2.05	2.06	2.07	2.07	2.07	2.08	2.07	2.06	2.06	2.08	2.07	2.06
U-50 (dB)	U50(8k)	3.28	5.29	4.14	1.43	2.10	2.13	0.11	0.39	1.78	-0.51	-0.17	-0.56
	U50(4k)	1.11	2.33	1.86	-0.12	0.18	-0.96	-0.99	-1.61	-0.01	-2.55	-1.96	-1.89
	U50(2k)	0.01	0.86	-0.05	-1.12	-1.58	-0.93	-2.42	-3.85	-1.83	-3.58	-3.91	-3.77
	U50(1k)	-2.80	-2.24	-1.75	-5.10	-5.06	-4.71	-5.96	-5.74	-5.18	-6.36	-6.64	-6.21
	U50(500)	-2.02	-2.35	-2.50	-4.33	-4.12	-4.22	-6.48	-7.14	-6.76	-6.35	-7.08	-7.41
	U50(250)	-3.12	-2.45	-2.16	-5.71	-5.12	-5.66	-6.70	-7.00	-7.00	-6.79	-7.55	-6.94
	U50(125)	-3.19	-3.00	-3.80	-5.19	-5.70	-5.64	-7.95	-8.09	-7.03	-7.48	-9.85	-7.58
G-50 (dB)	G50(8k)	10.13	12.51	11.50	7.23	7.75	8.04	4.58	4.88	6.21	3.13	3.62	3.35
	G50(4k)	10.23	11.93	11.68	7.76	8.65	7.49	6.07	5.44	7.28	3.48	4.03	4.66
	G50(2k)	11.41	12.75	12.06	9.08	8.83	9.95	6.66	5.47	7.71	4.86	4.66	4.82
	G50(1k)	12.74	13.45	14.11	9.19	9.58	9.90	7.18	7.66	8.41	6.14	5.88	6.55
	G50(500)	13.68	13.63	13.44	10.30	10.71	10.95	7.28	6.72	7.36	6.49	5.89	5.62
	G50(250)	12.19	13.10	13.31	8.98	9.45	8.96	6.73	6.53	6.68	5.98	5.16	5.78
	G50(125)	13.76	13.92	13.21	10.64	10.32	10.52	6.96	7.07	8.16	6.60	4.38	6.63
	STI	0.54	0.56	0.55	0.50	0.49	0.50	0.45	0.44	0.47	0.43	0.43	0.43

Table A. 2. Scenario EX | Ln,a

EX Ln,a (44dBA)	RECEIVER	1	2	3	4	5	6	7	8	9	10	11	12
MEAN	U50 (500-4k)	-1.30	-0.81	-1.08	-3.04	-3.27	-3.27	-4.63	-5.13	-4.49	-5.86	-6.31	-5.58
	T30 (500-4k)	1.48	1.48	1.48	1.50	1.50	1.49	1.50	1.52	1.51	1.51	1.51	1.51
	G50 (500-4k)	12.24	13.03	12.84	9.45	9.56	9.69	7.00	6.72	7.32	5.10	4.67	5.58
T-30 (s)	T30(8k)	0.69	0.68	0.68	0.70	0.70	0.70	0.71	0.72	0.72	0.73	0.74	0.72
	T30(4k)	1.10	1.10	1.09	1.12	1.12	1.11	1.11	1.13	1.12	1.12	1.12	1.12
	T30(2k)	1.34	1.33	1.34	1.36	1.36	1.35	1.37	1.37	1.38	1.37	1.37	1.37
	T30(1k)	1.66	1.65	1.65	1.67	1.68	1.67	1.69	1.70	1.69	1.68	1.68	1.68
	T30(500)	1.83	1.83	1.84	1.85	1.84	1.84	1.83	1.86	1.86	1.86	1.86	1.86
	T30(250)	2.00	2.01	2.01	2.02	2.02	2.02	2.04	2.03	2.01	2.05	2.04	2.03
	T30(125)	2.06	2.06	2.05	2.07	2.07	2.07	2.07	2.07	2.06	2.06	2.07	2.07
U-50 (dB)	U50(8k)	3.55	4.86	3.60	1.18	2.88	1.43	0.22	1.31	1.52	0.89	-0.19	-0.67
	U50(4k)	-0.67	0.76	0.14	-2.83	-3.14	-2.92	-4.40	-3.99	-3.67	-5.49	-5.80	-5.19
	U50(2k)	-0.34	0.45	-0.17	-1.48	-1.72	-1.43	-2.82	-3.41	-2.56	-3.73	-3.89	-3.73
	U50(1k)	-1.82	-2.52	-2.31	-3.48	-3.99	-4.29	-5.57	-6.64	-5.14	-7.69	-6.58	-6.31
	U50(500)	-2.35	-1.93	-1.96	-4.37	-4.22	-4.44	-5.73	-6.48	-6.58	-6.52	-8.98	-7.10
	U50(250)	-3.19	-2.61	-3.21	-5.44	-5.43	-4.43	-6.52	-6.43	-7.44	-7.31	-7.89	-6.62
	U50(125)	-3.28	-3.28	-3.93	-4.75	-5.79	-6.44	-7.42	-7.48	-6.80	-7.36	-8.69	-7.73
G-50 (dB)	G50(8k)	10.29	12.17	10.90	6.85	8.50	7.71	4.65	5.58	6.11	4.28	3.40	3.14
	G50(4k)	10.62	12.14	11.71	7.59	7.71	7.93	5.58	6.12	6.20	4.02	3.67	4.54
	G50(2k)	11.39	12.51	12.03	8.91	9.09	9.74	6.67	6.33	7.27	5.11	4.81	5.13
	G50(1k)	13.52	13.38	13.57	10.82	10.75	10.45	7.67	7.07	8.50	4.88	5.92	6.58
	G50(500)	13.41	14.07	14.03	10.46	10.69	10.62	8.07	7.36	7.31	6.39	4.26	6.05
	G50(250)	12.35	12.94	12.33	9.11	9.14	10.17	6.95	7.02	6.13	5.48	4.71	6.17
	G50(125)	13.76	13.73	13.18	11.23	10.35	9.60	7.71	7.64	8.25	6.91	5.50	6.47
	STI	0.53	0.54	0.53	0.47	0.47	0.47	0.43	0.42	0.43	0.41	0.40	0.40

Table A. 3. Scenario EX | Ln,a-v1

EX Ln,a-v1 (50 dBA)	RECEIVER	1	2	3	4	5	6	7	8	9	10	11	12
MEAN	U50 (500-4k)	-2.55	-1.34	-2.13	-4.89	-4.21	-4.81	-6.11	-6.88	-5.81	-7.48	-7.48	-6.47
	T30 (500-4k)	1.48	1.49	1.48	1.50	1.49	1.50	1.51	1.51	1.51	1.53	1.51	1.52
	G50 (500-4k)	13.20	14.39	13.87	10.38	11.02	11.02	8.26	8.09	9.19	6.78	6.63	7.55
T-30 (s)	T30(8k)	0.68	0.67	0.67	0.70	0.70	0.71	0.72	0.72	0.71	0.72	0.71	0.72
	T30(4k)	1.09	1.09	1.08	1.10	1.09	1.12	1.13	1.12	1.13	1.13	1.12	1.14
	T30(2k)	1.34	1.34	1.34	1.37	1.36	1.36	1.36	1.36	1.37	1.38	1.38	1.38
	T30(1k)	1.64	1.67	1.67	1.69	1.67	1.66	1.68	1.68	1.69	1.69	1.69	1.69
	T30(500)	1.84	1.84	1.83	1.85	1.85	1.86	1.85	1.86	1.84	1.90	1.84	1.87
	T30(250)	2.02	2.02	2.02	2.00	2.00	2.05	2.00	2.03	2.02	2.04	2.02	2.04
	T30(125)	2.06	2.05	2.07	2.07	2.05	2.06	2.07	2.04	2.07	2.08	2.05	2.04
U-50 (dB)	U50(8k)	0.76	3.09	0.77	-1.19	0.43	-0.44	-2.85	-1.83	-2.03	-4.38	-3.82	-3.74
	U50(4k)	-4.49	-2.28	-3.22	-7.27	-5.70	-6.19	-8.91	-9.44	-8.01	-9.80	-9.71	-8.10
	U50(2k)	-0.95	1.00	-1.05	-2.85	-0.90	-2.48	-4.06	-5.37	-2.63	-4.61	-5.94	-5.14
	U50(1k)	-1.84	-2.08	-2.00	-4.74	-5.54	-5.44	-5.49	-5.83	-6.32	-7.90	-6.38	-6.73
	U50(500)	-2.91	-1.99	-2.25	-4.68	-4.68	-5.11	-5.97	-6.88	-6.26	-7.62	-7.87	-5.90
	U50(250)	-2.83	-2.82	-3.50	-5.28	-5.41	-4.64	-8.01	-7.19	-6.74	-7.72	-7.50	-7.26
	U50(125)	-3.57	-3.02	-3.27	-5.39	-5.92	-5.12	-7.42	-8.91	-8.26	-7.51	-8.55	-7.81
G-50 (dB)	G50(8k)	10.44	13.12	11.06	7.96	9.39	8.60	5.15	6.70	6.31	3.91	4.25	4.67
	G50(4k)	11.17	13.01	12.42	8.15	9.36	9.34	6.04	6.20	7.28	5.14	5.51	6.80
	G50(2k)	12.31	14.22	12.56	9.72	11.33	10.93	7.65	6.92	9.24	6.91	5.72	6.28
	G50(1k)	14.99	15.21	15.15	11.56	11.14	11.98	9.29	9.50	10.08	7.02	7.83	8.23
	G50(500)	14.34	15.10	15.33	12.10	12.26	11.81	10.07	9.74	10.14	8.03	7.47	8.90
	G50(250)	14.06	13.97	13.55	10.90	11.12	12.21	8.40	9.13	9.57	7.36	7.68	7.41
	G50(125)	14.94	15.51	15.34	12.50	12.29	12.89	10.33	9.26	9.77	9.12	7.87	8.40
	STI	0.48	0.51	0.49	0.42	0.44	0.43	0.37	0.36	0.39	0.34	0.34	0.35

Table A. 4. Scenario EX | Ln,a-v2

EX Ln,a-v2 (55 dBA)	RECEIVER	1	2	3	4	5	6	7	8	9	10	11	12
MEAN	U50 (500-4k)	-3.88	-3.01	-3.61	-5.81	-5.61	-5.82	-7.68	-8.58	-6.67	-9.26	-8.49	-8.81
	T30 (500-4k)	1.49	1.49	1.48	1.51	1.50	1.50	1.51	1.51	1.51	1.52	1.52	1.51
	G50 (500-4k)	11.99	13.04	12.61	9.36	9.65	9.60	6.89	6.09	8.02	4.79	5.62	5.34
T-30 (s)	T30(8k)	0.68	0.68	0.67	0.70	0.70	0.70	0.72	0.72	0.72	0.73	0.73	0.73
	T30(4k)	1.10	1.09	1.08	1.11	1.10	1.11	1.11	1.12	1.13	1.14	1.14	1.14
	T30(2k)	1.34	1.35	1.34	1.38	1.37	1.36	1.38	1.39	1.37	1.38	1.38	1.37
	T30(1k)	1.68	1.68	1.66	1.67	1.68	1.69	1.71	1.68	1.69	1.69	1.69	1.68
	T30(500)	1.82	1.83	1.83	1.86	1.84	1.83	1.84	1.84	1.85	1.86	1.85	1.86
	T30(250)	2.00	2.00	2.01	2.02	2.02	2.03	2.03	2.03	2.03	2.03	2.02	2.02
	T30(125)	2.08	2.06	2.04	2.08	2.07	2.05	2.06	2.04	2.06	2.09	2.09	2.08
U-50 (dB)	U50(8k)	-1.25	-0.17	-0.45	-4.03	-3.36	-3.94	-6.99	-6.31	-5.22	-8.33	-6.91	-8.04
	U50(4k)	-8.20	-7.27	-6.52	-10.63	-10.88	-10.33	-12.52	-12.87	-10.59	-13.72	-13.50	-13.63
	U50(2k)	-2.14	-1.11	-2.26	-3.44	-2.67	-3.77	-5.45	-7.39	-4.85	-7.31	-5.82	-7.21
	U50(1k)	-2.55	-1.05	-3.37	-4.75	-5.19	-4.89	-7.30	-5.69	-5.27	-7.19	-7.68	-6.28
	U50(500)	-2.64	-2.61	-2.29	-4.43	-3.71	-4.29	-5.44	-8.37	-5.98	-8.83	-6.96	-8.12
	U50(250)	-3.17	-2.16	-3.08	-5.49	-5.54	-4.69	-5.99	-6.37	-6.32	-6.66	-7.55	-6.26
	U50(125)	-3.46	-3.91	-2.95	-7.25	-5.64	-4.87	-8.36	-7.27	-8.47	-7.82	-9.60	-8.05
G-50 (dB)	G50(8k)	10.79	11.83	11.78	7.58	8.44	7.83	4.33	5.08	6.26	2.92	4.31	3.22
	G50(4k)	10.32	11.29	12.04	7.76	7.47	8.10	5.85	5.43	7.69	4.50	4.74	4.60
	G50(2k)	11.19	12.40	11.56	8.95	10.02	9.12	6.56	4.86	7.32	4.29	5.79	4.56
	G50(1k)	13.34	14.98	12.96	10.16	9.87	10.34	6.62	8.33	8.82	5.89	5.59	6.91
	G50(500)	13.09	13.47	13.88	10.56	11.25	10.83	8.54	5.74	8.23	4.47	6.35	5.28
	G50(250)	12.52	13.49	12.73	9.19	9.08	10.05	7.78	7.28	7.42	6.14	5.39	6.85
	G50(125)	13.65	13.13	14.26	8.94	10.55	11.45	6.83	7.95	6.81	6.67	4.86	6.64
	STI	0.43	0.45	0.44	0.37	0.38	0.37	0.31	0.30	0.34	0.27	0.30	0.28

Table A. 5. Scenario ABS-C | Ln,u

ABS-C Ln,u (30dBA)	RECEIVER	1	2	3	4	5	6	7	8	9	10	11	12
MEAN	U50 (500-4k)	6.93	8.50	6.88	5.18	6.19	5.48	5.22	4.85	5.35	5.03	4.95	5.09
	T30 (500-4k)	0.66	0.68	0.66	0.66	0.71	0.66	0.73	0.70	0.73	0.74	0.80	0.76
	G50 (500-4k)	10.12	11.16	10.16	7.62	8.39	8.17	5.77	5.51	5.81	4.42	3.99	4.66
T-30 (s)	T30(8k)	0.38	0.38	0.40	0.40	0.39	0.40	0.42	0.40	0.42	0.41	0.42	0.40
	T30(4k)	0.51	0.51	0.52	0.52	0.55	0.52	0.58	0.55	0.57	0.59	0.61	0.56
	T30(2k)	0.60	0.66	0.63	0.59	0.66	0.59	0.68	0.65	0.65	0.66	0.69	0.65
	T30(1k)	0.68	0.70	0.65	0.67	0.75	0.69	0.76	0.68	0.75	0.72	0.92	0.82
	T30(500)	0.83	0.84	0.82	0.84	0.86	0.83	0.89	0.90	0.93	0.98	0.96	1.02
	T30(250)	0.93	0.95	0.93	0.95	0.96	0.92	0.99	0.99	0.94	0.99	1.07	1.03
	T30(125)	0.99	1.02	0.98	1.01	1.09	1.03	1.06	1.11	1.08	1.31	1.24	1.30
U-50 (dB)	U50(8k)	6.42	9.51	6.46	4.44	6.27	4.76	2.82	3.10	3.16	1.65	1.64	1.73
	U50(4k)	8.77	10.64	8.59	6.45	7.69	6.67	6.69	6.26	6.85	6.55	6.40	6.53
	U50(2k)	8.13	10.69	8.21	6.41	8.32	7.12	6.79	6.12	6.69	6.97	6.77	6.41
	U50(1k)	6.58	7.67	6.48	4.50	4.73	4.34	4.54	4.91	5.26	4.71	5.39	5.92
	U50(500)	4.25	4.99	4.25	3.35	4.02	3.78	2.84	2.12	2.61	1.87	1.23	1.51
	U50(250)	3.21	4.41	3.39	0.90	1.79	1.57	1.15	0.92	1.15	1.19	1.03	1.43
	U50(125)	2.46	2.65	2.84	1.43	1.66	1.94	1.48	0.89	1.57	1.53	0.96	1.79
G-50 (dB)	G50(8k)	8.23	11.11	8.29	5.89	7.61	6.35	3.69	3.92	3.90	2.13	2.10	2.27
	G50(4k)	9.08	10.28	8.99	6.13	6.83	6.69	4.37	3.94	4.41	3.19	2.69	3.44
	G50(2k)	8.95	10.31	8.95	6.46	7.74	7.60	4.47	3.90	4.22	3.54	2.65	3.15
	G50(1k)	10.40	11.30	10.54	7.46	7.94	7.51	5.79	6.20	6.39	4.65	5.04	5.96
	G50(500)	12.03	12.75	12.17	10.41	11.05	10.89	8.46	8.01	8.23	6.30	5.57	6.08
	G50(250)	11.67	12.63	11.90	8.70	9.53	9.40	7.59	7.58	7.67	6.71	6.43	7.13
	G50(125)	11.81	11.91	12.31	10.09	10.44	10.67	8.89	8.47	8.99	7.95	7.21	8.29
	STI	0.76	0.79	0.76	0.71	0.75	0.73	0.70	0.69	0.70	0.69	0.69	0.69

Table A. 6. Scenario ABS-C | Ln,a

ABS-C Ln,a (44dBA)	RECEIVER	1	2	3	4	5	6	7	8	9	10	11	12
MEAN	U50 (500-4k)	4.50	5.90	4.51	2.23	3.27	2.54	2.29	1.29	1.82	1.14	0.90	1.16
	T30 (500-4k)	0.68	0.67	0.69	0.69	0.69	0.66	0.71	0.74	0.70	0.78	0.79	0.74
	G50 (500-4k)	10.07	11.20	10.16	7.27	8.15	7.70	6.25	5.23	5.61	4.31	3.86	4.39
T-30 (s)	T30(8k)	0.38	0.38	0.40	0.40	0.39	0.40	0.41	0.41	0.42	0.44	0.41	0.40
	T30(4k)	0.55	0.55	0.56	0.52	0.55	0.53	0.55	0.57	0.57	0.59	0.63	0.56
	T30(2k)	0.63	0.62	0.63	0.66	0.64	0.60	0.71	0.69	0.66	0.81	0.73	0.67
	T30(1k)	0.69	0.68	0.70	0.72	0.69	0.68	0.76	0.77	0.69	0.79	0.89	0.81
	T30(500)	0.86	0.84	0.85	0.86	0.87	0.82	0.83	0.92	0.89	0.91	0.92	0.92
	T30(250)	0.94	0.93	0.93	0.93	0.95	0.94	0.96	0.98	0.95	0.99	1.02	0.95
	T30(125)	1.05	1.05	1.04	1.06	1.15	1.07	1.20	1.11	1.17	1.11	1.18	1.15
U-50 (dB)	U50(8k)	6.46	9.42	6.48	4.03	5.94	4.38	3.09	3.05	2.90	1.48	1.45	1.59
	U50(4k)	1.27	2.80	1.29	-1.85	-0.94	-1.40	-2.39	-3.48	-2.91	-4.13	-4.56	-3.97
	U50(2k)	6.49	8.62	6.45	4.24	6.05	5.11	4.37	3.21	3.60	3.56	2.86	2.79
	U50(1k)	6.06	7.29	5.97	3.62	4.20	3.06	4.32	3.79	4.39	3.77	4.43	4.96
	U50(500)	4.17	4.89	4.33	2.92	3.76	3.39	2.84	1.63	2.21	1.35	0.85	0.85
	U50(250)	3.17	4.29	3.27	0.37	1.12	0.98	0.85	0.22	0.72	1.11	0.62	0.98
	U50(125)	2.40	2.53	2.84	0.99	1.25	1.47	1.53	0.70	1.43	1.28	0.75	1.43
G-50 (dB)	G50(8k)	8.30	11.08	8.35	5.51	7.23	5.95	3.91	3.83	3.67	1.97	1.91	2.15
	G50(4k)	8.98	10.42	9.02	5.75	6.59	6.26	4.96	3.86	4.40	3.13	2.65	3.27
	G50(2k)	8.97	10.39	8.98	6.33	7.60	7.37	5.02	3.87	4.12	3.60	2.64	2.98
	G50(1k)	10.31	11.27	10.40	7.02	7.66	6.65	6.41	5.72	6.05	4.52	4.80	5.70
	G50(500)	12.03	12.71	12.23	9.97	10.75	10.53	8.59	7.45	7.87	5.98	5.36	5.61
	G50(250)	11.60	12.66	11.81	8.20	8.88	8.86	7.49	6.89	7.21	6.63	6.09	6.70
	G50(125)	11.85	11.92	12.47	9.69	10.02	10.28	9.15	8.31	8.90	7.85	7.07	7.99
	STI	0.69	0.73	0.69	0.62	0.66	0.64	0.61	0.58	0.60	0.57	0.57	0.58

Table A. 7. Scenario ABS-C | Ln,a-v1

ABS-C Ln,a-v1 (50dBA)	RECEIVER	1	2	3	4	5	6	7	8	9	10	11	12
MEAN	U50 (500-4k)	2.21	3.29	2.12	-0.14	0.65	0.42	-1.09	-1.40	-0.99	-2.01	-2.32	-1.85
	T30 (500-4k)	0.67	0.68	0.66	0.68	0.72	0.66	0.71	0.71	0.71	0.75	0.77	0.81
	G50 (500-4k)	10.61	11.44	10.60	8.07	8.73	8.72	6.34	6.12	6.31	4.93	4.47	5.10
T-30 (s)	T30(8k)	0.38	0.38	0.40	0.40	0.40	0.41	0.42	0.42	0.45	0.42	0.44	0.41
	T30(4k)	0.51	0.51	0.52	0.53	0.55	0.53	0.55	0.55	0.60	0.57	0.65	0.66
	T30(2k)	0.64	0.63	0.60	0.65	0.65	0.58	0.65	0.64	0.68	0.69	0.71	0.69
	T30(1k)	0.68	0.72	0.67	0.70	0.82	0.69	0.73	0.77	0.70	0.77	0.79	0.90
	T30(500)	0.86	0.87	0.84	0.84	0.84	0.85	0.90	0.89	0.86	0.96	0.94	0.97
	T30(250)	0.93	0.95	0.93	0.96	0.97	0.93	0.98	0.99	0.92	0.99	1.03	1.12
	T30(125)	1.05	1.11	1.03	1.08	1.08	1.09	1.13	1.28	1.12	1.17	1.43	1.11
U-50 (dB)	U50(8k)	1.89	4.77	1.97	-0.44	1.32	0.07	-2.41	-2.43	-2.29	-3.99	-3.95	-3.79
	U50(4k)	-3.99	-2.85	-4.08	-7.24	-6.42	-6.50	-8.70	-9.05	-8.47	-9.98	-10.39	-9.60
	U50(2k)	3.52	5.21	3.51	1.16	2.48	2.21	-0.17	-0.77	-0.33	-0.82	-1.73	-1.43
	U50(1k)	5.20	6.19	5.04	2.86	2.91	2.63	2.35	2.46	2.80	1.95	2.36	2.96
	U50(500)	4.09	4.62	4.00	2.67	3.62	3.35	2.17	1.76	2.06	0.81	0.47	0.68
	U50(250)	3.09	4.07	2.99	0.35	1.11	1.19	0.50	0.09	0.59	0.72	0.30	0.88
	U50(125)	2.40	2.35	2.50	0.78	1.19	1.75	0.93	0.46	1.18	0.91	0.26	1.05
G-50 (dB)	G50(8k)	8.50	11.22	8.62	6.20	7.75	6.72	3.91	3.90	4.02	2.26	2.29	2.49
	G50(4k)	9.43	10.45	9.34	6.37	7.05	7.10	4.73	4.45	4.92	3.39	2.96	3.74
	G50(2k)	9.29	10.52	9.32	6.92	7.86	8.06	4.90	4.34	4.69	3.97	2.96	3.48
	G50(1k)	10.93	11.57	10.89	8.14	8.26	8.17	6.55	6.65	6.80	5.33	5.32	6.29
	G50(500)	12.77	13.23	12.85	10.85	11.73	11.53	9.16	9.03	8.84	7.04	6.65	6.87
	G50(250)	12.43	13.25	12.49	9.64	10.22	10.34	8.52	8.22	8.56	7.71	7.24	7.88
	G50(125)	12.87	12.78	13.08	10.95	11.31	11.72	9.82	9.65	9.97	8.86	8.14	9.05
	STI	0.60	0.64	0.60	0.53	0.56	0.55	0.49	0.48	0.49	0.46	0.45	0.46

Table A. 8. Scenario ABS-C | Ln,a-v2

ABS-C Ln,a-v2 (55dBA)	MEAN			T-30 (s)							U-50 (dB)							G-50 (dB)							
RECEIVER	U50 (500-4k)	T30 (500-4k)	G50 (500-4k)	T30(8k)	T30(4k)	T30(2k)	T30(1k)	T30(500)	T30(250)	T30(125)	U50(8k)	U50(4k)	U50(2k)	U50(1k)	U50(500)	U50(250)	U50(125)	G50(8k)	G50(4k)	G50(2k)	G50(1k)	G50(500)	G50(250)	G50(125)	STI
1	-0.64	0.66	10.21	0.37	0.50	0.63	0.69	0.82	0.94	1.04	-2.69	-8.97	-0.22	3.17	3.48	2.51	1.69	8.30	9.04	9.13	10.48	12.18	11.66	11.97	0.49
2	0.39	0.68	11.15	0.38	0.51	0.61	0.73	0.86	0.93	1.09	0.15	-7.65	1.14	4.05	4.02	3.64	1.76	11.12	10.35	10.35	11.20	12.69	12.69	11.93	0.53
3	-0.69	0.64	10.22	0.40	0.51	0.59	0.64	0.80	0.93	1.00	-2.49	-8.98	-0.36	3.22	3.36	2.68	1.88	8.50	9.03	9.00	10.63	12.20	11.82	12.28	0.49
4	-3.15	0.67	7.41	0.40	0.54	0.59	0.69	0.85	0.94	1.06	-5.40	-12.13	-2.97	0.62	1.88	-0.20	0.00	5.55	5.87	6.29	7.48	10.00	8.34	9.63	0.42
5	-2.27	0.69	8.27	0.39	0.56	0.62	0.70	0.88	0.95	1.10	-3.51	-11.12	-1.59	0.81	2.82	0.67	0.48	7.42	6.87	7.60	7.75	10.87	9.20	10.15	0.45
6	-2.58	0.66	8.02	0.40	0.53	0.58	0.72	0.81	0.93	1.07	-4.69	-11.55	-1.66	0.25	2.65	0.46	0.80	6.27	6.45	7.65	7.23	10.76	9.03	10.52	0.44
7	-4.41	0.71	5.70	0.40	0.60	0.65	0.71	0.88	0.95	1.06	-7.11	-13.63	-4.57	-0.56	1.13	-0.22	0.05	3.78	4.34	4.46	5.73	8.25	7.42	8.77	0.37
8	-4.80	0.72	5.34	0.40	0.56	0.65	0.68	0.98	0.96	1.12	-7.22	-14.12	-5.01	-0.60	0.55	-0.74	-0.42	3.67	3.87	4.06	5.72	7.72	6.86	8.39	0.36
9	-4.31	0.73	5.74	0.41	0.58	0.67	0.69	0.97	0.98	1.04	-7.13	-13.45	-4.77	-0.07	1.06	-0.02	0.25	3.75	4.53	4.24	6.16	8.03	7.49	8.83	0.37
10	-5.51	0.74	4.28	0.41	0.60	0.74	0.72	0.91	1.03	1.35	-8.73	-14.85	-5.41	-1.34	-0.42	-0.12	-0.14	2.11	3.12	3.55	4.58	5.85	6.65	7.84	0.34
11	-5.80	0.82	3.91	0.41	0.60	0.77	0.96	0.93	1.02	1.27	-8.94	-15.39	-6.16	-0.96	-0.70	-0.57	-0.78	1.91	2.58	2.77	4.82	5.45	6.16	7.09	0.34
12	-5.32	0.78	4.47	0.40	0.56	0.73	0.91	0.93	0.99	1.16	-8.67	-14.58	-6.02	-0.07	-0.60	-0.09	0.06	2.18	3.39	2.94	5.83	5.72	6.73	8.01	0.34

Table A. 9. Scenario ABS-CW | Ln,u

ABS-CW Ln,u (30dBA)	RECEIVER	1	2	3	4	5	6	7	8	9	10	11	12
MEAN	U50 (500-4k)	9.63	10.67	8.96	8.56	8.65	8.62	9.31	8.09	8.75	7.55	8.15	7.56
	T30 (500-4k)	0.48	0.47	0.50	0.48	0.45	0.49	0.47	0.45	0.49	0.47	0.47	0.47
	G50 (500-4k)	9.68	10.89	9.69	7.04	8.18	7.61	6.44	5.38	5.50	2.79	3.57	2.67
T-30 (s)	T30(8k)	0.29	0.30	0.35	0.30	0.29	0.34	0.30	0.31	0.30	0.30	0.30	0.31
	T30(4k)	0.37	0.37	0.46	0.38	0.36	0.41	0.36	0.37	0.41	0.39	0.36	0.39
	T30(2k)	0.44	0.43	0.49	0.46	0.39	0.48	0.50	0.41	0.49	0.45	0.43	0.43
	T30(1k)	0.53	0.51	0.49	0.53	0.48	0.50	0.47	0.46	0.49	0.48	0.48	0.50
	T30(500)	0.56	0.56	0.57	0.56	0.56	0.55	0.56	0.57	0.55	0.57	0.59	0.56
	T30(250)	0.68	0.69	0.67	0.70	0.69	0.69	0.68	0.69	0.69	0.69	0.72	0.69
	T30(125)	0.80	0.81	0.78	0.85	0.80	0.81	0.83	0.83	0.79	1.03	0.81	0.88
U-50 (dB)	U50(8k)	7.16	9.94	6.89	4.98	6.73	5.31	4.01	3.40	3.46	0.33	1.65	0.41
	U50(4k)	11.46	12.80	10.69	9.65	9.87	9.61	10.07	8.88	9.86	7.75	8.65	7.92
	U50(2k)	11.59	13.24	10.66	10.96	10.71	11.31	11.46	9.77	10.61	9.86	10.44	9.67
	U50(1k)	8.98	9.64	8.38	7.72	7.47	6.96	8.96	8.17	8.62	8.19	9.10	8.78
	U50(500)	6.49	7.00	6.09	5.91	6.54	6.60	6.73	5.52	5.89	4.40	4.42	3.87
	U50(250)	4.72	5.59	4.58	2.44	3.34	3.29	4.16	2.95	3.26	3.23	3.22	3.44
	U50(125)	3.57	3.55	3.58	2.45	3.22	3.29	4.08	2.76	3.23	2.89	2.56	3.14
G-50 (dB)	G50(8k)	7.96	10.92	7.85	5.49	7.44	5.89	4.22	3.67	3.65	0.36	1.72	0.47
	G50(4k)	8.57	10.10	8.58	5.58	6.49	6.04	4.87	3.79	4.29	1.14	2.38	1.30
	G50(2k)	8.58	10.11	8.58	6.01	7.40	7.26	5.06	3.89	3.84	1.64	2.29	1.08
	G50(1k)	10.02	10.93	10.03	6.94	7.91	6.58	6.83	6.06	6.03	3.70	4.72	4.13
	G50(500)	11.56	12.40	11.57	9.62	10.90	10.54	9.00	7.78	7.85	4.69	4.87	4.15
	G50(250)	11.19	12.36	11.43	7.95	9.17	9.06	8.38	7.28	7.27	5.84	5.91	6.09
	G50(125)	11.69	11.67	11.89	9.58	10.58	10.49	9.88	8.57	8.93	7.45	6.97	7.81
	STI	0.81	0.84	0.80	0.78	0.80	0.79	0.79	0.76	0.77	0.74	0.76	0.74

Table A. 10. Scenario ABS-CW | Ln,a

ABS-CW Ln,a (44dBA)	RECEIVER	1	2	3	4	5	6	7	8	9	10	11	12
MEAN	U50 (500-4k)	6.10	7.19	5.69	4.18	4.90	4.56	4.60	2.90	3.57	1.80	2.51	1.63
	T30 (500-4k)	0.48	0.46	0.50	0.47	0.44	0.49	0.45	0.45	0.49	0.48	0.47	0.48
	G50 (500-4k)	9.73	10.94	9.66	6.94	8.27	7.55	6.65	5.00	5.36	2.74	3.57	2.55
T-30 (s)	T30(8k)	0.30	0.30	0.35	0.30	0.28	0.35	0.30	0.30	0.29	0.30	0.29	0.30
	T30(4k)	0.37	0.37	0.46	0.38	0.36	0.41	0.37	0.39	0.40	0.39	0.37	0.40
	T30(2k)	0.43	0.42	0.49	0.45	0.38	0.48	0.42	0.41	0.50	0.44	0.46	0.44
	T30(1k)	0.53	0.50	0.50	0.48	0.48	0.50	0.45	0.45	0.50	0.50	0.49	0.50
	T30(500)	0.58	0.56	0.56	0.55	0.54	0.55	0.56	0.56	0.56	0.57	0.57	0.57
	T30(250)	0.70	0.69	0.68	0.69	0.69	0.68	0.67	0.68	0.69	0.70	0.71	0.71
	T30(125)	0.79	0.80	0.82	0.82	0.77	0.80	0.81	0.80	0.92	0.86	0.84	0.86
U-50 (dB)	U50(8k)	7.04	10.12	6.80	4.90	7.12	5.31	4.32	3.33	3.36	0.49	1.59	0.34
	U50(4k)	1.35	2.90	1.10	-1.73	-0.58	-1.14	-1.97	-3.75	-2.93	-5.68	-4.75	-5.90
	U50(2k)	8.34	9.83	7.81	6.41	7.44	7.34	5.81	4.23	4.93	3.11	3.74	2.61
	U50(1k)	8.24	9.12	7.77	6.35	6.44	5.91	8.04	6.10	7.06	5.80	6.95	6.46
	U50(500)	6.48	6.91	6.07	5.67	6.30	6.12	6.52	5.01	5.20	3.95	4.08	3.34
	U50(250)	4.70	5.63	4.65	2.45	3.81	3.14	4.37	2.63	3.21	3.01	3.13	3.26
	U50(125)	3.40	3.71	3.52	2.33	3.16	3.15	3.96	2.70	3.04	2.77	2.26	2.78
G-50 (dB)	G50(8k)	7.85	11.01	7.79	5.41	7.82	5.84	4.55	3.59	3.57	0.54	1.66	0.38
	G50(4k)	8.62	10.18	8.45	5.44	6.66	6.06	5.13	3.36	4.14	1.35	2.29	1.12
	G50(2k)	8.61	10.09	8.57	5.91	7.60	7.16	4.86	3.29	3.85	1.67	2.33	1.03
	G50(1k)	10.04	11.10	10.02	6.92	7.86	6.63	7.57	5.68	5.86	3.37	4.67	3.94
	G50(500)	11.64	12.38	11.58	9.47	10.94	10.36	9.05	7.67	7.59	4.57	5.00	4.10
	G50(250)	11.29	12.47	11.48	8.07	9.75	8.95	8.75	7.18	7.41	6.00	6.11	6.00
	G50(125)	11.61	12.00	11.84	9.56	10.71	10.41	10.03	8.79	8.73	7.48	6.94	7.58
	STI	0.72	0.76	0.71	0.66	0.70	0.68	0.67	0.62	0.63	0.58	0.60	0.58

Table A. 11. Scenario ABS-CW | Ln,a-v1

ABS-CW Ln,a-v1 (50dBA)	RECEIVER	1	2	3	4	5	6	7	8	9	10	11	12
MEAN	U50 (500-4k)	3.06	4.17	2.89	0.86	1.27	1.41	0.38	-1.10	-0.34	-2.38	-1.67	-2.56
	T30 (500-4k)	0.47	0.48	0.50	0.47	0.45	0.49	0.45	0.46	0.49	0.48	0.49	0.48
	G50 (500-4k)	10.00	11.17	10.07	7.23	8.08	7.91	6.21	4.87	5.46	2.97	3.68	2.76
T-30 (s)	T30(8k)	0.30	0.29	0.34	0.31	0.30	0.34	0.30	0.30	0.30	0.30	0.30	0.32
	T30(4k)	0.36	0.37	0.46	0.39	0.36	0.44	0.37	0.37	0.42	0.39	0.38	0.40
	T30(2k)	0.43	0.43	0.49	0.44	0.40	0.48	0.43	0.42	0.49	0.44	0.42	0.46
	T30(1k)	0.52	0.52	0.50	0.50	0.49	0.50	0.46	0.47	0.50	0.51	0.53	0.48
	T30(500)	0.56	0.58	0.56	0.56	0.55	0.54	0.55	0.57	0.56	0.58	0.62	0.57
	T30(250)	0.68	0.68	0.68	0.69	0.69	0.71	0.69	0.72	0.71	0.74	0.72	0.69
	T30(125)	0.82	0.83	0.84	0.82	0.83	0.82	0.86	0.80	0.83	0.93	0.88	0.87
U-50 (dB)	U50(8k)	1.75	4.85	1.81	-0.75	0.96	-0.12	-2.35	-2.98	-2.64	-5.50	-4.26	-5.64
	U50(4k)	-4.41	-2.90	-4.49	-7.71	-6.90	-6.89	-8.43	-10.03	-8.97	-11.83	-10.92	-11.88
	U50(2k)	4.13	5.59	3.97	1.76	2.76	2.88	0.63	-1.10	-0.37	-2.36	-1.72	-2.98
	U50(1k)	6.52	7.48	6.38	4.41	4.05	3.99	4.46	3.23	3.79	2.31	3.36	2.93
	U50(500)	6.00	6.51	5.69	4.99	5.16	5.65	4.87	3.49	4.21	2.37	2.61	1.68
	U50(250)	4.66	5.36	4.49	1.80	2.22	2.73	2.57	1.29	2.15	2.20	2.17	2.18
	U50(125)	3.23	3.20	3.23	1.83	2.21	2.61	2.38	1.40	2.25	1.91	1.41	2.06
G-50 (dB)	G50(8k)	8.00	11.07	8.08	5.37	7.12	6.04	3.67	3.11	3.39	0.50	1.74	0.35
	G50(4k)	8.77	10.23	8.74	5.49	6.37	6.34	4.71	3.17	4.18	1.33	2.22	1.27
	G50(2k)	8.78	10.22	8.89	6.21	7.45	7.40	4.92	3.28	3.90	1.86	2.37	1.21
	G50(1k)	10.30	11.36	10.47	7.24	7.65	7.10	6.64	5.41	5.85	3.71	4.69	4.19
	G50(500)	12.15	12.87	12.18	9.99	10.85	10.81	8.55	7.62	7.90	4.98	5.42	4.35
	G50(250)	12.32	13.05	12.31	8.76	9.54	9.70	8.20	7.10	7.59	6.42	6.40	6.41
	G50(125)	12.55	12.57	12.76	10.39	10.95	11.10	9.57	8.90	9.28	8.03	7.60	8.16
	STI	0.61	0.66	0.61	0.54	0.57	0.57	0.52	0.48	0.50	0.44	0.46	0.43

Table A. 12. Scenario ABS-CW | Ln,a-v2

ABS-CW Ln,a-v2 (55dBA)	RECEIVER	1	2	3	4	5	6	7	8	9	10	11	12
MEAN	U50 (500-4k)	-0.37	0.94	-0.39	-2.55	-1.74	-2.14	-2.81	-4.22	-3.93	-6.23	-5.43	-6.34
	T30 (500-4k)	0.48	0.48	0.51	0.49	0.45	0.49	0.48	0.51	0.50	0.49	0.47	0.48
	G50 (500-4k)	9.58	10.99	9.69	7.06	8.06	7.51	6.52	5.13	5.32	2.75	3.56	2.63
T-30 (s)	T30(8k)	0.29	0.30	0.35	0.31	0.29	0.34	0.30	0.33	0.30	0.31	0.30	0.32
	T30(4k)	0.37	0.37	0.46	0.39	0.37	0.41	0.44	0.39	0.44	0.42	0.36	0.38
	T30(2k)	0.45	0.44	0.49	0.47	0.40	0.48	0.43	0.60	0.48	0.44	0.44	0.44
	T30(1k)	0.51	0.52	0.51	0.53	0.49	0.49	0.45	0.47	0.50	0.50	0.50	0.50
	T30(500)	0.57	0.58	0.58	0.57	0.55	0.56	0.58	0.58	0.59	0.58	0.56	0.61
	T30(250)	0.69	0.68	0.71	0.69	0.68	0.67	0.69	0.67	0.68	0.70	0.69	0.71
	T30(125)	0.80	0.79	0.80	0.81	0.79	0.83	0.83	0.81	0.84	0.88	0.86	0.83
U-50 (dB)	U50(8k)	-3.04	0.16	-3.09	-5.04	-3.53	-5.04	-6.50	-7.23	-7.30	-10.31	-9.11	-10.43
	U50(4k)	-9.49	-7.72	-9.53	-12.48	-11.55	-11.85	-13.10	-14.44	-13.81	-16.74	-15.61	-16.70
	U50(2k)	-0.52	1.21	-0.46	-2.82	-1.47	-1.65	-3.81	-5.45	-5.04	-7.19	-6.47	-7.76
	U50(1k)	3.66	4.75	3.61	1.17	1.46	0.68	1.61	0.27	0.40	-1.53	-0.56	-0.97
	U50(500)	4.86	5.52	4.83	3.93	4.60	4.27	4.08	2.74	2.73	0.53	0.91	0.09
	U50(250)	3.60	4.72	3.60	1.05	1.91	1.79	2.46	1.23	1.57	0.93	0.78	1.09
	U50(125)	2.39	2.51	2.54	1.15	1.55	1.71	2.23	1.23	1.42	0.62	0.33	0.69
G-50 (dB)	G50(8k)	7.84	11.05	7.81	5.81	7.34	5.82	4.32	3.60	3.53	0.50	1.71	0.38
	G50(4k)	8.48	10.25	8.45	5.48	6.41	6.11	4.86	3.53	4.14	1.21	2.34	1.25
	G50(2k)	8.46	10.18	8.59	6.07	7.49	7.28	5.03	3.42	3.78	1.60	2.33	1.03
	G50(1k)	9.88	11.01	10.05	6.94	7.51	6.52	7.12	5.73	5.76	3.64	4.56	4.16
	G50(500)	11.50	12.52	11.68	9.73	10.84	10.14	9.06	7.84	7.60	4.54	5.01	4.07
	G50(250)	11.21	12.42	11.36	7.90	8.99	8.67	8.45	7.25	7.33	5.72	5.77	5.96
	G50(125)	11.64	11.77	11.89	9.59	10.23	10.18	9.86	8.90	8.87	7.35	7.01	7.52
	STI	0.49	0.54	0.50	0.43	0.46	0.44	0.41	0.38	0.38	0.32	0.34	0.32

Table A. 13. Scenario ER | Ln,u

ER Ln,u (30dBA)	RECEIVER	1	2	3	4	5	6	7	8	9	10	11	12
MEAN	U50 (500-4k)	4.95	4.85	4.88	4.06	3.91	4.21	5.21	4.04	4.54	4.75	5.10	4.60
	T30 (500-4k)	0.64	0.65	0.63	0.64	0.64	0.64	0.64	0.69	0.67	0.63	0.64	0.64
	G50 (500-4k)	12.72	13.24	13.13	10.44	11.00	10.79	8.31	7.37	7.68	5.26	5.76	4.97
T-30 (s)	T30(8k)	0.43	0.42	0.42	0.42	0.42	0.43	0.43	0.42	0.44	0.44	0.43	0.42
	T30(4k)	0.54	0.58	0.54	0.53	0.54	0.53	0.52	0.58	0.53	0.52	0.52	0.53
	T30(2k)	0.56	0.55	0.56	0.57	0.55	0.56	0.55	0.57	0.59	0.55	0.57	0.61
	T30(1k)	0.64	0.64	0.64	0.66	0.65	0.65	0.65	0.69	0.68	0.61	0.68	0.65
	T30(500)	0.82	0.81	0.79	0.79	0.82	0.83	0.84	0.90	0.88	0.82	0.79	0.77
	T30(250)	1.01	1.01	1.00	0.97	0.98	1.00	0.99	1.00	1.01	0.99	1.00	1.00
	T30(125)	1.20	1.22	1.19	1.25	1.21	1.17	1.21	1.20	1.22	1.30	1.21	1.21
U-50 (dB)	U50(8k)	6.26	7.73	6.30	5.11	5.89	4.93	4.27	3.83	3.92	2.03	3.01	1.89
	U50(4k)	6.73	6.52	6.40	5.20	5.17	5.51	6.72	5.59	6.38	6.07	6.72	6.29
	U50(2k)	6.20	6.39	6.05	5.79	5.54	6.02	6.80	5.43	6.13	6.62	6.75	5.98
	U50(1k)	4.25	4.15	4.14	2.97	2.87	2.99	4.47	3.71	3.86	4.74	5.48	5.30
	U50(500)	2.61	2.32	2.94	2.28	2.06	2.33	2.85	1.43	1.77	1.58	1.43	0.84
	U50(250)	1.23	1.75	1.51	-0.72	-0.53	-0.17	0.61	-0.29	0.04	0.71	0.80	0.87
	U50(125)	-0.25	-0.50	0.48	-0.71	-0.67	-0.44	0.28	-0.92	-0.25	-0.11	-0.43	0.07
G-50 (dB)	G50(8k)	10.65	12.79	11.01	8.57	9.70	8.43	5.89	5.49	5.64	2.84	3.88	2.69
	G50(4k)	11.42	11.96	11.58	8.56	9.23	9.04	6.78	5.82	6.33	3.80	4.43	3.73
	G50(2k)	11.93	12.83	12.38	10.01	10.48	10.50	7.43	6.32	6.68	4.25	4.79	3.60
	G50(1k)	13.76	14.17	14.11	10.97	11.69	11.14	8.94	8.42	8.48	6.42	7.16	6.62
	G50(500)	13.77	14.00	14.44	12.23	12.61	12.49	10.10	8.90	9.21	6.57	6.66	5.93
	G50(250)	12.95	13.73	13.50	10.02	10.61	10.64	8.99	8.27	8.50	7.23	7.61	7.44
	G50(125)	13.58	13.66	14.57	12.06	12.41	12.49	10.76	9.84	10.38	8.89	8.68	9.14
	STI	0.71	0.72	0.72	0.69	0.70	0.70	0.71	0.68	0.69	0.69	0.70	0.69

Table A. 14. Scenario ER | Ln,a

ER Ln,a (44dBA)	RECEIVER	1	2	3	4	5	6	7	8	9	10	11	12
MEAN	U50 (500-4k)	3.78	3.80	3.83	2.50	2.58	2.76	2.53	1.62	1.93	1.32	1.73	1.25
	T30 (500-4k)	0.64	0.64	0.63	0.64	0.63	0.65	0.64	0.63	0.66	0.66	0.64	0.67
	G50 (500-4k)	12.78	13.38	13.21	10.44	11.02	10.84	8.15	7.39	7.63	5.18	5.76	5.00
T-30 (s)	T30(8k)	0.42	0.43	0.42	0.42	0.43	0.42	0.42	0.43	0.43	0.42	0.43	0.42
	T30(4k)	0.53	0.53	0.52	0.53	0.53	0.53	0.53	0.53	0.55	0.54	0.53	0.56
	T30(2k)	0.58	0.56	0.54	0.56	0.55	0.59	0.58	0.57	0.63	0.64	0.57	0.65
	T30(1k)	0.64	0.64	0.65	0.67	0.65	0.67	0.65	0.64	0.65	0.65	0.63	0.63
	T30(500)	0.81	0.81	0.79	0.79	0.80	0.79	0.80	0.78	0.79	0.81	0.83	0.84
	T30(250)	0.98	1.01	1.00	1.01	1.02	1.01	0.99	1.00	1.01	1.03	1.01	0.99
	T30(125)	1.18	1.18	1.15	1.15	1.18	1.17	1.21	1.20	1.22	1.24	1.21	1.25
U-50 (dB)	U50(8k)	7.00	7.99	6.39	5.35	5.95	5.12	4.23	3.96	3.75	2.22	2.89	1.86
	U50(4k)	2.53	2.94	2.62	0.20	0.60	0.63	-1.01	-1.93	-1.42	-3.63	-2.93	-3.60
	U50(2k)	5.81	5.90	5.49	4.86	4.78	5.21	4.78	3.80	4.30	3.48	4.02	3.03
	U50(1k)	4.28	3.94	4.54	2.98	2.86	2.89	4.02	3.49	3.28	4.11	4.60	4.51
	U50(500)	2.49	2.41	2.68	1.97	2.06	2.31	2.32	1.13	1.54	1.33	1.24	1.04
	U50(250)	1.19	1.86	1.40	-0.51	-0.64	-0.12	0.48	-0.59	0.05	0.73	0.57	0.76
	U50(125)	-0.15	-0.57	0.38	-0.89	-0.73	-0.35	-0.02	-0.81	-0.27	-0.09	-0.33	-0.11
G-50 (dB)	G50(8k)	11.33	12.82	11.07	8.61	9.67	8.75	5.89	5.71	5.44	3.00	3.78	2.68
	G50(4k)	11.44	12.15	11.73	8.63	9.25	9.09	6.62	5.77	6.24	3.69	4.41	3.73
	G50(2k)	12.17	12.94	12.35	9.93	10.50	10.53	7.20	6.31	6.77	4.18	4.76	3.63
	G50(1k)	13.84	14.28	14.52	11.19	11.68	11.20	8.94	8.55	8.39	6.28	7.13	6.61
	G50(500)	13.68	14.15	14.25	12.01	12.66	12.53	9.82	8.91	9.13	6.58	6.72	6.02
	G50(250)	12.91	13.97	13.37	10.26	10.42	10.70	8.87	8.08	8.50	7.32	7.45	7.40
	G50(125)	13.75	13.62	14.49	12.05	12.45	12.65	10.58	9.98	10.40	8.87	8.79	8.99
	STI	0.68	0.69	0.68	0.64	0.65	0.65	0.63	0.61	0.61	0.59	0.60	0.58

Table A. 15. Scenario ER | Ln,a-v1

ER Ln,a-v1 (50dBA)	RECEIVER	1	2	3	4	5	6	7	8	9	10	11	12
MEAN	U50 (500-4k)	2.29	2.35	2.20	0.80	1.09	1.02	0.00	-0.78	-0.37	-1.55	-1.07	-1.84
	T30 (500-4k)	0.64	0.64	0.63	0.65	0.66	0.64	0.65	0.63	0.65	0.65	0.65	0.67
	G50 (500-4k)	13.64	14.15	13.87	11.35	12.07	11.73	8.68	8.10	8.32	5.87	6.40	5.72
T-30 (s)	T30(8k)	0.43	0.42	0.43	0.43	0.43	0.42	0.43	0.43	0.43	0.43	0.43	0.43
	T30(4k)	0.52	0.53	0.53	0.53	0.52	0.52	0.52	0.51	0.56	0.52	0.53	0.53
	T30(2k)	0.59	0.58	0.57	0.58	0.60	0.58	0.58	0.56	0.59	0.63	0.64	0.56
	T30(1k)	0.65	0.64	0.62	0.68	0.69	0.64	0.65	0.64	0.63	0.63	0.63	0.78
	T30(500)	0.81	0.82	0.80	0.82	0.82	0.81	0.85	0.79	0.81	0.81	0.81	0.79
	T30(250)	1.00	1.00	1.00	1.01	1.03	0.99	0.99	0.99	0.99	1.02	1.00	1.01
	T30(125)	1.18	1.19	1.18	1.19	1.17	1.18	1.20	1.20	1.21	1.21	1.24	1.24
U-50 (dB)	U50(8k)	3.64	5.09	3.60	1.97	2.63	1.73	-0.64	-0.88	-0.95	-3.28	-2.28	-3.36
	U50(4k)	-1.89	-1.54	-1.67	-4.43	-4.07	-4.25	-6.51	-7.47	-6.94	-9.28	-8.54	-9.39
	U50(2k)	4.29	4.58	4.02	2.82	3.21	3.53	1.73	0.91	1.32	-0.44	0.11	-0.97
	U50(1k)	4.01	3.77	3.95	2.80	2.92	2.44	3.04	2.57	2.81	2.55	3.36	2.95
	U50(500)	2.73	2.58	2.48	1.99	2.30	2.36	1.74	0.86	1.34	0.96	0.81	0.07
	U50(250)	1.27	1.74	1.30	-0.45	-0.32	-0.32	0.00	-0.77	-0.13	0.21	0.24	0.39
	U50(125)	-0.04	-0.45	0.21	-0.81	-0.76	-0.47	-0.49	-1.06	-0.57	-0.41	-0.65	-0.36
G-50 (dB)	G50(8k)	11.47	13.13	11.64	9.32	10.19	9.26	6.03	5.86	5.79	3.14	4.11	3.06
	G50(4k)	12.09	12.57	12.42	9.49	10.02	9.70	7.06	6.24	6.69	4.18	4.89	4.10
	G50(2k)	12.73	13.43	12.81	10.35	11.31	11.20	7.62	6.94	7.31	4.62	5.21	4.22
	G50(1k)	14.75	15.29	15.08	12.43	13.02	12.37	9.64	9.18	9.23	7.04	7.74	7.29
	G50(500)	15.00	15.30	15.17	13.13	13.91	13.63	10.40	10.02	10.06	7.63	7.74	7.28
	G50(250)	14.03	14.92	14.45	11.76	12.25	12.07	9.91	9.43	9.81	8.34	8.39	8.47
	G50(125)	15.03	15.12	15.57	13.54	13.90	13.87	11.58	11.24	11.56	10.03	9.89	10.18
	STI	0.62	0.63	0.62	0.57	0.58	0.58	0.53	0.51	0.52	0.48	0.49	0.47

Table A. 16. Scenario ER | Ln,a-v2

ER Ln,a-v2 (55dBA)	RECEIVER	1	2	3	4	5	6	7	8	9	10	11	12
MEAN	U50 (500-4k)	0.02	0.28	0.24	-1.65	-1.21	-1.15	-2.81	-3.58	-3.22	-4.94	-4.48	-5.03
	T30 (500-4k)	0.64	0.65	0.65	0.63	0.64	0.63	0.66	0.65	0.64	0.64	0.67	0.65
	G50 (500-4k)	12.86	13.45	13.29	10.49	11.23	11.10	8.06	7.34	7.68	5.12	5.67	5.00
T-30 (s)	T30(8k)	0.43	0.42	0.44	0.42	0.42	0.42	0.43	0.43	0.43	0.42	0.42	0.43
	T30(4k)	0.52	0.54	0.53	0.54	0.54	0.52	0.66	0.59	0.51	0.55	0.65	0.50
	T30(2k)	0.54	0.56	0.54	0.55	0.58	0.55	0.56	0.55	0.60	0.59	0.59	0.58
	T30(1k)	0.62	0.65	0.64	0.64	0.64	0.66	0.65	0.65	0.65	0.59	0.60	0.70
	T30(500)	0.86	0.86	0.87	0.80	0.81	0.80	0.77	0.80	0.81	0.81	0.83	0.82
	T30(250)	1.00	0.99	0.98	1.00	1.01	0.99	0.99	1.00	0.99	1.00	1.00	0.99
	T30(125)	1.17	1.17	1.17	1.18	1.17	1.18	1.19	1.19	1.22	1.24	1.22	1.23
U-50 (dB)	U50(8k)	-0.53	1.37	-0.07	-2.61	-1.51	-2.25	-5.18	-5.36	-5.36	-8.11	-7.23	-8.16
	U50(4k)	-6.77	-6.01	-6.32	-9.33	-8.68	-8.77	-11.56	-12.20	-11.74	-14.33	-13.61	-14.22
	U50(2k)	1.68	2.13	1.72	-0.33	0.40	0.73	-2.08	-2.85	-2.55	-4.86	-4.42	-5.32
	U50(1k)	2.98	2.94	3.00	1.59	1.79	1.51	1.39	0.55	0.81	-0.12	0.60	0.29
	U50(500)	2.17	2.04	2.54	1.46	1.64	1.92	1.01	0.18	0.62	-0.45	-0.47	-0.85
	U50(250)	1.34	1.56	1.01	-1.02	-0.94	-0.35	-0.56	-1.39	-0.67	-0.64	-0.53	-0.37
	U50(125)	-0.54	-0.86	0.15	-1.22	-1.20	-0.64	-0.73	-1.49	-0.95	-1.28	-1.46	-0.97
G-50 (dB)	G50(8k)	10.88	12.89	11.43	8.62	9.79	9.01	5.81	5.64	5.63	2.78	3.66	2.72
	G50(4k)	11.38	12.18	11.85	8.77	9.44	9.34	6.45	5.82	6.27	3.64	4.38	3.76
	G50(2k)	12.24	12.89	12.39	9.72	10.66	10.88	7.24	6.53	6.77	4.16	4.64	3.70
	G50(1k)	13.84	14.45	14.25	11.34	12.07	11.46	9.07	8.29	8.51	6.31	7.17	6.65
	G50(500)	13.98	14.28	14.66	12.14	12.75	12.72	9.47	8.71	9.15	6.35	6.50	5.90
	G50(250)	13.47	14.10	13.44	10.14	10.65	11.00	8.65	7.91	8.42	6.99	7.28	7.31
	G50(125)	13.74	13.71	14.63	12.07	12.44	12.79	10.52	9.95	10.39	8.67	8.61	9.00
	STI	0.53	0.55	0.54	0.48	0.50	0.49	0.43	0.41	0.42	0.36	0.38	0.36

Table A. 17. Mean Absorption Percentage of Each Room Scenario

	MEAN ABSORPTION %						
SCENARIO	MA%(125)	MA%(250)	MA%(500)	MA%(1k)	MA%(2k)	MA%(4k)	MA%(8k)
EX	3.70	3.70	4.10	4.50	5.70	6.10	6.70
ABS-C	16.10	15.20	18.10	25.40	28.80	26.80	24.80
ABS-CW	17.60	18.00	22.40	29.40	32.80	31.30	29.90
ER	12.20	13.60	17.30	23.00	25.80	24.40	23.10

APPENDIX B

SPEECH RECOGNITION TESTS DATA

Table B. 1. Speech Recognition Test Data

DATA #	SCENARIO	TEST ROUND	RECEIVER	TMWRT LIST	LIST SCORE	P.#	AGE	GENDER
1	ABS-C Ln,a	1	R10	A_LIST	49	1	21	F
2	ABS-C Ln,a	1	R11	B_LIST	49	1	21	F
3	ABS-C Ln,a	1	R12	C_LIST	47	1	21	F
4	ABS-C Ln,a	1	R10	A_LIST	48	2	21	M
5	ABS-C Ln,a	1	R11	B_LIST	46	2	21	M
6	ABS-C Ln,a	1	R12	C_LIST	43	2	21	M
7	ABS-C Ln,a	1	R10	A_LIST	45	3	22	F
8	ABS-C Ln,a	1	R11	B_LIST	46	3	22	F
9	ABS-C Ln,a	1	R12	C_LIST	45	3	22	F
10	ABS-C Ln,a	1	R10	A_LIST	48	4	24	F
11	ABS-C Ln,a	1	R11	B_LIST	45	4	24	F
12	ABS-C Ln,a	1	R12	C_LIST	46	4	24	F
13	ABS-C Ln,u	1	R10	A_LIST	47	5	28	M
14	ABS-C Ln,u	1	R11	B_LIST	49	5	28	M
15	ABS-C Ln,u	1	R12	C_LIST	47	5	28	M
16	ABS-C Ln,u	1	R10	A_LIST	49	6	24	F
17	ABS-C Ln,u	1	R11	B_LIST	46	6	24	F
18	ABS-C Ln,u	1	R12	C_LIST	50	6	24	F
19	ABS-C Ln,u	1	R10	A_LIST	45	7	23	F
20	ABS-C Ln,u	1	R11	B_LIST	46	7	23	F
21	ABS-C Ln,u	1	R12	C_LIST	43	7	23	F
22	ABS-C Ln,u	1	R10	A_LIST	48	8	29	F
23	ABS-C Ln,u	1	R11	B_LIST	48	8	29	F
24	ABS-C Ln,u	1	R12	C_LIST	47	8	29	F
25	ABS-CW Ln,a	1	R10	A_LIST	49	9	33	M
26	ABS-CW Ln,a	1	R11	B_LIST	46	9	33	M
27	ABS-CW Ln,a	1	R12	C_LIST	47	9	33	M

(cont. on next page)

Table B. 1. (cont.)

DATA #	SCENARIO	TEST ROUND	RECEIVER	TMWRT LIST	LIST SCORE	P.#	AGE	GENDER
28	ABS-CW Ln,a	1	R10	A_LIST	48	10	22	F
29	ABS-CW Ln,a	1	R11	B_LIST	47	10	22	F
30	ABS-CW Ln,a	1	R12	C_LIST	44	10	22	F
31	ABS-CW Ln,a	1	R10	A_LIST	49	11	21	F
32	ABS-CW Ln,a	1	R11	B_LIST	50	11	21	F
33	ABS-CW Ln,a	1	R12	C_LIST	47	11	21	F
34	ABS-CW Ln,a	1	R10	A_LIST	46	12	22	F
35	ABS-CW Ln,a	1	R11	B_LIST	49	12	22	F
36	ABS-CW Ln,a	1	R12	C_LIST	44	12	22	F
37	ABS-CW Ln,u	1	R10	A_LIST	47	13	23	FF
38	ABS-CW Ln,u	1	R11	B_LIST	50	13	23	F
39	ABS-CW Ln,u	1	R12	C_LIST	48	13	23	F
40	ABS-CW Ln,u	1	R10	A_LIST	49	14	41	F
41	ABS-CW Ln,u	1	R11	B_LIST	50	14	41	F
42	ABS-CW Ln,u	1	R12	C_LIST	49	14	41	F
43	ABS-CW Ln,u	1	R10	A_LIST	49	15	53	M
44	ABS-CW Ln,u	1	R11	B_LIST	50	15	53	M
45	ABS-CW Ln,u	1	R12	C_LIST	49	15	53	M
46	ABS-CW Ln,u	1	R10	A_LIST	46	16	23	M
47	ABS-CW Ln,u	1	R11	B_LIST	50	16	23	M
48	ABS-CW Ln,u	1	R12	C_LIST	48	16	23	M
49	ER Ln,a	1	R10	A_LIST	44	17	21	F
50	ER Ln,a	1	R11	B_LIST	45	17	21	F
51	ER Ln,a	1	R12	C_LIST	43	17	21	F
52	ER Ln,a	1	R10	A_LIST	45	18	21	F
53	ER Ln,a	1	R11	B_LIST	44	18	21	F
54	ER Ln,a	1	R12	C_LIST	46	18	21	F
55	ER Ln,a	1	R10	A_LIST	45	19	23	F
56	ER Ln,a	1	R11	B_LIST	44	19	23	F
57	ER Ln,a	1	R12	C_LIST	44	19	23	F
58	ER Ln,a	1	R10	A_LIST	50	20	23	F
59	ER Ln,a	1	R11	B_LIST	45	20	23	F
60	ER Ln,a	1	R12	C_LIST	44	20	23	F
61	ER Ln,u	1	R10	A_LIST	47	21	22	F

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Table B. 1. (cont.)

DATA #	SCENARIO	TEST ROUND	RECEIVER	TMWRT LIST	LIST SCORE	P.#	AGE	GENDER
62	ER Ln,u	1	R11	B_LIST	46	21	22	F
63	ER Ln,u	1	R12	C_LIST	47	21	22	F
64	ER Ln,u	1	R10	A_LIST	48	22	25	M
65	ER Ln,u	1	R11	B_LIST	48	22	25	M
66	ER Ln,u	1	R12	C_LIST	46	22	25	M
67	ER Ln,u	1	R10	A_LIST	49	23	21	F
68	ER Ln,u	1	R11	B_LIST	49	23	21	F
69	ER Ln,u	1	R12	C_LIST	48	23	21	F
70	ER Ln,u	1	R10	A_LIST	47	24	23	F
71	ER Ln,u	1	R11	B_LIST	50	24	23	F
72	ER Ln,u	1	R12	C_LIST	48	24	23	F
73	EX Ln,a	1	R10	A_LIST	42	25	21	F
74	EX Ln,a	1	R11	B_LIST	40	25	21	F
75	EX Ln,a	1	R12	C_LIST	38	25	21	F
76	EX Ln,a	1	R10	A_LIST	39	26	27	M
77	EX Ln,a	1	R11	B_LIST	39	26	27	M
78	EX Ln,a	1	R12	C_LIST	37	26	27	M
79	EX Ln,a	1	R10	A_LIST	36	27	21	F
80	EX Ln,a	1	R11	B_LIST	36	27	21	F
81	EX Ln,a	1	R12	C_LIST	37	27	21	F
82	EX Ln,a	1	R10	A_LIST	39	28	22	F
83	EX Ln,a	1	R11	B_LIST	37	28	22	F
84	EX Ln,a	1	R12	C_LIST	32	28	22	F
85	EX Ln,u	1	R10	A_LIST	36	29	34	F
86	EX Ln,u	1	R11	B_LIST	42	29	34	F
87	EX Ln,u	1	R12	C_LIST	40	29	34	F
88	EX Ln,u	1	R10	A_LIST	41	30	23	F
89	EX Ln,u	1	R11	B_LIST	41	30	23	F
90	EX Ln,u	1	R12	C_LIST	38	30	23	F
91	EX Ln,u	1	R10	A_LIST	40	31	21	F
92	EX Ln,u	1	R11	B_LIST	39	31	21	F
93	EX Ln,u	1	R12	C_LIST	40	31	21	F
94	EX Ln,u	1	R10	A_LIST	36	32	24	F
95	EX Ln,u	1	R11	B_LIST	38	32	24	F

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Table B. 1. (cont.)

DATA #	SCENARIO	TEST ROUND	RECEIVER	TMWRT LIST	LIST SCORE	P.#	AGE	GENDER
96	EX Ln,u	1	R12	C_LIST	35	32	24	F
97	ABS-C Ln,a	2	R12	A_LIST	44	33	23	F
98	ABS-C Ln,a	2	R10	B_LIST	47	33	23	F
99	ABS-C Ln,a	2	R11	C_LIST	41	33	23	F
100	ABS-C Ln,a	2	R12	A_LIST	47	34	23	F
101	ABS-C Ln,a	2	R10	B_LIST	47	34	23	F
102	ABS-C Ln,a	2	R11	C_LIST	46	34	23	F
103	ABS-C Ln,a	2	R12	A_LIST	48	35	20	F
104	ABS-C Ln,a	2	R10	B_LIST	49	35	20	F
105	ABS-C Ln,a	2	R11	C_LIST	46	35	20	F
106	ABS-C Ln,a	2	R12	A_LIST	46	36	21	F
107	ABS-C Ln,a	2	R10	B_LIST	47	36	21	F
108	ABS-C Ln,a	2	R11	C_LIST	46	36	21	F
109	ABS-C Ln,u	2	R12	A_LIST	49	37	23	F
110	ABS-C Ln,u	2	R10	B_LIST	49	37	23	F
111	ABS-C Ln,u	2	R11	C_LIST	48	37	23	F
112	ABS-C Ln,u	2	R12	A_LIST	47	38	23	M
113	ABS-C Ln,u	2	R10	B_LIST	50	38	23	M
114	ABS-C Ln,u	2	R11	C_LIST	46	38	23	M
115	ABS-C Ln,u	2	R12	A_LIST	47	39	21	M
116	ABS-C Ln,u	2	R10	B_LIST	50	39	21	M
117	ABS-C Ln,u	2	R11	C_LIST	49	39	21	M
118	ABS-C Ln,u	2	R12	A_LIST	46	40	21	F
119	ABS-C Ln,u	2	R10	B_LIST	47	40	21	F
120	ABS-C Ln,u	2	R11	C_LIST	47	40	21	F
121	ABS-CW Ln,a	2	R12	A_LIST	46	41	19	F
122	ABS-CW Ln,a	2	R10	B_LIST	49	41	19	F
123	ABS-CW Ln,a	2	R11	C_LIST	45	41	19	F
124	ABS-CW Ln,a	2	R12	A_LIST	46	42	18	F
125	ABS-CW Ln,a	2	R10	B_LIST	46	42	18	F
126	ABS-CW Ln,a	2	R11	C_LIST	45	42	18	F
127	ABS-CW Ln,a	2	R12	A_LIST	47	43	19	F
128	ABS-CW Ln,a	2	R10	B_LIST	46	43	19	F
129	ABS-CW Ln,a	2	R11	C_LIST	43	43	19	F

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Table B. 1. (cont.)

DATA #	SCENARIO	TEST ROUND	RECEIVER	TMWRT LIST	LIST SCORE	P.#	AGE	GENDER
130	ABS-CW Ln,a	2	R12	A_LIST	50	44	19	F
131	ABS-CW Ln,a	2	R10	B_LIST	45	44	19	F
132	ABS-CW Ln,a	2	R11	C_LIST	48	44	19	F
133	ABS-CW Ln,u	2	R12	A_LIST	47	45	20	M
134	ABS-CW Ln,u	2	R10	B_LIST	50	45	20	M
135	ABS-CW Ln,u	2	R11	C_LIST	47	45	20	M
136	ABS-CW Ln,u	2	R12	A_LIST	47	46	20	M
137	ABS-CW Ln,u	2	R10	B_LIST	48	46	20	M
138	ABS-CW Ln,u	2	R11	C_LIST	48	46	20	M
139	ABS-CW Ln,u	2	R12	A_LIST	47	47	18	F
140	ABS-CW Ln,u	2	R10	B_LIST	49	47	18	F
141	ABS-CW Ln,u	2	R11	C_LIST	48	47	18	F
142	ABS-CW Ln,u	2	R12	A_LIST	50	48	50	M
143	ABS-CW Ln,u	2	R10	B_LIST	49	48	50	M
144	ABS-CW Ln,u	2	R11	C_LIST	49	48	50	M
145	ER Ln,a	2	R12	A_LIST	47	49	22	F
146	ER Ln,a	2	R10	B_LIST	46	49	22	F
147	ER Ln,a	2	R11	C_LIST	43	49	22	F
148	ER Ln,a	2	R12	A_LIST	49	50	23	F
149	ER Ln,a	2	R10	B_LIST	45	50	23	F
150	ER Ln,a	2	R11	C_LIST	46	50	23	F
151	ER Ln,a	2	R12	A_LIST	47	51	25	F
152	ER Ln,a	2	R10	B_LIST	44	51	25	F
153	ER Ln,a	2	R11	C_LIST	44	51	25	F
154	ER Ln,a	2	R12	A_LIST	46	52	23	M
155	ER Ln,a	2	R10	B_LIST	42	52	23	M
156	ER Ln,a	2	R11	C_LIST	46	52	23	M
157	ER Ln,u	2	R12	A_LIST	48	53	22	F
158	ER Ln,u	2	R10	B_LIST	48	53	22	F
159	ER Ln,u	2	R11	C_LIST	48	53	22	F
160	ER Ln,u	2	R12	A_LIST	49	54	28	M
161	ER Ln,u	2	R10	B_LIST	47	54	28	M
162	ER Ln,u	2	R11	C_LIST	49	54	28	M
163	ER Ln,u	2	R12	A_LIST	48	55	23	M

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Table B. 1. (cont.)

DATA #	SCENARIO	TEST ROUND	RECEIVER	TMWRT LIST	LIST SCORE	P.#	AGE	GENDER
164	ER Ln,u	2	R10	B_LIST	48	55	23	M
165	ER Ln,u	2	R11	C_LIST	46	55	23	M
166	ER Ln,u	2	R12	A_LIST	45	56	25	M
167	ER Ln,u	2	R10	B_LIST	46	56	25	M
168	ER Ln,u	2	R11	C_LIST	48	56	25	M
169	EX Ln,a	2	R12	A_LIST	35	57	20	M
170	EX Ln,a	2	R10	B_LIST	40	57	20	M
171	EX Ln,a	2	R11	C_LIST	35	57	20	M
172	EX Ln,a	2	R12	A_LIST	38	58	21	F
173	EX Ln,a	2	R10	B_LIST	33	58	21	F
174	EX Ln,a	2	R11	C_LIST	36	58	21	F
175	EX Ln,a	2	R12	A_LIST	37	59	22	M
176	EX Ln,a	2	R10	B_LIST	42	59	22	M
177	EX Ln,a	2	R11	C_LIST	43	59	22	M
178	EX Ln,a	2	R12	A_LIST	34	60	21	F
179	EX Ln,a	2	R10	B_LIST	39	60	21	F
180	EX Ln,a	2	R11	C_LIST	36	60	21	F
181	EX Ln,u	2	R12	A_LIST	37	61	25	M
182	EX Ln,u	2	R10	B_LIST	38	61	25	M
183	EX Ln,u	2	R11	C_LIST	37	61	25	M
184	EX Ln,u	2	R12	A_LIST	35	62	19	F
185	EX Ln,u	2	R10	B_LIST	41	62	19	F
186	EX Ln,u	2	R11	C_LIST	39	62	19	F
187	EX Ln,u	2	R12	A_LIST	39	63	25	M
188	EX Ln,u	2	R10	B_LIST	44	63	25	M
189	EX Ln,u	2	R11	C_LIST	41	63	25	M
190	EX Ln,u	2	R12	A_LIST	36	64	22	M
191	EX Ln,u	2	R10	B_LIST	37	64	22	M
192	EX Ln,u	2	R11	C_LIST	38	64	22	M
193	ABS-C Ln,a	3	R11	A_LIST	44	65	20	M
194	ABS-C Ln,a	3	R12	B_LIST	46	65	20	M
195	ABS-C Ln,a	3	R10	C_LIST	44	65	20	M
196	ABS-C Ln,a	3	R11	A_LIST	47	66	20	F
197	ABS-C Ln,a	3	R12	B_LIST	41	66	20	F

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Table B. 1. (cont.)

DATA #	SCENARIO	TEST ROUND	RECEIVER	TMWRT LIST	LIST SCORE	P.#	AGE	GENDER
198	ABS-C Ln,a	3	R10	C_LIST	46	66	20	F
199	ABS-C Ln,a	3	R11	A_LIST	50	67	21	M
200	ABS-C Ln,a	3	R12	B_LIST	46	67	21	M
201	ABS-C Ln,a	3	R10	C_LIST	44	67	21	M
202	ABS-C Ln,a	3	R11	A_LIST	44	68	21	F
203	ABS-C Ln,a	3	R12	B_LIST	46	68	21	F
204	ABS-C Ln,a	3	R10	C_LIST	43	68	21	F
205	ABS-C Ln,u	3	R11	A_LIST	49	69	21	M
206	ABS-C Ln,u	3	R12	B_LIST	49	69	21	M
207	ABS-C Ln,u	3	R10	C_LIST	49	69	21	M
208	ABS-C Ln,u	3	R11	A_LIST	47	70	21	M
209	ABS-C Ln,u	3	R12	B_LIST	47	70	21	M
210	ABS-C Ln,u	3	R10	C_LIST	50	70	21	M
211	ABS-C Ln,u	3	R11	A_LIST	46	71	20	F
212	ABS-C Ln,u	3	R12	B_LIST	49	71	20	F
213	ABS-C Ln,u	3	R10	C_LIST	46	71	20	F
214	ABS-C Ln,u	3	R11	A_LIST	49	72	19	M
215	ABS-C Ln,u	3	R12	B_LIST	50	72	19	M
216	ABS-C Ln,u	3	R10	C_LIST	49	72	19	M
217	ABS-CW Ln,a	3	R11	A_LIST	49	73	24	F
218	ABS-CW Ln,a	3	R12	B_LIST	47	73	24	F
219	ABS-CW Ln,a	3	R10	C_LIST	44	73	24	F
220	ABS-CW Ln,a	3	R11	A_LIST	48	74	18	M
221	ABS-CW Ln,a	3	R12	B_LIST	46	74	18	M
222	ABS-CW Ln,a	3	R10	C_LIST	42	74	18	M
223	ABS-CW Ln,a	3	R11	A_LIST	48	75	23	F
224	ABS-CW Ln,a	3	R12	B_LIST	48	75	23	F
225	ABS-CW Ln,a	3	R10	C_LIST	48	75	23	F
226	ABS-CW Ln,a	3	R11	A_LIST	48	76	25	M
227	ABS-CW Ln,a	3	R12	B_LIST	48	76	25	M
228	ABS-CW Ln,a	3	R10	C_LIST	47	76	25	M
229	ABS-CW Ln,u	3	R11	A_LIST	48	77	20	F
230	ABS-CW Ln,u	3	R12	B_LIST	50	77	20	F
231	ABS-CW Ln,u	3	R10	C_LIST	49	77	20	F

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Table B. 1. (cont.)

DATA #	SCENARIO	TEST ROUND	RECEIVER	TMWRT LIST	LIST SCORE	P.#	AGE	GENDER
232	ABS-CW Ln,u	3	R11	A_LIST	50	78	20	M
233	ABS-CW Ln,u	3	R12	B_LIST	49	78	20	M
234	ABS-CW Ln,u	3	R10	C_LIST	49	78	20	M
235	ABS-CW Ln,u	3	R11	A_LIST	45	79	27	F
236	ABS-CW Ln,u	3	R12	B_LIST	49	79	27	F
237	ABS-CW Ln,u	3	R10	C_LIST	44	79	27	F
238	ABS-CW Ln,u	3	R11	A_LIST	50	80	22	M
239	ABS-CW Ln,u	3	R12	B_LIST	50	80	22	M
240	ABS-CW Ln,u	3	R10	C_LIST	48	80	22	M
241	ER Ln,a	3	R11	A_LIST	47	81	20	F
242	ER Ln,a	3	R12	B_LIST	47	81	20	F
243	ER Ln,a	3	R10	C_LIST	48	81	20	F
244	ER Ln,a	3	R11	A_LIST	47	82	22	M
245	ER Ln,a	3	R12	B_LIST	45	82	22	M
246	ER Ln,a	3	R10	C_LIST	47	82	22	M
247	ER Ln,a	3	R11	A_LIST	49	83	20	M
248	ER Ln,a	3	R12	B_LIST	48	83	20	M
249	ER Ln,a	3	R10	C_LIST	48	83	20	M
250	ER Ln,a	3	R11	A_LIST	46	84	23	M
251	ER Ln,a	3	R12	B_LIST	44	84	23	M
252	ER Ln,a	3	R10	C_LIST	46	84	23	M
253	ER Ln,u	3	R11	A_LIST	46	85	30	F
254	ER Ln,u	3	R12	B_LIST	47	85	30	F
255	ER Ln,u	3	R10	C_LIST	48	85	30	F
256	ER Ln,u	3	R11	A_LIST	49	86	19	F
257	ER Ln,u	3	R12	B_LIST	49	86	19	F
258	ER Ln,u	3	R10	C_LIST	49	86	19	F
259	ER Ln,u	3	R11	A_LIST	48	87	22	F
260	ER Ln,u	3	R12	B_LIST	47	87	22	F
261	ER Ln,u	3	R10	C_LIST	46	87	22	F
262	ER Ln,u	3	R11	A_LIST	49	88	19	F
263	ER Ln,u	3	R12	B_LIST	50	88	19	F
264	ER Ln,u	3	R10	C_LIST	49	88	19	F
265	EX Ln,a	3	R11	A_LIST	37	89	21	F

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Table B. 1. (cont.)

DATA #	SCENARIO	TEST ROUND	RECEIVER	TMWRT LIST	LIST SCORE	P.#	AGE	GENDER
266	EX Ln,a	3	R12	B_LIST	40	89	21	F
267	EX Ln,a	3	R10	C_LIST	39	89	21	F
268	EX Ln,a	3	R11	A_LIST	40	90	30	F
269	EX Ln,a	3	R12	B_LIST	37	90	30	F
270	EX Ln,a	3	R10	C_LIST	35	90	30	F
271	EX Ln,a	3	R11	A_LIST	36	91	32	F
272	EX Ln,a	3	R12	B_LIST	39	91	32	F
273	EX Ln,a	3	R10	C_LIST	36	91	32	F
274	EX Ln,a	3	R11	A_LIST	40	92	22	F
275	EX Ln,a	3	R12	B_LIST	34	92	22	F
276	EX Ln,a	3	R10	C_LIST	38	92	22	F
277	EX Ln,u	3	R11	A_LIST	41	93	23	F
278	EX Ln,u	3	R12	B_LIST	39	93	23	F
279	EX Ln,u	3	R10	C_LIST	40	93	23	F
280	EX Ln,u	3	R11	A_LIST	37	94	25	M
281	EX Ln,u	3	R12	B_LIST	43	94	25	M
282	EX Ln,u	3	R10	C_LIST	37	94	25	M
283	EX Ln,u	3	R11	A_LIST	40	95	19	F
284	EX Ln,u	3	R12	B_LIST	40	95	19	F
285	EX Ln,u	3	R10	C_LIST	41	95	19	F
286	EX Ln,u	3	R11	A_LIST	41	96	22	M
287	EX Ln,u	3	R12	B_LIST	39	96	22	M
288	EX Ln,u	3	R10	C_LIST	41	96	22	M

VITA

Mahmut SÖZER

His engineering background and a keen interest in music composition and production led him to the field of room acoustics, where his diverse interests intersected. After receiving his master's degree in music technology, he founded SONIC DESIGN Noise Control and Acoustics Engineering Incorporate in 2017, where he currently works as a professional consultant, providing planning services for room acoustics, electroacoustics, and building acoustics.

Degrees

Bachelor of Science in Mining Engineering, Middle East Techincal University, 1997

Pre-Bachelor of Arts in Music, Ege University Turkish Music State Conservatory, 2008

Master of Science in Music Technology, Dokuz Eylul University, 2016

Memberships

Turkish Acoustical Society

Member of the Audio Engineering Society