MASTER

The acoustic comfort of restaurants

a research into the relation between the acoustic comfort and the design of a restaurant including a literature study, prediction methods, an experimental research and a case study

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GRADUATION REPORT Jorinde Bijpost

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Abstract

In this thesis the relation between acoustic comfort in a restaurant and the design of a restaurant is researched. The high amount of simultaneously speaking persons in a restaurant often result in an excessive ambient noise level. A situation where conversations are only possible with a raised voice and at a close distance is created, resulting in people leaving the place with an exhausted feeling. The acoustician Rindel introduces a prediction formula for the 'Acoustic Capacity' of a facility, defined as the limited number of persons that should be allowed in a room for sufficient verbal communication. The formula is based on the volume and reverberation time of the space and takes the Lombard effect into account. The acoustician Nijs, also developed predicition formula for multi-talkers environments. He takes the Lombard effect into account as well and his model is based on the amount of sound absorption in the room. These formulae are examined and compared to each other.

Rindel also developed a computer-based prediction model for multi-talkers environments, which also takes te Lombarde effect into account. A case study about a design of a restaurant is both tested with this model and Rindels prediction formula. The results for the acoustic capacity derived by these models, are compared with eachother and the accuracy is considered.

Apart from the importance of lower sound levels, the speech intelligibility and speech privacy are important parameters concerning the acoustic comfort. The speech intelligibility is affected by the room acoustics and the signal-to-noise ratio (SNR). Good speech intelligibility is desired for people dining together while the unintelligibility of speech, called speech privacy, is desired at the surroundings of the dining table. The effect of a solid reflective panel above a table on the speech intelligibility and speech privacy is measured. The results of this measurement are used for the verification of the simulation model. Whereby different heights, sizes and materials than used in the measurements can be tested.

In the end, the results for the acoustic capacity, derived by the prediction methods, and the study with the reflective panels are used for the redesign of the case study.

The results for the acoustic capacity derived by the prediction methods differ a lot from each other. These differences are even higher than 100% at some points. The results derived by Rindels prediction formula are seen as most trustworthy, excluding the method where the sound pressure level in the restaurant is simulated by placing speech sources for every talker in the restaurant. However, the latter method is quite time consuming.

When placing a solid reflective panel above a table the STI near the table increases significantly, with increments of 0.19-0.25. This means that the speech intelligibility increases by placing a panel above the table because the differences are higher than the JND = 0.03. A comparison of the STI values of the measurements near the table and at three meters from the table, for the situations with a panel, give differences of 0.32-0.36, while these differences for the situation without a panel are 0.13. Resulting in an increasing speech privacy at the surroundings of the dining table with placing a solid reflective panel above the table. The STI values for the measurements and the simulations give differences smaller than 0.03 (JND) near the table and at three meters from the table, but higher differences than 0.03 at one meter from the table.

Samenvatting

In dit verslag wordt de relatie tussen het akoestische comfort in een restaurant en het ontwerp van een restaurant onderzocht. De grote hoeveelheid sprekers in een restaurant leidt vaak tot een hoog omgevingsgeluidsniveau. Dit zorgt ervoor dat gesprekken alleen op een korte afstand en met stemverheffing mogelijk zijn, waardoor mensen het restaurant verlaten met een uitgeput gevoel. De akoesticus Rindel introduceert een voorspellingsformule voor de 'Akoestische capaciteit' van een faciliteit, gedefinieerd als het maximaal aantal personen dat in een ruimte mag worden toegestaan voor een toereikende verbale communicatie. De formule is gebaseerd op het volume en de nagalmtijd van de ruimte en houdt rekening met het Lombard effect. De akoesticus Nijs beschrijft ook een voorspellingsformule voor omgevingen met meerdere sprekers. Hierin is ook het Lombard effect meegenomen en de formule is gebaseerd op de hoeveelheid absorptie in de ruimte. Deze formules zijn onderzocht en met elkaar vergeleken.

Rindel heeft ook een computer-gebaseerd voorspellingsmodel voor omgevingen met meerdere sprekers ontwikkeld waarbij ook rekening gehouden wordt met het Lombard effect. Een case study van een ontwerp van een restaurant is getest met zowel dit model als met Rindels voorspellings-formule. De resultaten voor de akoestische capaciteit verkregen met deze modellen zijn met elkaar vergeleken en de nauwkeurigheid is in beschouwing genomen.

Naast het belang van lagere geluidsniveaus, zijn ook de spraakverstaanbaarheid en spraak privacy belangrijke parameters met betrekking tot het akoestisch comfort. De spraakverstaanbaarheid wordt beïnvloed door de ruimte akoestiek en de signaal-ruis verhouding (SNR). Goede spraakverstaan-baarheid is gewenst voor mensen die samen dineren, terwijl de onverstaanbaarheid van spraak, oftewel spraak privacy juist gewenst is rondom de tafel. De effecten van het plaatsen van een stevig reflecterend paneel boven een tafel op de spraakverstaanbaarheid en spraak privacy is gemeten. Deze resultaten zijn gebruikt voor het verifiëren van het simulatiemodel, waardoor verschillende hoogtes, maten en materialen van het paneel dan bij de metingen kunnen worden getest.

Uiteindelijk zijn de resultaten voor de akoestisch capaciteit, bepaald met de voorspellingsmodellen, en de resultaten van de studie met de reflecterende panelen, gebruikt voor het herontwerp van de case study.

De resultaten voor de akoestische capaciteit verkregen met de verschillende voorspellingsmethodes, verschillen sterk van elkaar. Deze verschillen kunnen zelfs oplopen tot meer dan 100% op sommige punten. De resultaten verkregen met Rindels voorspellingsformule worden gezien als meest betrouwbare resultaten, met uitzondering van de resultaten van de methode waarbij het geluidsdrukniveau in het restaurant wordt gesimuleerd door het plaatsen van spraak bronnen voor elke spreker in het restaurant. De laatste methode is echter zeer tijdrovend.

Met het plaatsen van een stevig reflecterend paneel boven een tafel is er een significante verhoging van de STI naast de tafel, met verhogingen van 0,19-0,25. Deze verschillen zijn groter dan de JND = 0.03, wat betekent dat de spraakverstaanbaarheid hier toeneemt. Een vergelijking van de STI waardes voor de situaties met platen naast de tafel en drie meter van de tafel geeft verschillen van 0.32-0.36, terwijl deze verschillen voor de situatie zonder plaat 0.13 zijn. Dit resulteert in een toenemende speech privacy rondom de eettafel met het plaatsen van een stevig reflecterend paneel boven de tafel. De STI waardes voor de metingen en de simulaties geven naast de tafel en op drie meter van de tafel verschillen kleiner dan 0.03 (JND, maar hogere verschillen dan 0.03 op één meter van de tafel.

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List of symbols

A	equivalent absorption area (m^2)
c	Lombard slope (dB/dB)
F	room transfer function (dB)
g	group size (p)
ΔL	gain A-weighted ambient noise level for one speaker for total ambient noise level (dB)
$L_{N,A}$	A-weighted sound pressure level of ambient noise (dB)
$L_{N.A.Areas}$	A-weighted sound pressure level of ambient noise received from other areas (dB)
$L_{N,A,1p}$	A-weighted sound pressure level of ambient noise for one speaker (dB)
$L_{p,A,S}$	A-weighted sound pressure level of speech (dB)
$L_{S,A,r}$	A-weighted sound pressure level in the distance r (dB)
$L_{S,A,1m}$	A-weighted sound pressure level of speech at a distance of 1 m from the source (dB)
$L_{W,A}$	A-weighted sound power level (dB)
$L_{W,A,1p}$	A-weighted sound power level for one speaker (dB)
N	number of people present in the room (p)
N_{max}	acoustic capacity (p)
N_s	number of simultaneously speaking persons in the room (p)
T_{20}	reverberation time (s)
Q	directivity factor (-)
q	height between table and reflective panel (cm)
r	geometrical distance (m)
$\mathrm{r_g}$	corrected distance (m)
SNR_{1m}	signal to noise ratio at a distance of 1 m from the source (dB)
U_{50}	useful to detrimental index (dB)
V	volume of the room (m^3)

1 Introduction

This report is written in the context of the graduation project of the master track ‘Building Physics and Services’ which is linked to the Architecture graduation project “MMK Benelux”. For the latter project, a Museum of Modern Art is designed, including a restaurant. This project will focus on the acoustic comfort of restaurants in general and the analysis and improvement of the acoustic comfort in the above mentioned restaurant design in particular.

Recently, there is an increased notion of the importance of proper acoustic conditions in spaces for social gatherings where verbal communication is very important, like in restaurants[1,2,3]. Acoustic comfort is important in restaurants; it has a high impact on the satisfaction of the visitors and because of the high amount simultaneously speaking persons it can become a problem. Conversations are often only possible with a raised voice and at a close distance, resulting in people leaving the place with an exhausted feeling. Besides this exhaustion, research shows another negative impact of bad acoustic comfort: sound influences the perception of food and diminishes gustatory food properties[4].

Apart from lower sound levels, also the speech intelligibility and speech privacy have to be considered in this project. The speech intelligibility is affected by the acoustic conditions of the space and the signal-to-noise ratio (SNR). Speech intelligibility is the rating of the proportion of speech that is understood[5] and can be investigated by the use of the Speech Transmission Index (STI). This parameter includes the effect of reverberation as well as the effect of background noise on the intelligibility of speech. Good speech intelligibility is desired for people dining together. The contrary situation, the unintelligibility of speech, is called speech privacy. This is desired between different groups of people dining.

The goal of this thesis is to gain more insights into the limited number of persons that should be allowed in a restaurant for sufficient verbal communication, how to predict and increase this number and the effect of reflective surfaces above a table on the speech intelligibility and speech privacy. This will be achieved by a literature study in Chapter 1, the comparison and use of two prediction formulae for multi-talkers environments developed by Rindel[1] and Nijs[6] in Chapter 2, the use of a computer-based prediction model developed by Rindel[7] in Chapter 3, the verification of these prediction methods in Chapter 4, an experimental research into the effects of reflective panels above the tables and the verification of a simulation model for these effects in Chapter 5. The design of the restaurant of the graduation project MMK Benelux will be used as a case study and will be discussed at the end of each chapter. In Chapter 6 the case study will be redesigned considering the gained knowledge from the other chapters.

1.1 Literature

Vocal effort

The vocal effort can be described as the equivalent continuous A-weighted sound pressure level (SPL) of the direct sound in front of a speaker at a distance of 1 m from the mouth. Table 1.1 shows a description of the vocal effort at various speech levels as given in ISO 9921[8]. Whispering can have a SPL of 35-50 dB while by shouting the SPL can reach 84-90 dB.

Table 1.1 *Description of vocal effort at various speech levels after ISO 9921*[8]

$L_{S,A,1m}$ (dB)	Vocal effort
54	Relaxed
60	Normal
66	Raised
72	Loud
78	Very loud

Speech Intelligibility and speech privacy

Speech intelligibility can be described as the rating of the proportion of speech that is understood and can be investigated by the use of the Speech Transmission Index (STI) (IEC 60268-16[5]). It is important to realize that the speech intelligibility is not only depending on the absolute SPL people produce when speaking, but on a large amount of aspects.

The STI produces a metric on a scale of 0 to 1. Table 1.2 shows the intelligibility and privacy qualification for normal listeners[5]. Good speech intelligibility is reached with a STI > 0.60, whereas good speech privacy is reached with a STI <0.17[9]. The Just Noticeable Difference (JND) for the STI is estimated to be 0.03[10].

Table 1.2 *Intelligibility and privacy qualification of STI-values for normal listeners*[23]

Speech Intelligibility	Speech privacy	Normal listeners (standard STI)
Very bad	Confidential	0.00 – 0.05
Bad	Good	0.05 – 0.20
Poor	Reasonable	0.20 – 0.40
Fair	Poor	0.40 – 0.60
Good	Very poor	0.60 – 0.75
Excellent	No	0.75 – 0.99

STI takes the effect of reverberation as well as the effect of background noise and hearing related aspects, such as auditory masking and the absolute reception threshold, on the intelligibility of speech into account. Auditory masking describes an effect of the human hearing process whereby a loud, low frequency sound masks higher frequencies[5]. The masking effect at high sound pressure levels is greater than at low sound pressure levels. The absolute speech reception threshold is the absolute threshold of hearing increased by the minimal required dynamic range for the correct recognition of speech[5].

The Lombard effect

The 'Lombard effect' describes the phenomenon that when many people are simultaneously speaking in a room the sound level increases, because people raise their voice because of the ambient noise of the conversations from other people[11]. Hence when the number of people speaking in a room doubles, the sound level will normally rise with 3 dB, but because of the Lombard effect it will increase even more. This effect was found to start at an ambient noise level of around 45 dB(A) and a speech level of 55 dB(A). The A-weighted sound pressure level for speech in a distance of 1 m from the mouth of the speaker can be expressed in the equation[1]:

$$L_{S,A,1m} = 55 + c \cdot (L_{N,A} - 45) \quad \text{(dB)} \quad (1)$$

Rate *c* describes the Lombard slope and $L_{N,A}$ is the ambient noise level. The Lombard slope *c* = 0,5 dB/dB is based on several cases of dining rooms and social-hour type of assemblies[1]. The equation can only be used for rooms where the noise level is higher than 45 dB(A) and the assumption can be made that the speech level is higher than 55 dB(A).

The Cocktail party effect

People have the ability to localize a sound in a space and focus on one out of many voices. Hereby other voices will be suppressed as background noise resulting in the intelligibility of a person at signal-to-noise levels far below 0 dB[12]. This phenomenon is called the 'Cocktail party effect' and works best when the listener is right in front of the person who speaks. A certain critical number of participants is found. When this number is exceeded people break up in smaller groups to talk. Thereby the talker-listener distance will decrease in order to maintain the minimum signal-to-noise ratio at higher noise levels. Since the amount of people talking increases substantially, the noise level increases also immediately extensively[6].

1.2 Case study

The design of the restaurant of the graduation project MMK Benelux will be used as a case study and tested for different situations. Figure 1.1 shows an impression of the building. The facades of the restaurant are made of glass, the floor is made of wood and the ceiling of concrete. Figure 1.2 shows the floorplan of the building, with a grid of 1.80 to 3.60 m. The restaurant is rectangular shaped with a floor surface of 19.80 m to 28.80 m and a height of 5.40 m. In the middle of the restaurant is a concrete volume which houses the kitchen and the restrooms. The volume of the dining space is 2,100 m^3. The original program of requirements prescribes a capacity of 120 people for the restaurant. However, in the current design 128 seats are present.

Figure 1.1 *The restaurant design*

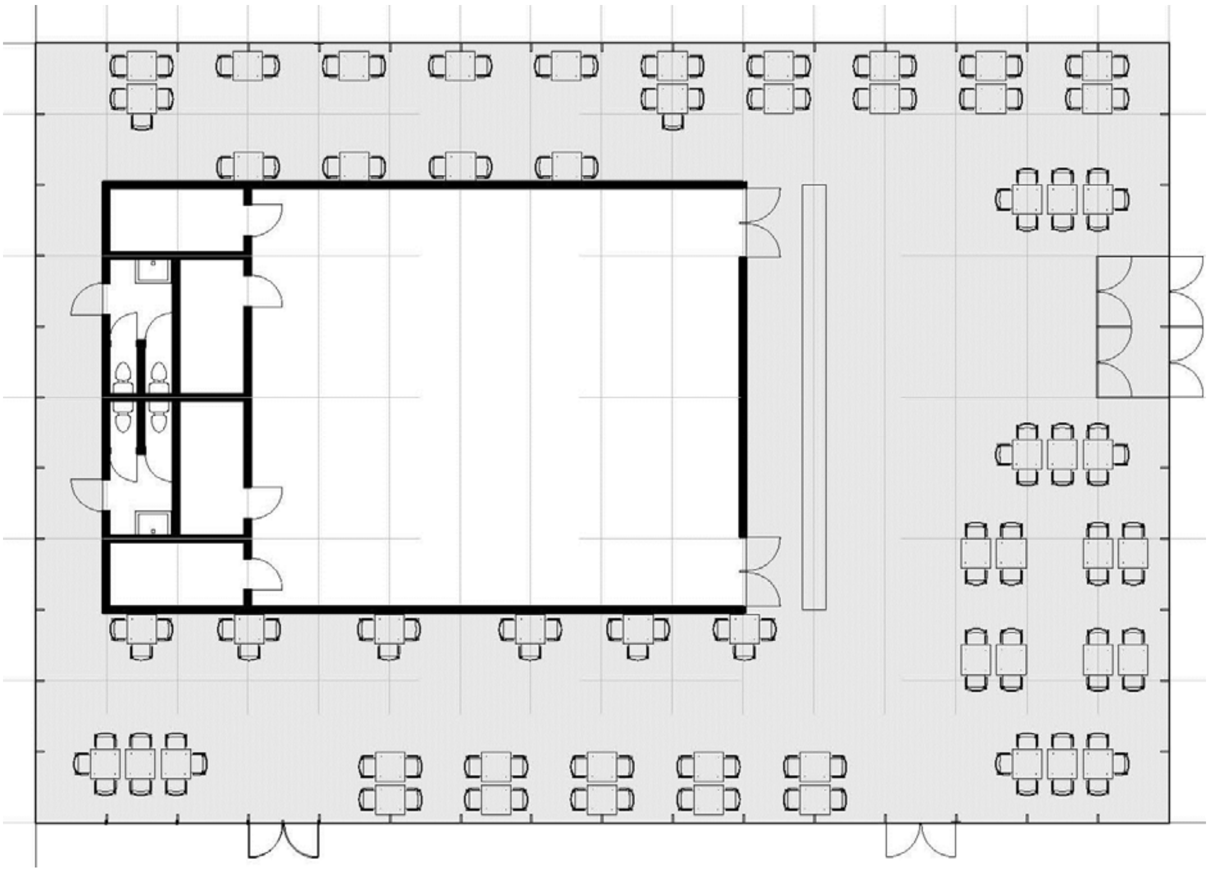

Figure 1.2 *Floorplan of the restaurant*

2 Prediction formulae for multi talker environments

2.1 Comparison Rindels and Nijs' prediction formulae

The volume of the room, reverberation time, number of people and the number of people speaking are the most influencing values regarding the ambient noise. However, also social circumstances as the type of gathering, the age of people, the consumption of alcohol, etc. can influence the noise level, but these effects have not been studied yet. So all prediction methods have a certain uncertainty.

In this report two theories for the description of multi-talkers environments will be discussed. These two methods developed by Rindel[1] and Nijs[6] both describe prediction formulae for the ambient noise due to speech in multi-talkers environments. The formulae take the Lombard effect into account and have been verified for several test cases. Rindels prediction formula is presented at the Euronoise in Maastricht in 2015[1] and Nijs' formula can be found on his website (bk.nijsnet.com[6]). These formulae will be compared to each other in an additional study. The formulae and the characteristics which have to be taken into account will be explained in the upcoming paragraphs.

Rindels prediction formula

Rindel[1] suggests a prediction formula for ambient noise which is verified by the comparison with measured data for a varying number of persons in two large food courts, a canteen, a foyer and three dining halls.

In a free sound field, the sound pressure level in the distance r (m) from the sound source can be expressed in the equation:

$$L_{S,A,r} = L_{W,A} + 10\log Q - 10\log(4\pi r^2) \qquad \text{(dB)} \qquad (2)$$

Where $L_{W,A}$ is the A-weighted sound power level (in dB) and Q the directivity factor. Rindel[22] assumes that when the sound source is a talker, a rough approximation of $Q = 2$ can be made. With a distance of $r = 1$ m, the A-weighted sound power level for one person speaking is:

$$L_{W,A} = L_{S,A,1m} + 8 \qquad \text{(dB)} \qquad (3)$$

When assuming a diffuse sound field, the A-weighted sound pressure level of the ambient noise from N_s simultaneously speaking persons is:

$$L_{N,A} = L_{W,A} + 10\log N_s - 10\log\left(\frac{4}{A}\right) \qquad \text{(dB)} \qquad (4)$$

Where A is the equivalent absorption area (m^2) of the room. Insertion of Formulae 1 and 3 in 4 yields:

$$L_{N,A} = \frac{1}{1-c}\cdot\left(69 - c\cdot 45 - 10\log\left(\frac{A}{N_s}\right)\right) \qquad \text{(dB)} \qquad (5)$$

$$= 93 - 20\log\left(\frac{A}{N_s}\right) \qquad \text{(dB)} \qquad (6)$$

Where the Lombard slope c is assumed to be 0.5 dB/dB. Formula 7 introduces the total number of people N present in the room and group size g, defined as the average number of people per speaking person. The cases studied by Rindel show most groups in eating establishments have a size of around 3 to 4 persons, resulting in an average value of g = 3.5, recommended for the noise prediction. Also the volume V (m^3) and the reverberation time T (s) are introduced using Sabine's equation (Formula 8).

$$g = \frac{N}{N_S} \qquad (7)$$

$$T = \frac{0{,}161 \cdot V}{S \cdot \alpha} \qquad \text{(Sabine equation)} \qquad (8)$$

Insertion of Formulae 7 and 8 in 6 yields the suggested prediction formula:

$$L_{N,A} = 93 - 20\log\left(\frac{0.16 \cdot V \cdot g}{T \cdot N}\right) \qquad \text{(dB)} \qquad (9)$$

Analyzing the last equation, there can be concluded that the SPL will rise with 6 dB when there is a doubling of people in the room, which is different from the 3 dB which is standard with a doubling of non-human sound sources. The accuracy of this model depends mostly on the prediction of the group size, if the actual group size varies between 2.5 and 5, an uncertainty of ± 3 dB arises. Furthermore, the model can't be used for rooms with a capacity less than 50 persons because the model is based on statistical conditions.

Rindel[1] introduces the concept 'Acoustic Capacity' to make the acoustic quality of a room more comprehensible for not-acousticians. He defines the Acoustic Capacity for an eating establishment as; '*the maximum number of persons in a room allowing sufficient quality of verbal communication between persons'.*

Lazarus[16] suggests to relate the signal-to-noise ratio (SNR) to the quality of verbal communication to evaluate the acoustic quality of a multi-talker environment. The SNR will be defined by a simple approach; as the level difference between the direct sound from a speaking person with a distance of 1 m and the ambient noise. This can be expressed in the following equation:

$$SNR_{1m} = L_{S,A,1m} - L_{N,A} \qquad (10)$$

Insertion of Formulae 3, 4 and yields:

$$SNR_{1m} = -14 + 10\log\left(\frac{A \cdot g}{N}\right) \qquad \text{(dB)} \qquad (11)$$

Table 2.1 shows this relation and the corresponding levels of vocal effort, ambient noise and absorption area per number of people present in the room, derived by the use of Formulae 1, 8 and 9.

Table 2.1 *Quality of verbal communication and the relation to SNR and the corresponding levels of vocal effort, ambient noise and absorption area per number of people present in the room*[7]

Quality of verbal communication	SNR_{1m} (dB)	$L_{S,A,1m}$ (dB)	$L_{N,A}$ (dB)
Very good	> 9	<56	<47
Good	3 – 9	56 – 62	47 – 59
Satisfactory	0 – 3	62 – 65	59 – 65
Sufficient	-3 – 0	65 – 68	65 – 71
Insufficient	-9 – -3	68 – 74	71 – 83
Very bad	< -9	>74	>83

Figure 2.1 shows the influence of the reverberation time of the room, the volume of the room and the SNR on the quality of verbal communication. Elderly often have a slight hearing disorder and require in that case an improvement of 3 dB for the SNR, or the distance between the speaker and the listener has to be reduced.

Rindel[1] suggests a simplified equation for the limited number of persons that should be allowed in a room for sufficient verbal communication, in other words, the Acoustic Capacity of the room:

$$N_{max} \cong \frac{V}{20 \cdot T} \tag{12}$$

In the equation T is the reverberation time in seconds of the room in a furnished but unoccupied state at mid frequencies (500-1000 Hz). The equation is derived from Formula 11 with $SNR_{1m} = -3$. The maximum noise level for a sufficient quality of verbal communication is assumed to be 71 dB(A), which means that the average SNR_{1m} is at least -3 dB (Table 2.1). The applied absorption per person is 0.35 m^2.

Figure 2.2 shows the Ambient noise level as a function of the number of people relative to the acoustic capacity of the room.

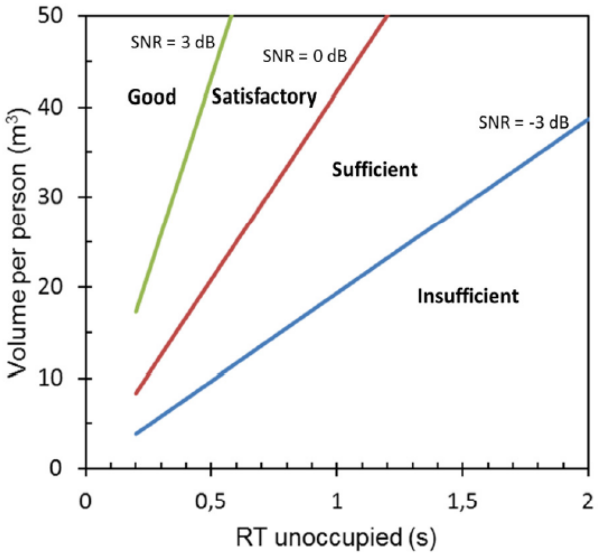

Figure 2.1 *Quality of verbal communication as a function of room volume per person and reverberation time*[1]

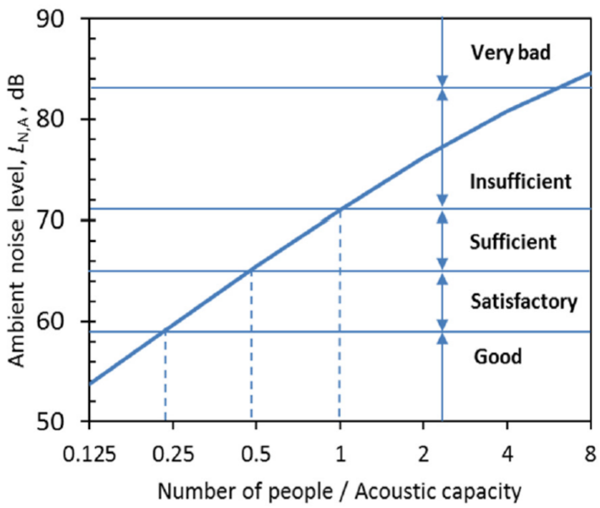

Figure 2.2 *Ambient noise level as a function of the number of people relative to the acoustic capacity of the room*[1]

Nijs' prediction formula

Nijs[6] states that the distance r between the listener and the person who speaks, the direction of the voice from the person who speaks, the amount N_S of people who are speaking and the equivalent absorption area A (m^2) of the room with occupants, are the most influencing factors on the speech intelligibility in a multi-talker environment. The room surface is disregarded, because when the surface of the room increases the amount of people and absorption also increase simultaneously, which results in no change in the speech intelligibility. When the volume of the room increases by raising the ceiling, the ambient noise decreases while the direct sound from the speaker remains the same, so the speech intelligibility will increase. However, this prediction method does not take this effect into account.

Nijs[6] developed a graph which shows the speech intelligibility as a result of the number of speakers and the amount of absorption (Figure 2.3). On the horizontal axis A/N_s is plotted which describes the amount of absorption per speaking person (m^2), on the vertical axis the speech intelligibility is plotted and the distance from the speaker to the listener is plotted as a parameter which varies between 1 m and 35 cm. This distance is rectified so the human capacity to produce a higher sound level in front of the mouth is taken into account. This distance r_g can be calculated by:

$$r_g = \sqrt{\frac{r^2}{Q}} \quad \text{(m)} \qquad (13)$$

The direction Q in front of a speaker is 2.5 and r is the geometrical distance.

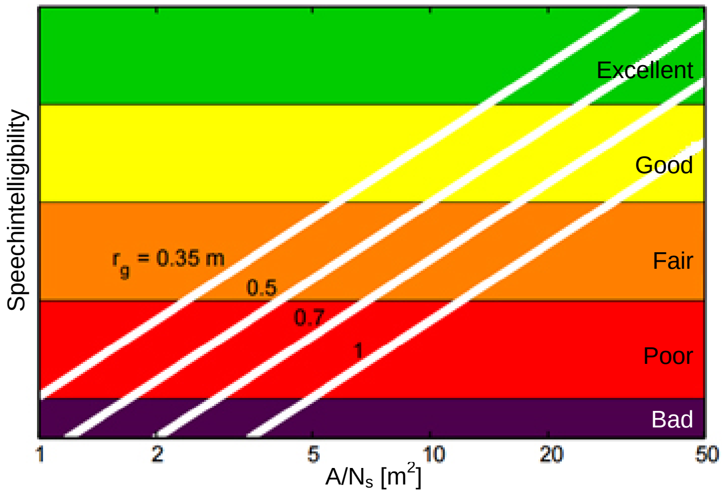

Figure 2.3 *Speech intelligibility as a result of the number of speakers and amount of absorption*[6]

Figure 2.3 is a derivative from a simplified equation which explains the speech intelligibility using the useful to detrimental index U_{50}[21], which is the difference between the direct sound and early sound across from the ambient noise and late sound. This equation is:

$$U_{50} = 10\,log\left(\frac{Q}{r^2}\right) + 13\,log\left(\frac{A}{N_s}\right) - 18 \quad \text{(dB)} \qquad (14)$$

It has to be taken into account that the equation is simplified, which results in an uncertainty of ±2 dB. There couldn't be reached an understanding how the formula and the qualification of the speech intelligibility is derived for this method.The relation between the quality of verbal communication and U_{50} is shown in Table 2.2.

Table 2.2 *Quality of verbal communication and the relation to* U_{50}[17]

Quality of verbal communication	U_{50} (dB)
Excellent	6.5 – 11.5
Good	1.5 – 6.5
Fair	-3.5 – 1.5
Poor	-8.5 – -3.5
Bad	< -8.5

Comparison Rindels and Nijs' prediction formulae

Rindel and Nijs both describe a relation between the quality of verbal communication and the absorption area per number of people present or speaking in a room. With the use of Formula 11 and Table 2.1, the quality of verbal communication for the absorption area per number of people present in a room, is calculated for Rindels method. The same is calculated for Nijs' method with the use of Formula 14 and Table 2.2. In the latter, the absorption area per number of people speaking in a room is divided by the group size g = 3.5 to obtain the absorption area per number of people present in a room. Table 2.3 and Figure 2.4 show the differences between Rindels and Nijs' methods. It shows that Rindel uses six quality standards of verbal communication while Nijs uses only five standards. Next to that, Rindels demands according to the amount of absorption per person present in the room are significant higher than Nijs' demands. Remarkable is also that Nijs gives a limit for the maximum amount of absorption per person.

Table 2.3 *Quality of verbal communication for the absorption per number of people present in a room according to Rindel and Nijs*

Rindel		Nijs	
Quality of verbal communication	A/N (m^2)	Quality of verbal communication	A/N (m^2)
Very good	> 57	-	-
Good	14.3 – 57	Excellent	10.8 – 26.25
Satisfactory	7.2 – 14.3	Good	4.5 – 10.8
Sufficient	3.6 – 7.2	Fair	1.8 – 4.5
Insufficient	0.9 – 3.6	Poor	0.8 – 1.8
Very bad	< 0.9	Bad	< 0.8

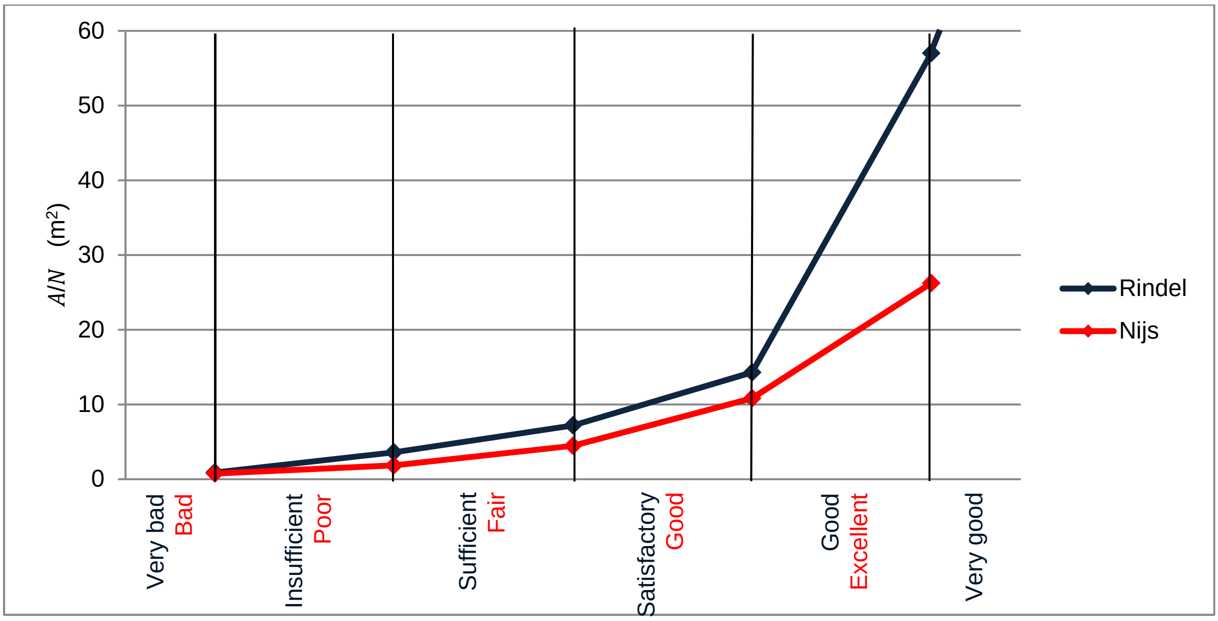

Figure 2.4 *Quality of verbal communication for the absorption per number of people present in a room according to Rindel and Nijs*

In the following research Rindels method will be used to rate the quality of verbal communication whereby there will be aimed for a 'sufficient' communication.

2.2 Case study tested with Rindels prediction formula

Method

Formula 12 describes Rindels prediction formula for calculating the Acoustic Capacity of a room. There should be noted that this equation will only be accurate when an assumption of a diffuse sound field can be made. The room in the case study is a large rectangular room. However, the concrete volume in the middle of the space will block the travelling sound waves. Hereby an assumption of a diffuse sound field will not be accurate when used for the restaurant in its total form, but the room will be divided in four rectangular areas (Figure 2.5). Then the blocking effect of the concrete volume is bypassed, which approaches the situation of a diffuse sound field a bit more. However, there should be noted that it still is not a diffuse field. For every area, except area 4, the acoustic capacity will be calculated by using Formula 12 and the reverberation time simulated for every area. The reverberation per area will be calculated by averaging the outcomes for eight simulations in every area. Area 4 will be excluded from the calculations, because there are no seats in this area. These outcomes will be compared to the outcomes of the acoustic capacity of the restaurant when the blocking effects of the concrete volume are neglected. In this case there will be made an assumption that the entire dining area has a diffuse sound field. Thereby, the reverberation time of the restaurant will be simulated in total. These data will be derived by using the 'Global estimate' function in ODEON. This function uses the method proposed by Schöder, which sends out particles in random directions and ODEON records the loss of energy in each particle as a function of time occurring because of absorption at room surfaces and in the air[15]. This function does not make any assumptions about diffuse field conditions and takes the room shape and position of absorbing material into account.

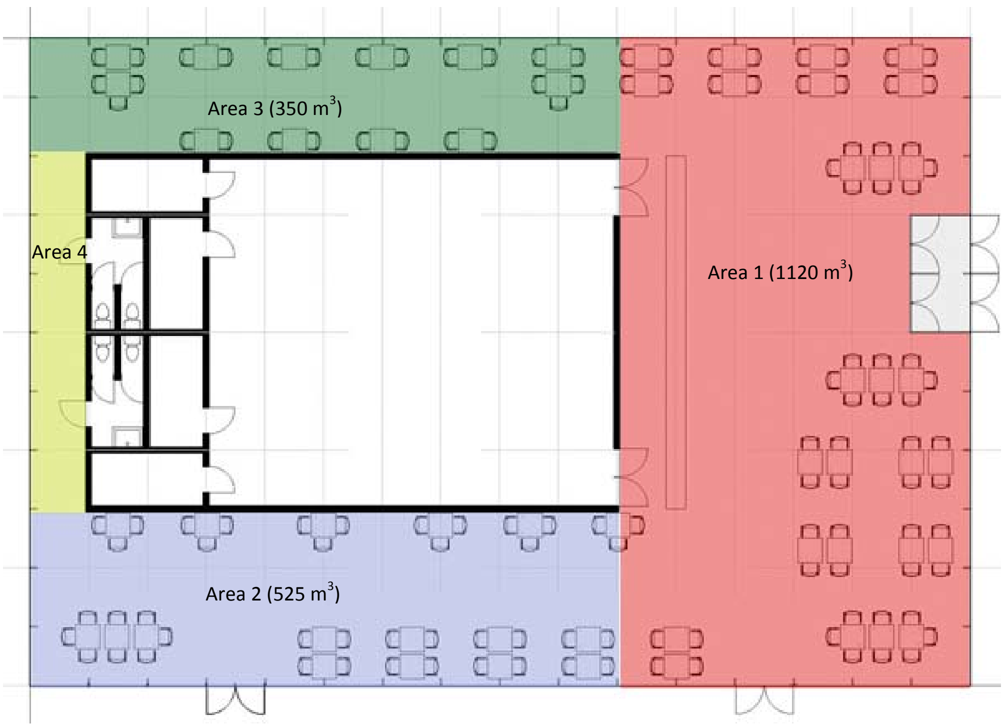

Figure 2.5 *Floorplan of the restaurant with the four areas*

The program of requirements prescribes a capacity of 120 people for the restaurant. This will probably not be achieved by the original design if a good acoustic quality is desired. In order to improve this situation more absorption should be added to lower the reverberation time. An additional option is to increase the volume of the dining area.

Modelling in ODEON

In this research the room acoustics software 'ODEON' (12.12) and 3D modeling software 'SketchUp' (2015) are used. The geometry of the furniture in the restaurant is simplified to lower the number of surfaces and thereby decreasing the calculation time. Figure 2.6 shows the simplified geometry of the furniture. The table plate has a height of 750 mm and the seats have a height of 425 mm above the ground. The ODEON model of the restaurant with the furniture can be seen in Figure 2.7.

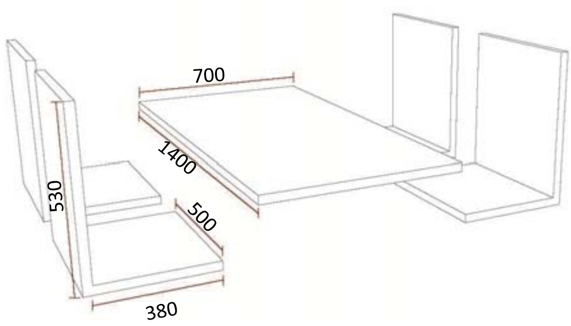

Figure 2.6 *Simplified geometry of the furniture*

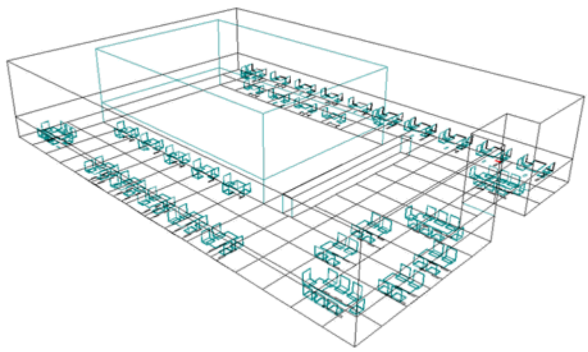

Figure 2.7 *ODEON model of the restaurant*

Table 2.4 shows the absorption and scattering coefficients as assigned to the materials in the ODEON model. For the glass panels a material with double glazing is used, the wooden floor is made of wood parquet in asphalt on concrete, the concrete is smooth and unpainted and for the tables a material described as a 'Hollow wooden podium' from the material library in ODEON[13] is used. The material selected for the tables is chosen because it is the most similar material from the standard material library in ODEON. However, this material has higher absorption values in the lower frequencies than expected for real tables, which should be kept in mind. For the seats the absorption of upholstered seats from the TU Delft Tabellarium[14] is used. In the Tabellarium, the absorption coefficients of the materials for 63 Hz and 8000 Hz are not provided, so they will be approached by copying the adjacent coefficients of respectively 125 Hz and 4000 Hz. There should be noted that the used absorption is an approximation of the absorption of the real materials. The scattering coefficient describes the 'roughness' of the material and a coefficient of 0,05 should be assigned to smooth materials[15].

Table 2.4 *Absorption and scattering coefficients as assigned to the materials in the ODEON model*

Material	Absorption coefficient								Scattering coefficient
	63	125	250	500	1000	2000	4000	8000	
Glass[13]	0.10	0.10	0.07	0.05	0.03	0.02	0.02	0.02	0.05
Wooden floor[13]	0.04	0.04	0.04	0.07	0.06	0.06	0.07	0.07	0.05
Concrete[13]	0.01	0.01	0.01	0.02	0.02	0.02	0.05	0.05	0.05
Table[13]	0.40	0.40	0.30	0.20	0.17	0.15	0.10	0.10	0.05
Seats[14]	0.15	0.15	0.30	0.30	0.40	0.40	0.40	0.40	0.05

ODEON is a ray-based prediction software and the effect of the wave phenomena are only included to a limited extend in the calculations. This program can be used to generate a plausible reverberation time by assuming a homogeneous reverberant field. However, there should be noted that the algorithms used by ODEON are only a rough representation of the real world.[15]

Eight simulations are conducted on different spots in the room to determine the reverberation time. The restaurant without furniture has a reverberation time of 4.6 s for the mid-frequencies (500 Hz and 1000 Hz) and the restaurant with furniture, as presented in the original design, a reverberation time of 2.6 s (Table 2.5 and Figure 2.8).

Table 2.5 *Reverberation time in the restaurant with and without furniture*

Frequency (Hz)		63	125	250	500	1000	2000	4000	8000	Avg $_{500,\ 1000\ Hz}$
T_{20} (s)	Without furniture	4.57	4.53	5.33	4.29	4.95	4.56	2.33	1.14	4.62
	With furniture	2.55	2.76	2.51	2.49	2.64	2.66	1.80	0.98	2.57

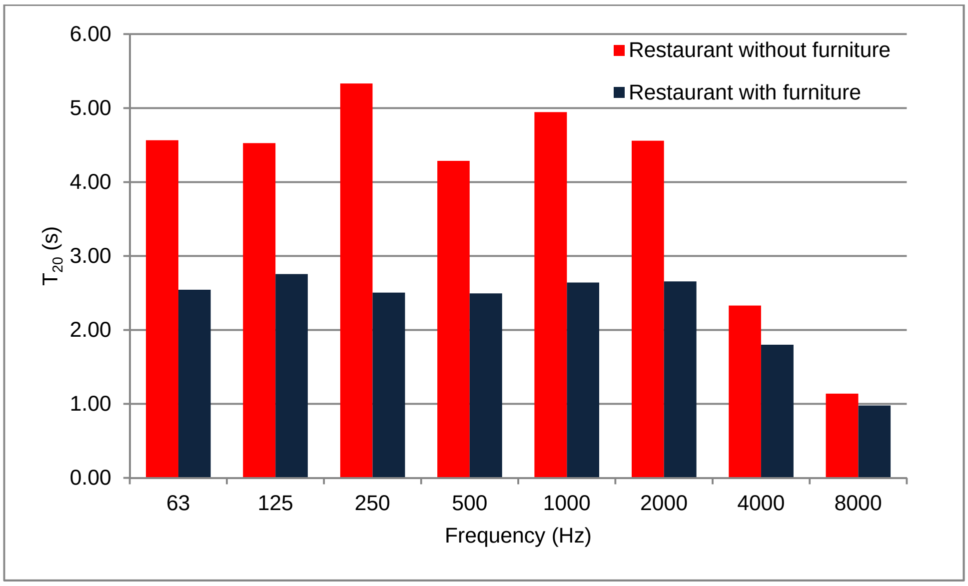

Figure 2.8 *Reverberation time in the restaurant with and without furniture*

Improvements original situation

In order to improve the original situation, the different surface materials will be changed to increase the amount of absorption. Firstly, the floor will be replaced by a wooden floor on joists instead of on concrete. Secondly, absorption material will be placed at the ceiling. There is chosen to place Akustika ceiling panels[18] with felt against the ceiling. These panels are made of 25 mm acoustic PET substrate with a finish layer of 3 mm felt. The third improvement is placing felt shingles[19], as shown in Figure 2.9, against the concrete walls at a height of 0.75 m to 2.10 m. These panels are consisting of 10 mm acoustic PET substrate with a finish layer of 3 mm felt shingles on battens connected to the wall. The height is chosen by the height of people's heads. In the fourth situation the same amount of shingles is placed just underneath the ceiling, to investigate the effect of the height of the absorption.

Figure 2.9 *Filzfelt Aro Shingles*[19]

Table 2.6 shows the absorption and scattering coefficients as assigned to the materials in the ODEON model. The absorption coefficients of the Filzfelt materials for 63 Hz en 8000 Hz are not provided. They will be approached by copying the adjacent coefficients of respectively 125 Hz and 4000 Hz. Table 2.7 shows the materials assigned to the surfaces in ODEON for the original situation and the adjustments of the materials for the improved situations.

Table 2.6 *Absorption and scattering coefficients as assigned to the materials in the ODEON model*

Material	Absorption coefficient								Scattering coefficient
	63	125	250	500	1000	2000	4000	8000	
Floor on joists[13]	0.15	0.15	0.11	0.10	0.07	0.06	0.07	0.07	0.05
Filzfelt Akustika ceiling[18]	0.19	0.19	0.48	0.87	0.94	0.90	0.83	0.83	0.05
Filzfelt Aro shingle wall[19]	0.05	0.05	0.36	0.95	0.87	0.73	0.81	0.81	0.05

Table 2.7 *Different situations simulated in ODEON*

Original situation	Floor: wooden parquet in asphalt on concrete Facade: double glazing
	Ceiling: smooth unpainted concrete Walls: smooth unpainted concrete
	Walls: smooth unpainted concrete
	Facade: double glazing
Situation A	Floor: wooden floor on joists
Situation B	Floor: wooden floor on joists
	Ceiling: Filzfelt Akustika ceiling
Situation C	Floor: wooden floor on joists
	Ceiling: Filzfelt Akustika ceiling
	Walls: Filzfelt Aro shingle at the side walls at a height of 0.75 m to 2.1 m
Situation D	Floor: wooden floor on joists
	Ceiling: Filzfelt Akustika ceiling
	Walls: Filzfelt Aro shingle at the side walls at a height of 4.05 m to 5.4 m
Situation E	Floor: wooden floor on joists
	Ceiling: Filzfelt Akustika ceiling and raised from 5.4 m to 7.2 m
	Walls: Filzfelt Aro shingle at the side walls at a height of 0.65 m to 2 m

Figure 2.10 shows the simulated reverberation time for every area for the different situations (for the exact values see Table I.I in Annex I). It shows a significant difference between the reverberation times of the different areas. Area 3 has the smallest volume and in ratio the highest amount of absorption, followed by Area 2 and at last Area 1, which results in a lower reverberation time. Figure 2.10 shows that by placing the wooden floor on joist, the reverberation time at the low frequencies decreases substantially. Placing absorption at the ceiling also results in a reduction of the reverberation time in the mid- and high frequencies. Placing the Filzfelt Aro shingles on the wall, decreases the reverberation time even more. Noteworthy is the decrease of the reverberation time in Situation D compared to Situation C. In this situation the same amount of absorption on the wall is placed just below the ceiling instead of at the height of people's heads. In Situation E the same absorption is used as in Situation C, but the ceiling is raised from 5,4 m to 7,2 m. This results in a higher reverberation time, because there is less absorption in ratio. However, because of the increasing volume the acoustic capacity will nevertheless increase.

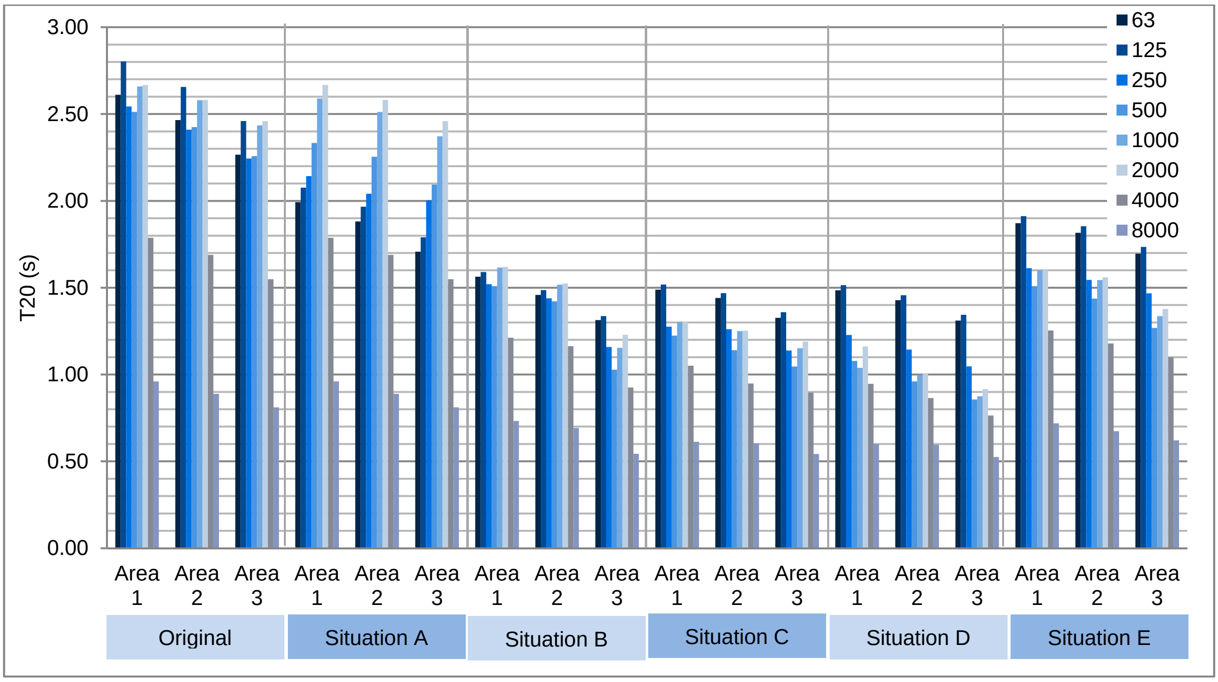

Figure 2.10 *Reverberation time (T_{20}) in the restaurant, derived by conducting eight simulations on different spots in the area, for the different situations and areas per frequency band (for the exact values see Table I.I in Annex I)*

Figure 2.11 shows the simulated reverberation time of the entire restaurant, derived by the 'Global estimate' function, for the different situations when the effects of the concrete volume are neglected (for the exact values see Table I.II in Annex I). Situation A and B give similar results as in the previous method, shown in Figure 2.10. However, when the amount of absorption increases the differences become more extensive. Resulting in lower reverberation times at the method where the reverberation time is measured for the entire restaurant in once.

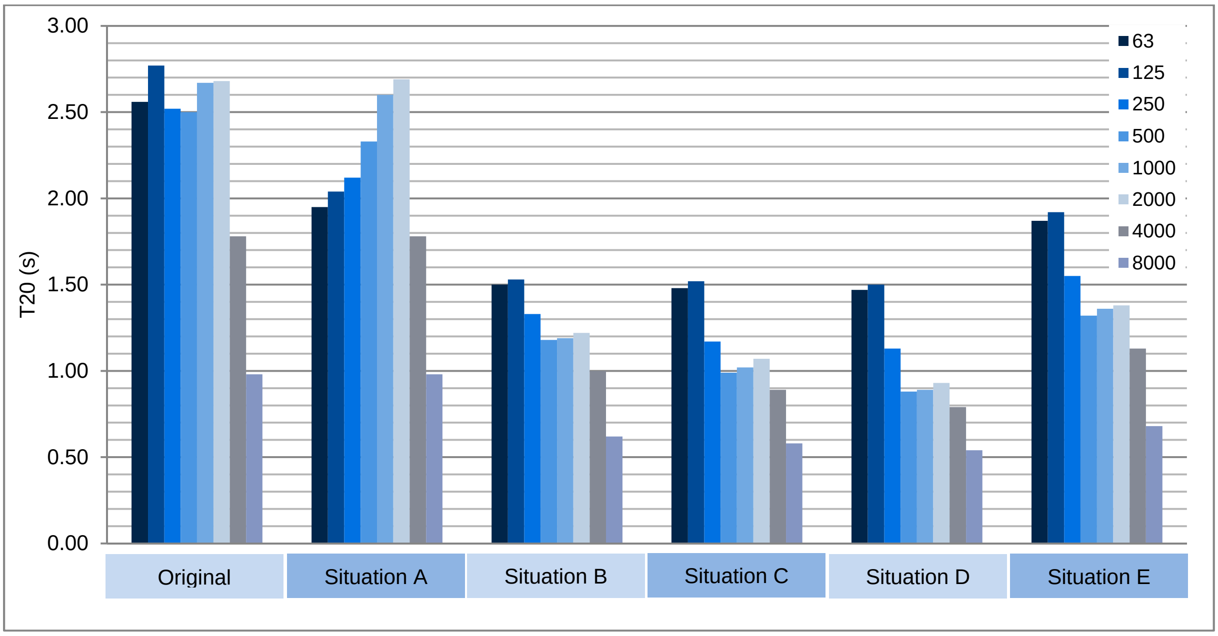

Figure 2.11 *Reverberation time (T_{20}) of the entire restaurant for the different situations derived by the 'Global estimate' function and acoustic capacity N_{max}, derived by Rindels prediction formula(for the exact values see Table I.II in Annex I)*

The acoustic capacity is calculated with the average reverberation time at the mid-frequencies and the volume of the specific area. Table 2.8 shows the acoustic capacities for the different areas, the sum of the areas and for the restaurant in its total form when the effects of the concrete volume are neglected. The results for the case where the reverberation time is measured for the entire restaurant in once gives the highest results for the acoustic capacity. Situation D gives the highest results in general. Whereby for the last method the demanded capacity of 120 persons is almost reached.

Table 2.8 *Acoustic capacity (N_{max}) for the different situations per area, the sum of the areas and for the restaurant in its total form*

N_{max}	Area 1	Area 2	Area 3	Area 1+2+3	Total
Original situation	22	10	7	40	41
Situation A	23	11	8	42	43
Situation B	36	18	12	66	89
Situation C	44	22	16	82	104
Situation D	50	27	20	97	119
Situation E	48	23	18	89	104

Rindel states that the model will only be accurate for rooms with a capacity of more than 50 persons, because the model is based on statistical conditions. By simulating and calculating the three areas seperately, these can be seen as different rooms. The acoustic capacity of these areas don't reach 50 persons (Table 2.8). Thus the results should be seen as an approximation and not as exact numbers.

Conclusion

Rindels prediction formula for calculating the acoustic capacity of the room uses an assumption of a diffuse sound field. In the current case study this will not be accurate, because of a concrete volume placed in the middle of the space. A method with dividing the room in seperate areas gives different results than a method where the effects of the volume are neglected and the reverberation time of the entire room is simulated in once with the 'Global estimate' function in ODEON. Resulting in lower acoustic capacities for the first method.

Another method which bypasses the effects of the concrete volume, is simulating the room with seperate areas, whereby the separation plane will be simulated as a virtual wall. This can be interesting to look into with further research. Also the comparison of simulations to measurements of existing restaurants will give good insights in which method gives the most accurate results.

3 Computer-based prediction model for multi talker environments

3.1 Rindels computer-based model

Rindel developed a method for modeling the ambient noise of many people in multi-talker environments with the use of ODEON[7,20]. The source is modeled as a horizontal surface source with the A-weighted sound power level for one speaker $L_{W,A,1p}$, at a height of 1.5 m above the floor[20]. Table 3.1 shows speech power octave band spectrum for the four ranges of speech radiated by the source, thus not at a distance of 1 m from the mouth. The transfer function is defined as:

$$F = L_{W,A,1p} - L_{N,A,1p} \quad \text{(dB)} \quad (15)$$

Here $L_{N,A,1p}$ is the A-weighted sound pressure level at the receiver, taken from the grid response as the 50% percentile. A grid with receivers at a height of 1.2 m above the floor is used.

The ambient noise level $L_{N,A}$ can be calculated by the following functions:

$$L_{N,A} = L_{W,A,total} - F \quad \text{(dB)} \quad (16)$$

$$L_{N,A} = 81 - 2 \cdot F + 20\log(N_s) \quad \text{(dB)} \quad (17)$$

In the first function the ambient noise level is expressed by the same transfer function as for a single person using $L_{W,A,total}$, which is the A-weighted sound power level emitted from all the speaking persons. In the second equation the noise level is expressed using the transfer function F, which is used instead of the assumption of a diffuse sound field. The sound power level of the sound source of one speaker increases by the amount of ΔL because of the other speakers in the restaurant and the Lombard effect and can be expressed as:

$$\Delta L = L_{W,A,total} - L_{W,A,1p} \quad \text{(dB)} \quad (18)$$

$$= 81 + 20\log(N_s) + L_{N,A,1p} - 2 \cdot L_{W,A,1p} \quad \text{(dB)} \quad (19)$$

Finally, for the ambient noise level $L_{N,A}$ and the acoustic capacity N_{max} can be found:

$$L_{N,A} = L_{N,A,1p} + \Delta L \quad \text{(dB)} \quad (20)$$

Combining Formula 9, Formula 12 and group size $g = 3.5$ yields:

$$L_{N,A} = 93 - 20\log\left(\frac{0.16 \cdot 3.5}{N} \cdot 20N_{max}\right) \quad \text{(dB)} \quad (21)$$

$$N_{max} = N \cdot 10^{(71 - L_{N,A})/20} \quad (22)$$

Table 3.1 *Speech power octave band spectrum depending on vocal effort, A-weighted sound power level for one speaker and the valid range of ambient noise level (dB)*[20]

Frequency (Hz)	63	125	250	500	1000	2000	4000	8000	$L_{W,A,1p}$	$L_{N,A}$ range
Normal	45.0	55.0	65.3	69.0	63.0	55.8	49.8	44.5	68.4	45; 61
Raised	48.0	59.0	69.5	74.9	71.9	63.8	57.3	48.4	75.5	61; 75
Loud	52.0	63.0	72.1	79.6	80.2	72.9	65.9	54.8	82.6	57; 91
Shouted	52.0	63.0	73.1	84.0	89.3	82.4	74.9	64.1	91.0	>91

3.2 Case study tested with Rindels computer-based prediction model

Method

The room transfer function used in the simulation model is at the transfer function when relying on a diffuse sound field. Because of the concrete volume placed in the middle of the restaurant, the room transfer function will not be accurate when used for the restaurant in his total form. Thus the restaurant will be divided in four rectangular areas, as in the previous Chapter (Figure 2.5). For every area the acoustic capacity will be calculated by using a surface source and receiver grid with the size of the specific area at respectively 1.5 m and 1.2 m above the ground. The surface source will radiate the sound power level for one speaker as given in Table 3.1. The ambient noise level $L_{N.A}$ of every area will be calculated by Formula 20.

The noise received from the other areas $L_{N.A.Areas}$ will be simulated by using the receiver grid at the current area and the sound sources at the other two areas. The sound sources at the other areas will be adjusted to an ambient noise level $L_{N.A}$ = 71 dB received at those two areas taken from the grid response as the 50% percentile, because Formula 22 uses 71 dB as the recommended maximum for sufficient quality of verbal communication and the goal is to have a sufficient quality of verbal communication in the total restaurant. The maximum capacity N_{max} of the specific area is calculated by Formula 23. Formula 23 is an adjusted version of Formula 22. Here, the ambient noise received from the other areas $L_{N.A.Areas}$ is logarithmically subtracted from the recommended 71 dB.

$$N_{max} = N \cdot 10^{\left(10\log\left(10^{\frac{71}{10}} - 10^{\frac{L_{N.A.Areas}}{10}}\right) - L_{N.A}\right)/20} \quad \text{(dB)} \qquad (23)$$

The same room model as in the previous Chapter is used with one adjustment; people. In Rindels simple prediction model the absorption of 0.35 m^2 per person is included, but in the simulation model this is not the case. A simplified geometry of a person is made, which is placed on the seats in the restaurant. Figure 3.1 shows the simplification of the geometry of a person, the third model will be used in the simulations. Figure 3.2 shows the receiver grid which is used for the simulations with a grid size 0f 1.8 m to 1.8 m and a height of 1.2 m.

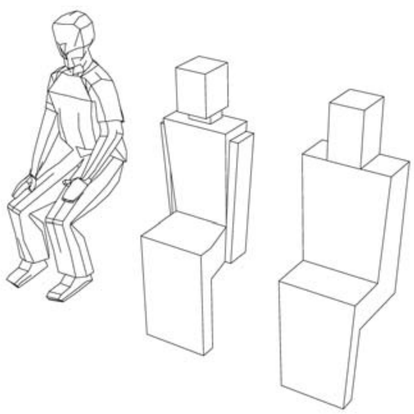

Figure 3.1 *Simplification geometry of a person*

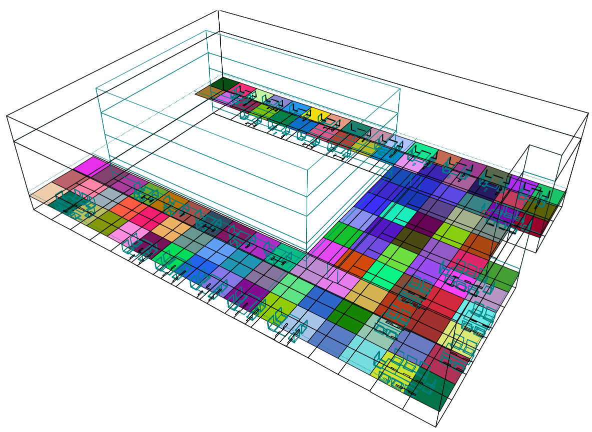

Figure 3.2 *Receiver grid in the ODEON model*

Table 3.2 shows the absorption and scattering coefficient as assigned to the person and the seats, obtained from the TU Delft Tabellarium.[14] In the Tabellarium. the absorption coefficients of the materials for 63 Hz en 8000 Hz are not provided. They will be approached by copying the adjacent coefficients of respectively 125 Hz and 4000 Hz. The scattering coefficient is approached with 0.30, because of the use of a simplified geometry. Figure 3.3 shows the simulation model of the restaurant with people.

Table 3.2 *Absorption and scattering coefficients as assigned to the people and seats in the ODEON model*

Material	Absorption coefficient								Scattering coefficient
	63	125	250	500	1000	2000	4000	8000	
Person sitting[14]	0.15	0.15	0.30	0.45	0.45	0.45	0.45	0.45	0.30

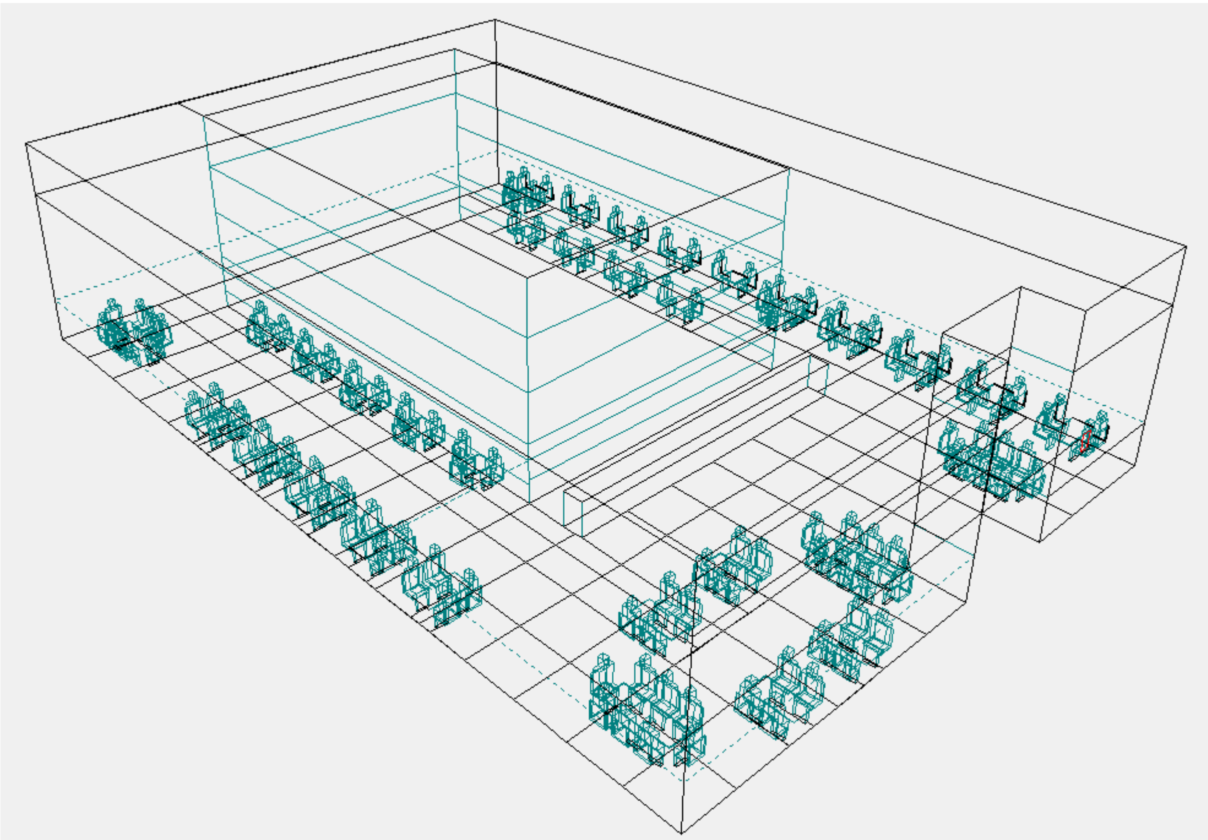

Figure 3.3 *ODEON model of the restaurant with people*

Table 3.3 shows the acoustic capacity for the different situations per area and in total, calculated with Rindels computer-based prediction model as explained in the Method (for the values for $L_{N.A.1}$, ΔL, $L_{N.A}$ and $L_{N.A.Areas}$ see Table II.I in Annex II). The table shows that in situation B, with placing the Filzfelt Akustika ceiling, the capacity of 120 people prescribed in the program of requirements is exceeded and a capacity of 206 is achieved.

Table 3.3 *Acoustic capacity (N_{max}) for the different situations per area and in total (for the values for $L_{N.A.1}$, ΔL, $L_{N.A}$ and $L_{N.A.Areas}$ see Table II.I in Annex II)*

N_{max}	Area 1	Area 2	Area 3	Total
Original situation	31	21	15	67
Situation A	29	22	17	68
Situation B	111	57	38	206
Situation C	119	59	46	224
Situation D	120	61	40	221
Situation E	103	54	39	196

Figure 3.4 shows a comparison between the results of the acoustic capacity of the case study for Rindels prediction formula (see previous Chapter) and Rindels computer-based prediction model. The differences between the results from Rindels prediction formula and computer-based model are significant. When there is more absorption these differences increase even more. An explanation can be that with more absorption the situation differs more from a diffuse sound field than with less absorption.

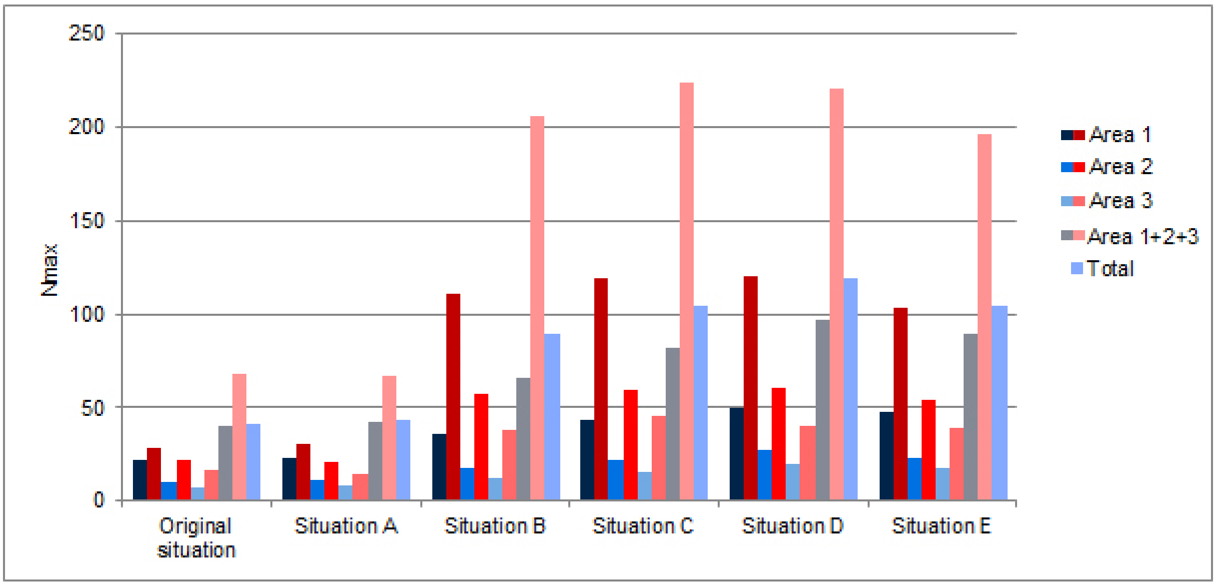

Figure 3.4 *Comparison Acoustic capacity (N_{max}) of the case study for Rindels prediction formula (blue) and computer-based prediction model (red)*

Conclusion

The differences between the results from Rindels prediction formula and computer-based model are significant. Supposedly the adjusted computer-based method is not correct. In the next Chapter an extra study will be conducted to validate both models and determine which method gives the most accurate results.

4 Validating Rindels prediction formula and computer-based prediction model for a room divided in different areas

4.1 Validation study

In the previous two Chapters Rindels prediction formula and computer-based prediction model for calculating the acoustic capacity in multi-talkers environments are explained and tested for a case study. Because of a concrete volume placed in the middle of the restaurant the assumption of a diffuse field can't be made. To bypass the effect of this concrete volume, Rindels method is slightly changed and the room is divided in four rectangular areas. The results from the methods differ a lot, thus in this Chapter a study will be conducted to validate these methods.

Method

For the validation study a model with the same size as the case study is used (19.8 m * 28.8 m * 5.4 m) with 20 simplified boxes (7.2 m * 0.9 m * 0.75 m) for the tables, seats and people, like Rindel also uses in his simulation models[7]. Corresponding to the method used for the case study, the model is divided in three areas as shown in Figure 4.1. The same absorption and scattering coefficients as assigned to the materials in the ODEON model of the case study are used. Glass for the walls, 'wood parquet in asphalt on concrete' for the floor, 'rough concrete' at the ceiling and 'sitting people' for the tables. Unlike the case study in this model the assumption of a diffuse field can be made. To validate the methods, the acoustic capacity N_{max} is calculated per area, like explained in Chapter 2 and 3 and compared to the acoustic capacity simulated by Rindels computer-based prediction method for the total model.

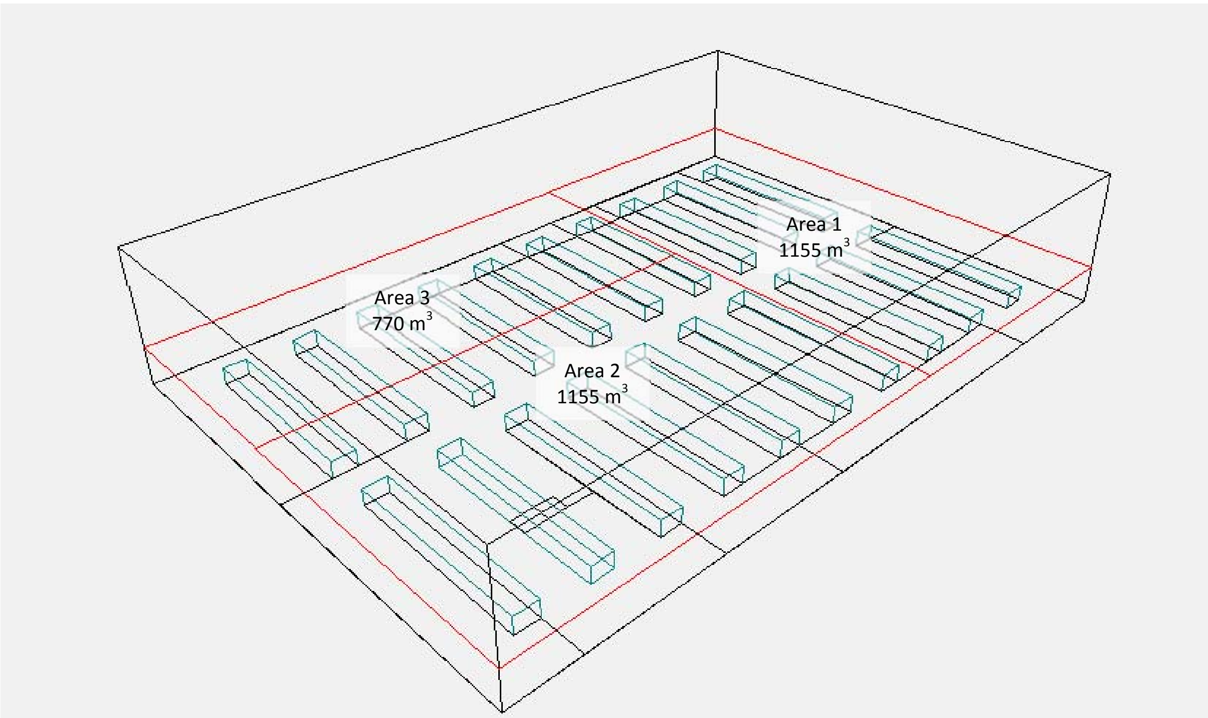

Figure 4.1 *Model for validation study*

Results

Table 4.1 shows the simulated reverberation time, derived by conducting eight simulations on different spots in every area, and the acoustic capacity N_{max} calculated with Rindels prediction formula described in Chapter 2. The total acoustic capacity of the restaurant is 69 persons, according to this method.

Table 4.1 *Reverberation time (T_{20}), derived by conducting eight simulations on different spots in the area, and acoustic capacity N_{max}, derived by Rindels prediction formula for the different areas*

Frequency (Hz)	63	125	250	500	1000	2000	4000	8000	Avg $_{500.\ 1000}$	N_{max}
Area 1	3.90	3.87	2.50	2.14	2.30	2.23	1.65	0.93	2.22	26
Area 2	3.86	3.83	2.51	2.16	2.31	2.24	1.68	0.94	2.23	26
Area 3	3.90	3.75	2.56	2.15	2.33	2.25	1.70	0.94	2.24	17

Table 4.2 shows the simulated reverberation time (derived by using the 'Global estimate' function in ODEON) and the acoustic capacity $\mathrm{N_{max}}$ calculated with Rindels prediction formula for the entire restaurant as described in Chapter 2. The acoustic capacity of the restaurant is 77 persons, according to this method.

Table 4.2 *Reverberation time (T_{20}), derived by the 'Global estimate' function, and acoustic capacity N_{max} derived by Rindels prediction formula for the entire restaurant*

Frequency (Hz)	63	125	250	500	1000	2000	4000	8000	Avg $_{500.\ 1000}$	N_{max}
Total room	3.88	3.84	2.42	1.90	2.09	2.04	1.52	0.86	2.00	77

Table 4.3 shows the ambient noise level and the acoustic capacity for the different areas with a speech spectrum of a raised voice, calculated with Rindels computer-based prediction model as explained in Chapter 3. According to this method the total acoustic capacity of the restaurant is 84 persons.

Table 4.3 *Ambient noise levels and acoustic capacity N_{max} derived by Rindels computer-based prediction model for the different areas*

	Area 1	Area 2	Area 3
$L_{W.A.1}$ (dB)	75.5	75.5	75.5
N	20	20	20
N_s (g = 3.5)	6	6	6
$L_{N.A.1}$ (50%) (dB)	59.8	58.9	59.5
ΔL (dB)	4.9	4.0	4.6
$L_{N.A}$ (dB)	64.7	62.9	64.1
$L_{N.A.Areas}$ (dB)	68.2	69.0	69.3
N_{max}	28	31	25

Table 4.4 shows the acoustic capacity simulated by Rindels computer-based prediction method for the total model, as explained in Chapter 3. The acoustic capacity of the restaurant is 71 persons.

Table 4.4 *Ambient noise level and Acoustic capacity N_{max} derived by Rindels computer-based prediction model for the total restaurant*

$L_{W.A.1}$ (dB)	75.5
N	60
N_s (g = 3.5)	17
$L_{N.A.1}$ (50%) (dB)	50.3
ΔL (dB)	19.2
$L_{N.A}$ (dB)	69.5
N_{max}	71

The acoustic capacity simulated by Rindels computer-based prediction method for the total model is seen as most accurate. When comparing this capacity to the other capacities, the capacity calculated by Rindels prediction formula, where the room is divided in areas, is pretty similar with a difference of only two persons. The acoustic capacity calculated for the entire restaurant with Rindels prediction formula and the use of the 'Global estimate' function in ODEON and the computer-based method per area differ a lot with the capacity calculated with the computer-based method for the restaurant in total. Hereby there will be concluded that these methods will probably be incorrect. In the first the use of the 'Global estimate' function will probably give errors. In the latter an error occurs probably with extracting the noise received from the other areas from 71 dB. However, there is a possibility that this method gives the most accurate results for situations where the assumption of a diffuse sound field can't be made, as in the case study, while it gives incorrect results for a situation with a diffuse sound field.

Conclusion

For further studies it can be interesting to look into the computer-based prediction model and make an attempt to adjust it to make it usable for different types of rooms, like for the case study with a concrete volume in the middle of the room. Next to that, the accuracy of the ´Global estimate´ function and the method which uses eight simulations conducted at different spots, to derive the reverberation time, should be tested. For this research, there will be concluded that the acoustic capacities of the case study calculated for the different areas, given in Chapter 2, will be seen as correct.

5 The effects of solid reflective panels above the tables

5.1 Experimental research

In this research. the effects of a solid reflective panel placed above a table on the speech intelligibility and speech privacy is measured. Situations with different heights of the panel and without a panel are investigated. Also two situations with oblique panels are investigated, these results can be found in Annex III.

Method

Situation

The space that is used for the experiment is the main space in the building 'Gaslab' located at the campus of the Technical University in Eindhoven. In Annex IV the floorplan of the Gaslab can be found. The ceiling height in this space is 10.40 m and in the middle of the space is a void with a height of 4.20 m. There is a glass facade at three sides of the room with venetian blinds, the other facade is made of perforated steel plates. One of the doors, connecting the space with the storage room, was open during the measurements. There is a concrete ceiling and a tiled floor. Figure 5.1 gives an impression of the space.

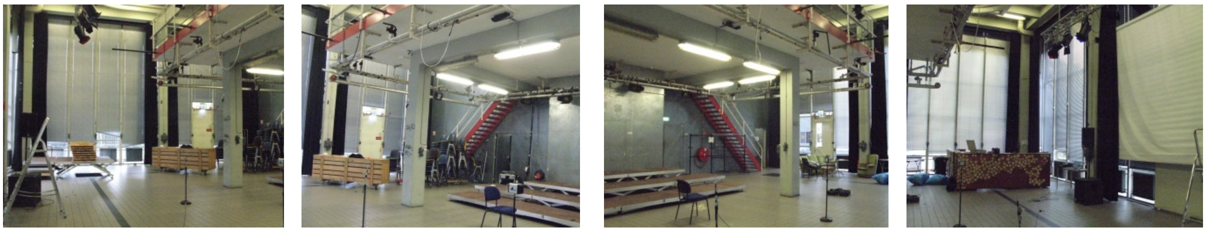

Figure 5.1 *Impression Gaslab*

The average reverberation time is 0.9 s for the mid-frequencies (Table 5.1 and Figure 5.2). To determine the reverberation time, eight measurements are carried out on different spots in the room. The used measurement equipment can be found in Annex V. A calibrated speech source and an omnidirectional microphone are used

Table 5.1 *Reverberation time Gaslab*

Frequency (Hz)	125	250	500	1000	2000	4000	8000	Avg $_{500.\ 1000\ Hz}$
T_{20} (s)	1.38	1.03	0.90	0.92	0.92	0.84	0.70	0.91

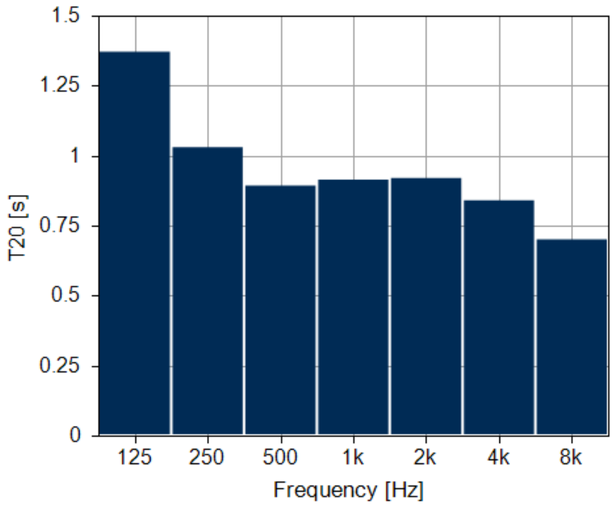

Figure 5.2 *Reverberation time Gaslab*

Measurement method

The measurement setup is made of a scaffolding with three wooden tables in between. Three panels are placed on three tubes above the tables (Figure 5.3). The diameter of the tubes is 60 mm. The setup is placed in the middle of the space (Figure 5.4) and the tables have a length of 2.4 m to 2.2 m. Figure 5.5 shows the source (S) and receiver (R) positions.


Figure 5.3 *Measurement situation*

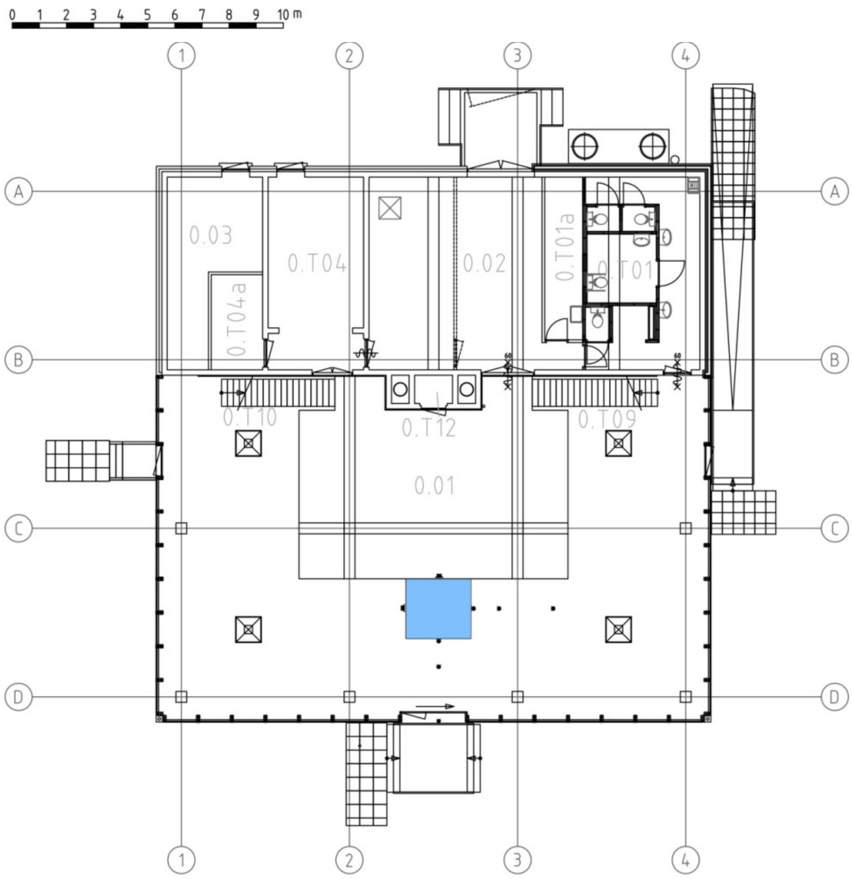

Figure 5.4 *Floorplan with measurement setup*

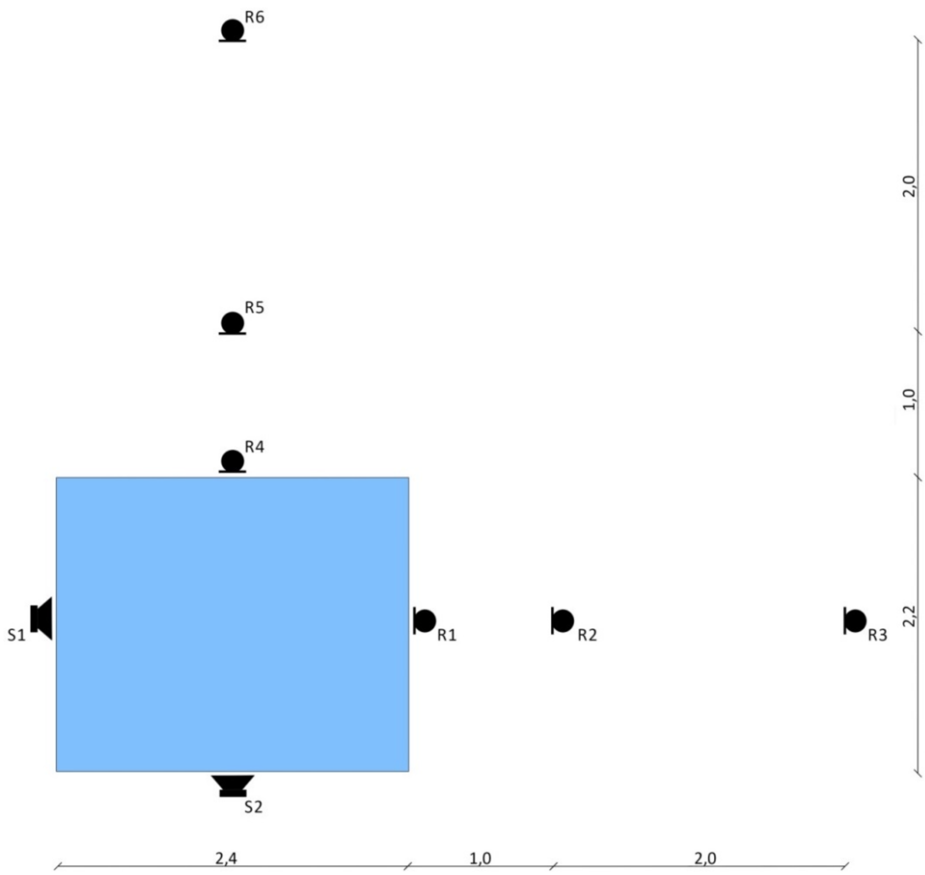

Figure 5.5 *Source and receiver positions*

A situation with the panel at three different heights (height between table and panel = q [cm]) and without a panel are investigated (Figure 5.6). In all measurements the source and receiver positions had a height of 1.2 m, except during the measurement where the plates were the closest to the table and the source and receiver positions had a height of 0.95 m. The table has a height of 0.8 m.

Figure 5.6 *Different measurement situations with height of the panel above the table q (cm)*

The sound source is a calibrated speech source. With the use of the program Dirac 6.0 (type 7841), the signal to noise ratio (SNR) or noise can be set to a certain level. This will only give accurate results if the decay range (INR) has higher levels than 25 dB(A) (estimated value obtained from a personal conversation with ir. C.C.J.M. Hak). Thereby the program can give insights into the effects for a situation without ambient noise and a situation with ambient noise. For the first situation, the SNR is set to 100 dB (speech level = 50 (dB) background level = -50 dB). In the latter the noise level is raised. In the previous Chapters 71 dB(A) is recommended as the maximum ambient noise level for sufficient quality of verbal communication. Hereby a sound pressure level at 1 m from the mouth of 66.5 dB(A) with a raised speech spectrum is valid.[7] The program Dirac sets the sound pressure level at 1 m from the source of the calibrated source automatically to 60 dB(A), resulting in a recommended maximum ambient noise of 64.5 dB(A). The used spectrum for the ambient noise, shown in Table 5.2, is derived with the speech power octave band spectrum shown in Table 3.1.

Table 5.2 *Sound power octave band spectrum for the ambient noise used in Dirac*

Frequency (Hz)	63	125	250	500	1000	2000	4000	8000	A-weighted
$L_{N,A}$ (dB)	41.1	59.1	61.4	65.1	59.1	51.9	45.9	40.6	64.5

Results

Table 5.3 shows the results and a comparison of the STI between the situations with a reflective panel and without a panel for the measurements without ambient noise (SNR = 100 dB). Also some diagonal measurements are carried out (from S1 to R4, R5 and R6 and from S2 to R1, R2 and R3), these results can be found in Annex III. Table 5.3 shows a comparison between the STI near the table (R1 and R4) and the STI further from the table (R2, R3, R5 and R6). The dark grey columns show that for all situations there is a significant difference between the situations with a reflective panel and without a reflective panel, because these differences are higher than the JND 0f 0.03. This means that next to the speech intelligibility also the speech privacy will improve noticeably with placing panels above the table.

The STI for the measurements with source position S2 is for most measurements lower than the STI for the measurements with source positions S1. This can eventually be explained by the sound scattering by the supporting tubes in the middle of the reflective plates. However. the dimensions of these tubes are that small that it probably does not have that much effect. The shape of the room and reflections by the back wall can have caused the difference.

The situation where the panel has a height (q) of 27 cm above the table has overall the highest STI. This is probably because the table and reflective panel create a kind of 'sound tunnel' where the sound waves are reflected from the panel to the table and reverse.

Table 5.3 *STI results and comparison for the measurements without ambient noise (SNR = 100 dB)*

STI (SNR = 100 dB)	A q = 27 cm	B q = 54.5 cm	C q = 82 cm	D Without reflective panel	A minus D	B minus D	C minus D
S1R1	0.96	0.93	0.93	0.83	0.13	0.10	0.10
S1R2	0.83	0.81	0.83	0.75	0.08	0.06	0.08
S1R3	0.74	0.72	0.72	0.69	0.05	0.03	0.03
S1R1 minus S1R2	0.13	0.12	0.10	0.08	0.05	0.04	0.02
S1R1 minus S1R3	0.22	0.21	0.21	0.14	0.08	0.07	0.07
S2R4	0.93	0.90	0.93	0.84	0.09	0.06	0.09
S2R5	0.80	0.76	0.79	0.76	0.04	0.00	0.03
S2R6	0.75	0.72	0.73	0.70	0.05	0.02	0.03
S2R4 minus S2R5	0.13	0.14	0.14	0.08	0.05	0.06	0.06
S2R4 minus S6R6	0.18	0.18	0.20	0.14	0.04	0.04	0.06

Table 5.4 shows the results and a comparison of the STI between the situations with a reflective panel and without a panel for the measurements with the recommended maximum ambient noise level for sufficient quality of verbal communication ($L_{N,A}$ = 64.5 dB(A)). The differences between the STI near the table (R1 and R4) and the STI further from the table (R2, R3, R5 and R6) are higher than the differences shown in Table 5.3. This means that the speech privacy increases when the ambient noise increases. Also the differences between the situations with a reflective panel and the situation without a reflective panel increase. This means that the effects of placing a reflective panel above a table become more significant when the ambient noise increases.

Table *5.4* *STI results and comparison for the measurements with recommended maximum ambient noise level for sufficient quality of verbal communication ($L_{N,A}$ = 64.5 dB(A))*

STI ($L_{N,A}$ = 64.5 dB(A))	A q = 27 cm	B q = 54.5 cm	C q = 82 cm	D Without reflective panel	A minus D	B minus D	C minus D
S1R1	0.42	0.36	0.38	0.17	0.25	0.19	0.21
S1R2	0.15	0.13	0.17	0.06	0.09	0.07	0.11
S1R3	0.06	0.04	0.04	0.04	0.02	0.00	0.00
S1R1 minus S1R2	0.27	0.23	0.21	0.11	0.16	0.12	0.10
S1R1 minus S1R3	0.36	0.32	0.34	0.13	0.23	0.19	0.21
S2R4	0.34	0.30	0.26	0.20	0.14	0.10	0.06
S2R5	0.11	0.08	0.10	0.07	0.04	0.01	0.03
S2R6	0.04	0.04	0.04	0.04	0.00	0.00	0.00
S2R4 minus S2R5	0.23	0.22	0.16	0.13	0.10	0.09	0.03
S2R4 minus S6R6	0.30	0.26	0.22	0.16	0.14	0.10	0.06

Table 5.5 shows the A-weighted SPL from the speech source at the receiver positions. It shows that for the situations with a reflective panel, the SPL increases towards the receiver next to the table. Further from the table the SPL decreases. The sound pressure levels shown in Table 5.5 also explain the STI values in Table 5.4 which are all lower than 0.50. This is because the SPL of the speech source is for al situations lower than the ambient noise level.

Table 5.5 *A-weighted SPL from the speech source (SPL at 1 m = 60,0 dB(A)) at the receiver positions*

$L_{p,A,S}$ [dB(A)]	A q = 27 cm	B q = 54.5 cm	C q = 82 cm	D Without reflective panel
S1R1	64.1	62.4	62.2	56.0
S1R2	55.5	55.4	55.5	53.2
S1R3	51.6	51.6	51.7	49.4
S2R4	63.0	61.0	62.2	56.3
S2R5	55.9	54.6	55.4	53.2
S2R6	53.2	52.4	52.8	51.0

Figure 5.7 and 5.8 show the STI values of the measurements for the three receiver positions R1, R2 and R3 and source position S1 for respectively the situation without ambient noise (SNR = 100 dB) and with ambient noise ($L_{N,A}$ = 64.5 dB(A)). It shows that for all situations without a reflective panel the STI is more than 0.03 higher at the table (R1 and R4) than the STI for the situation without a panel, which means that the speech intelligibility increases with placing a reflective panel above a table. The differences for the results with ambient noise are even higher than the situations without ambient noise.

Figure 5.9 and 5.10 show that the differences between the STI of the situations with reflective panels and without a panel decrease when the distance to the table increases (for receiver positions R1, R2 and R3 and source positions S1). This means that not only the speech intelligibility increases with placing a reflective panel above a table, but also the speech privacy increases. The effect becomes more significant when the ambient noise is included. In Figure 5.10, where the ambient noise is included, the STI at 3 m from the table for two situations with a panel and the situation without a panel even have the same values, while at the table the differences are around 0.20.

Figure 5.11 shows the A-weighted SPL of speech for receiver positions R1, R2 and R3 and source position S1. It shows The SPL of the situation without a reflective panel is significantly lower at the table than the SPL of the situations with panel, but is converging when the distance to the table increases. This effect is one of the components which can explain the improved STI for the situations with a reflective panel.

The hypotheses is that because of the increasing STI and SPL at the table when placing a reflective panel, people will lower their speech volumes when sitting at the table. Resulting in another increase of the speech privacy.

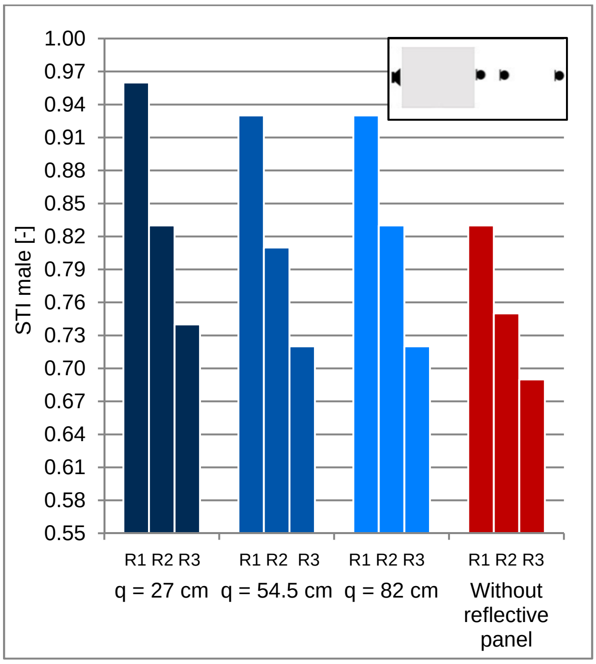

Figure 5.7 *STI of the measurements without ambient noise (SNR = 100 dB) for R1, R2 and R3 and S1*

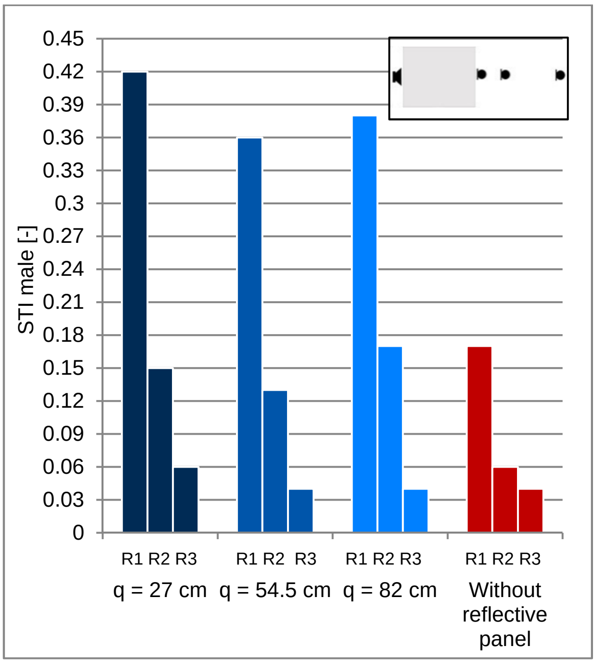

Figure 5.8 *STI of the measurements with ambient noise ($L_{N,A}$ = 64.5 dB(A)) for R1, R2 and R3 and S1*

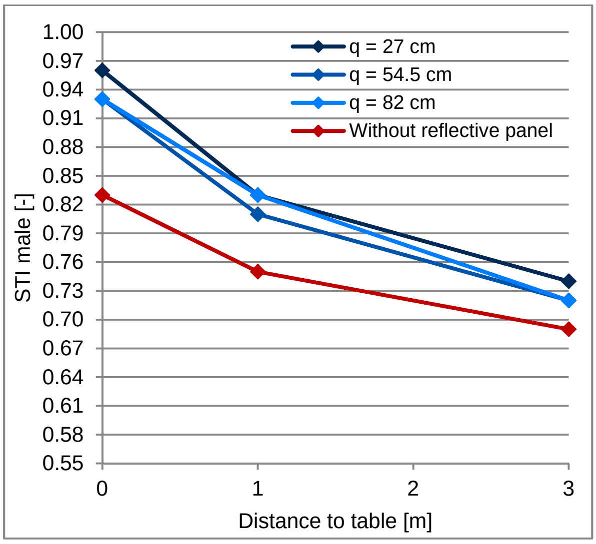

Figure 5.9 *STI of the measurements without ambient noise (SNR = 100 dB) for R1, R2 and R3 and S1*

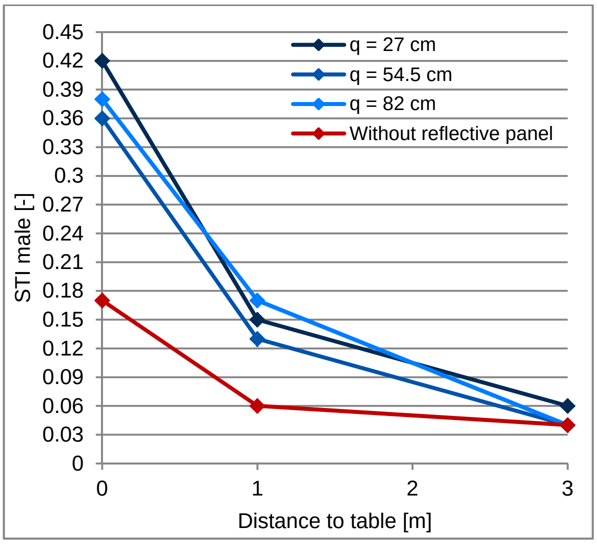

Figure 5.10 *STI of the measurements with ambient noise ($L_{N,A}$ = 64.5 dB(A)) for R1, R2 and R3 and S1*

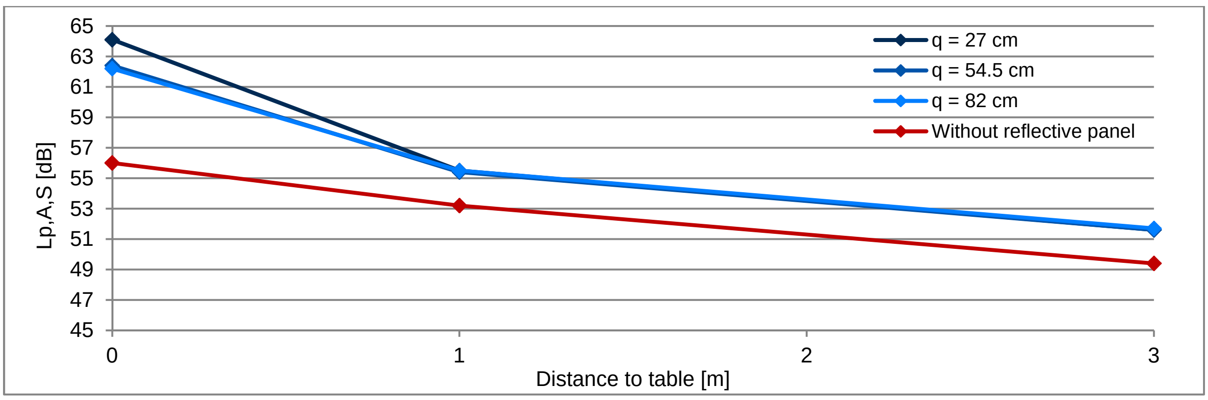

Figure 5.11 *A-weighted SPL of speech ($S_{p,A,L}$) for R1, R2 and R3 and S1*

Figure 5.12 and 5.13 show the STI values of the measurements for the three receiver positions R4, R5 and R6 and source position S2 for respectively the situation without ambient noise (SNR = 100 dB) and with ambient noise ($L_{N,A}$ = 64.5 dB(A)). It shows similar results as shown in Figure 5.7 and 5.8, resulting in an increasing speech intelligibility when placing a reflective panel above the table.

Figure 5.14 and 5.15 show that the differences between the STI of the situations with reflective panels and without a panel decrease when the distance to the table increases (for receiver positions R4, R5 and R6 and source positions S2). These results are also similar to the results shown in Figure 5.9 and 5.10, resulting in an increasing speech privacy when placing a reflective panel and a higher increase when the ambient noise is included.

Figure 5.16 shows the A-weighted SPL of speech for receiver positions R4, R5 and R6 and source position S2. It shows the SPL of the situation without a reflective panel is significantly lower at the table than the SPL of the situations with panel, but is converging when the distance to the table increases.

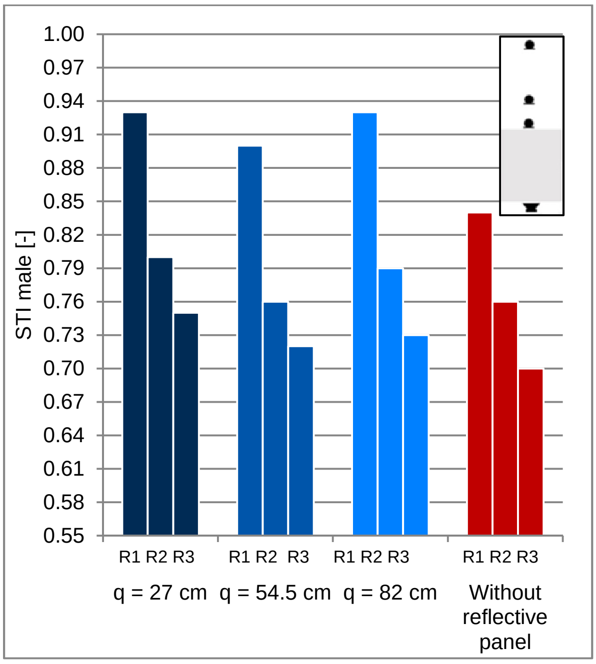

Figure 5.12 *STI of the measurements without ambient noise for R4, R5 and R6 and S2*

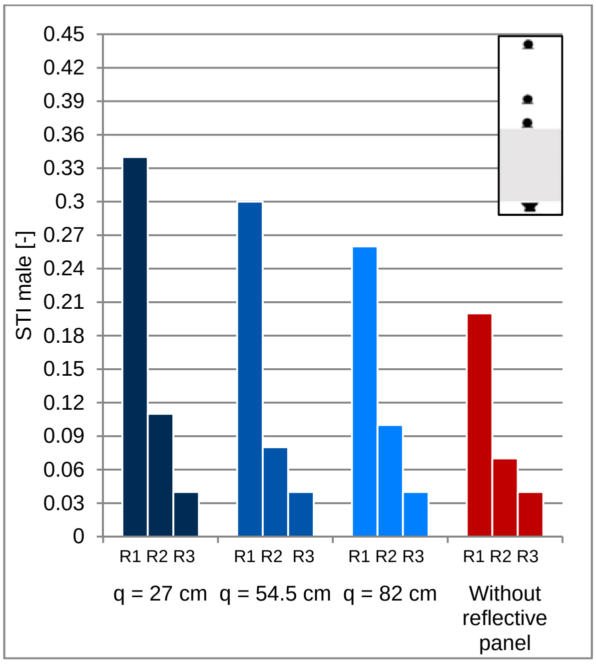

Figure 5.13 *STI of the measurements with ambient noise for R4, R5 and R6 and S2*

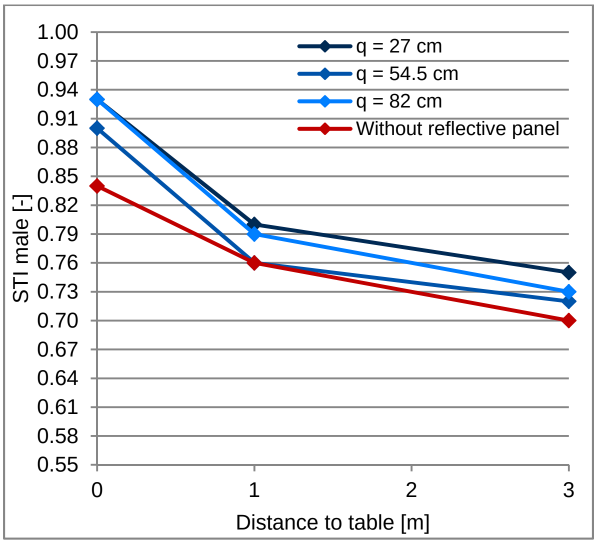

Figure 5.14 *STI of the measurements without ambient noise for R4, R5 and R6 and S2*

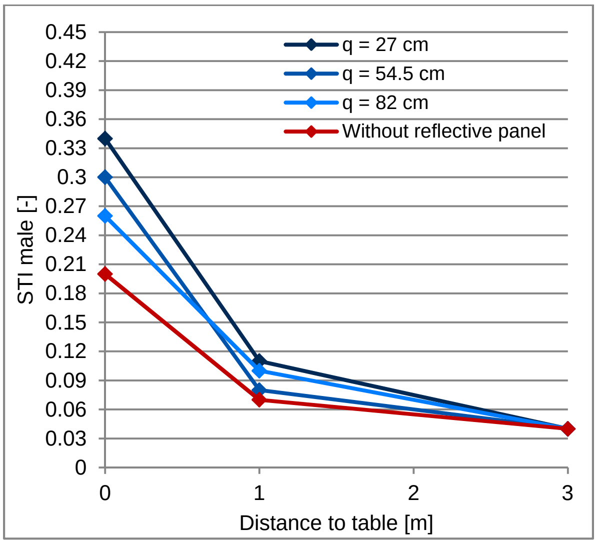

Figure 5.15 *STI of the measurements with ambient noise for R4, R5 and R6 and S2*

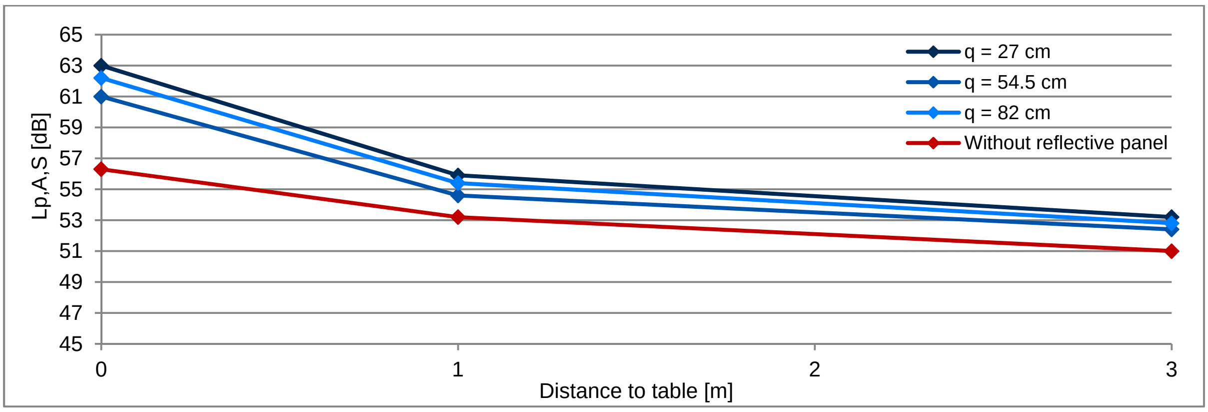

Figure 5.16 *A-weighted SPL of speech ($S_{p,A,L}$) for R4, R5 and R6 and S2*

Conclusion

Looking at the results it can be concluded when placing a solid reflective panel above a table the STI near the table increases significantly (more than JND = 0.03), which means that the speech intelligibility increases with placing a panel above a table. A comparison of the STI values of the measurements near the table and at three meters from the table, differ more than 0.03 for the situations with panels compared to the situation without a panel. Resulting in an increasing speech privacy at the surroundings of the dining table with placing a solid reflective panel above the table.

For future research it can be interesting to do also measurements with other kind of panels. Hereby there can be thought of different shapes, materials, dimensions and heights. Next to that, there can be thought of the effect of different shapes of, for example the ceiling, wall or even decoration at the table. It can also be interesting to look more thoroughly into the formula which describes the STI and try to calculate the most optimal situation.

5.2 Validation ODEON model for the effects of placing reflective panels above the tables

In order to test the effects of placing reflective panels above the tables on the speech intelligibility and speech privacy in the case study, firstly an ODEON model for these effects should be validated.

Method

With the use of 'SketchUp' (2015) the space used for the experiment is modelled and exported to an ODEON file. The geometry of the space is simplified to lower the number of surfaces and thereby decreasing the calculation time. Figure 5.17 shows the ODEON model of the space, the main space in the building 'Gaslab' located at the campus of the Technical University in Eindhoven.

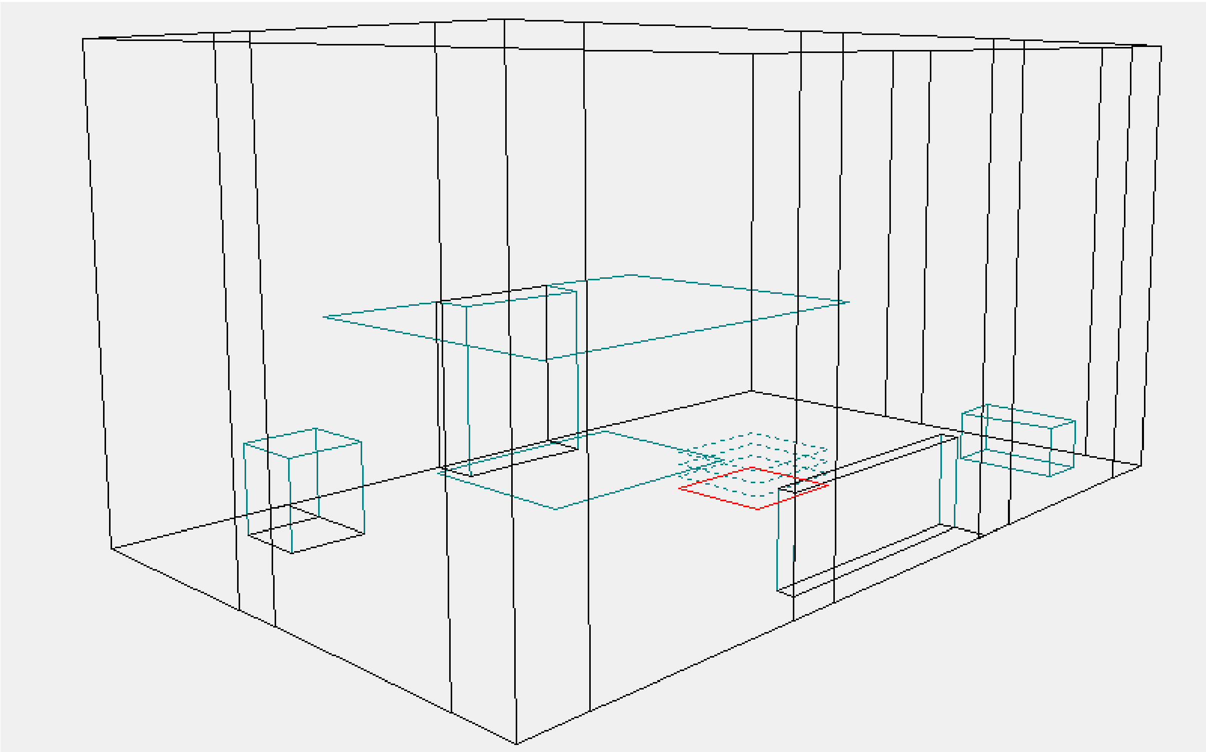

Figure 5.17 *ODEON model of the Gaslab*

Table 5.6 shows the absorption and scattering coefficients as assigned to the materials in the ODEON model. For the floor tiles a material described as 'linoleum or vinyl stuck to concrete' is used, 'ordinary window glass' for the windows, the ceiling is made of 'rough concrete', the curtains are 'densly woven curtains' and for the table and reflective panels a material described as a 'Hollow wooden podium' from the material library in ODEON[13] is used. In front of the windows are venetian blinds, whereby the glass material gets a scattering coefficient of 0.30. Some furniture was standing around the space, of which the geometry is simplified and where a scattering coefficient of 0.30 and a material described as 'lightly upholstered seats' from the material library in ODEON is assigned to. An approximation of the absorption of the perforated steel wall is made, resulting in a simulated reverberation time T_{20} (s) close to the measured reverberation time in the space. The just noticeble difference (JND) for T_{20} is 5%[15], thus the absorption of the wall is adapted untill this demand is met.

Table 5.7 shows the reverberation time for the measured and simulated situation. In both cases eight measurements are conducted on different spots in the room to determine the reverberation time.

The simulations are made with the use of ODEON 12.12, like already mentioned in a previous Chapter, this is a ray-based prediction software and the effect of the wave phenomena are only included to a limited extend in the calculations. This program can be used to generate a plausible reverberation time by assuming a homogeneous reverberant field. However, there should be noted that the algorithms used by ODEON are only a rough representation of the real world.[15]

Table 5.6 *Absorption and scattering coefficients as assigned to the materials in the ODEON model*

Material	Absorption coefficient								Scattering coefficient
	63	125	250	500	1000	2000	4000	8000	
Vinyl floor tiles[13]	0.02	0.02	0.02	0.03	0.04	0.04	0.05	0.05	0.05
Glass[13]	0.35	0.35	0.25	0.18	0.12	0.07	0.04	0.04	0.30
Concrete ceiling[13]	0.02	0.02	0.03	0.03	0.03	0.04	0.07	0.07	0.05
Curtains[13]	0.06	0.06	0.10	0.38	0.63	0.70	0.73	0.73	0.05
Perforated steel wall	0.06	0.06	0.10	0.38	0.63	0.70	0.73	0.73	0.05
Furniture[13]	0.51	0.51	0.64	0.75	0.80	0.82	0.83	0.83	0.30
Table and panels[13]	0.15	0.15	0.11	0.10	0.07	0.06	0.07	0.07	0.05

Table 5.7 *Reverberation time T_{20} (s) Gaslab measured and simulated*

Frequency (Hz)	125	250	500	1000	2000	4000	8000	Avg $_{500.\ 1000\ Hz}$
Measured	1.38	1.03	0.90	0.92	0.92	0.84	0.70	0.91
Simulated	1.39	1.06	0.95	0.94	0.94	0.87	0.69	0.95

For the simulations of the STI in ODEON a 'Rasti.SO8' point source is chosen, which should have similar characteristics as the speech source used during the measurements. The used spectrum for the source, shown in Table 5.8, is derived with the speech power octave band spectrum shown in Table 3.1. The used spectrum for the ambient noise is shown in Table 5.2. The SPL of the ambient noise ($L_{N,A}$) is 64.5 dB(A) and the SPL of the source 68.9 dB(A). These have the same ratio as the recommended maximum ambient noise level for sufficient quality of verbal communication (71 dB(A)) and the SPL for raised speech (75.5 dB(A)).

Table 5.8 *Speech power octave band spectrum for the SPL of the source*

Frequency (Hz)	63	125	250	500	1000	2000	4000	8000	A-weighted
SPL source (dB)	45.5	55.5	65.8	69.5	63.5	56.3	49.8	44.5	68.9

Results

Table 5.9 shows the results and a comparison of the STI between the situations with a reflective panel and without a panel for the simulations. Table 5.10 shows the A-weighted SPL from the speech source at the receiver positions.

Table 5.9 *STI results and comparison for the simulations with recommended maximum ambient noise level for sufficient quality of verbal communication ($L_{N,A}$ = 64.5 dB(A))*

STI ($L_{N,A}$ = 64.5 dB(A))	A q = 27 cm	B q = 54.5 cm	C q = 82 cm	D Without reflective panel	A minus D	B minus D	C minus D
S1R1	0.41	0.38	0.37	0.23	0.18	0.15	0.14
S1R2	0.25	0.23	0.22	0.14	0.11	0.09	0.08
S1R3	0.08	0.06	0.06	0.01	0.07	0.05	0.05
S1R1 minus S1R2	0.16	0.15	0.15	0.09	0.07	0.06	0.06
S1R1 minus S1R3	0.33	0.32	0.31	0.22	0.11	0.10	0.09
S2R4	0.42	0.40	0.38	0.26	0.16	0.14	0.12
S2R5	0.26	0.24	0.23	0.18	0.08	0.06	0.05
S2R6	0.10	0.07	0.06	0.07	0.03	0.00	-0.01
S2R4 minus S2R5	0.16	0.16	0.15	0.08	0.08	0.08	0.07
S2R4 minus S6R6	0.32	0.33	0.32	0.19	0.13	0.14	0.13

Table 5.10 *A-weighted SPL from the speech source (SPL source = 68.9 dB(A)) at the receiver positions*

$L_{p,A,S}$ [dB(A)]	A q = 27 cm	B q = 54.5 cm	C q = 82 cm	D Without reflective panel
S1R1	61.0	60.2	60.0	56.4
S1R2	56.5	55.9	55.8	53.9
S1R3	52.2	51.8	51.5	50.7
S2R4	61.2	60.6	60.4	56.9
S2R5	56.7	56.2	55.8	54.5
S2R6	52.4	51.6	51.0	51.6

Figure 5.18 shows a comparison between the results of the STI simulations (orange) and the STI measurements (blue) for source position S1 to receiver positions R1, R2 and R3. It shows that the STI values derived with the simulations at the table, for the situations with a reflective panel, are really close to the STI values derived with the measurements. At three meters from the table, these values are also very close, but at a distance of one meter from the table the simulations give higher values for the STI than the measurements. These differences are larger than the just noticeable difference (JND = 0.03). The situation without a reflective plate gives higher STI values at the table and at a distance of one meter from the table for the simulations than for the measurements. However, the results derived with the simulations also show that the differences between the STI of the situations with reflective panels and without a panel decrease when the distance to the table increases. These differences are smaller than with the measurements, which means that the simulations give less optimistic results for the speech privacy than the measurements.

Figure 5.19 shows a comparison between the results of the STI simulations (orange) and the STI measurements (blue) for source position S2 to receiver positions R4, R5 and R6. It shows that the STI values derived with the simulations are significant higher (differ more than the JND = 0.03) than the STI values derived with the measurements. This can eventually be explained by the sound scattering by the supporting tubes in the middle of the reflective plates which are used with the measurements. These tubes are not included in the ODEON model. The results derived with the simulations also show that the differences between the STI of the situations with reflective panels and without a panel decrease when the distance to the table increases.

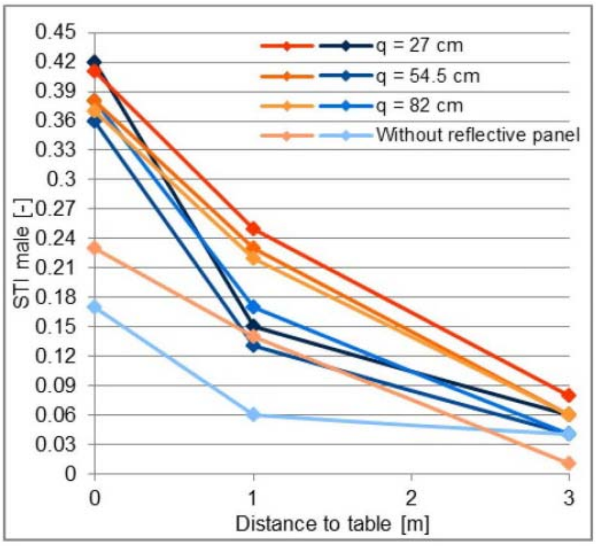

***Figure 5.18** Comparison STI simulations (orange) to STI measurements (blue) for source position S1 to receiver positions R1, R2 and R3*

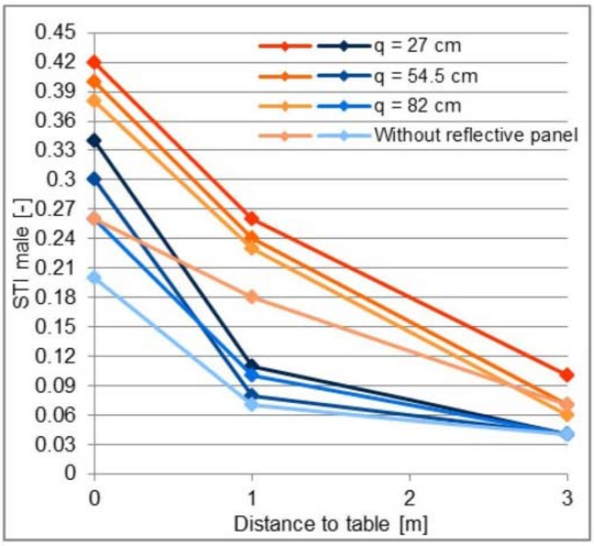

***Figure 5.19** Comparison STI simulations (orange) to STI measurements (blue) for source position S2 to receiver positions R2, 32 and R4*

Figure 5.20 shows the A-weighted SPL of speech for receiver positions R1, R2 and R3 and source position S1. It shows the SPL derived with the simulations are slightly lower, at the table and at a distance of three meters for the situations with reflective panel, than the values derived with the measurements. At one meter from the table the values derived with the simulations are a bit higher than the values derived with the measurements. The values for the situation without a reflective panel derived with the simulations are slightly higher than the values derived with the measurements. Comparing Figure 5.20 to Figure 5.18 shows that the simulations give similar STI values as the measurements when the SPL values of the simulations are lower than the SPL values of the measurements.

Figure 5.21 shows the A-weighted SPL of speech for receiver positions R4, R5 and R6 and source position S2. It shows the SPL derived with the simulations are slightly lower, at the table for the situations with reflective panel, than the values derived with the measurements. At one meter from the table the values derived with the simulations are a bit higher than the values derived with the measurements. The values for the situation without a reflective panel derived with the simulations are slightly higher than the values derived with the measurements. Comparing Figure 5.19 to Figure 5.21 also shows that the simulations give higher STI values with lower SPL values than the measurements.

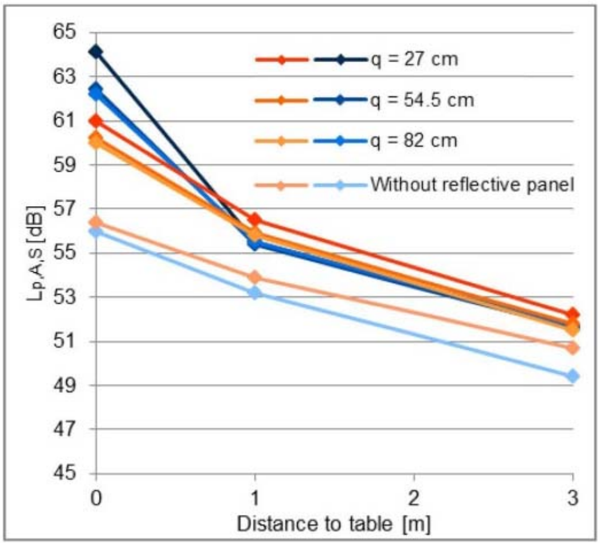

Figure 5.20 *Comparison A-weighted SPL of speech ($L_{p,A,S}$) simulations (orange) to measurements (blue) for R1, R2 and R3 and S1*

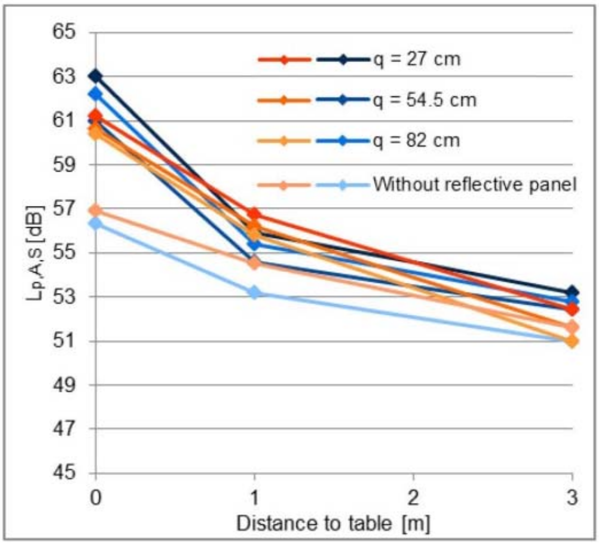

Figure 5.21 *Comparison A-weighted SPL of speech ($L_{p,A,S}$) simulations (orange) to measurements (blue) for R4, R5 and R6 and S2*

Conclusion

The differences between the STI values for the measurements and the simulations from source position S1 to receiver positions R1 (at the table) and R3 (three meters from the table) for the situations with a panel are smaller than 0.03 (JND STI), but these difference are higher than 0.03 at receiver position R2 (one meter from the table). However, the results at the table and at three meters from the table are the most meaningful for the effects of the reflective panel. In addition, the trend shown by the STI values derived by the simulations and by the measurements as a function of the distance to the table are roughly comparable.

The STI values for the measurements from source position S2 to receiver positions R4, R5 and R6 will be neglected, because of the sound scattering by the supporting tubes used with the measurements. However, the trend of the STI values as a function of the distance to the table is still similar to the trend of the results derived by the simulations.

The STI values derived by the simulations for the situation without a panel differ a lot when comparing to the STI values derived by the measurements. The differences between these values are higher than the JND and the trend is different.

The use of ODEON and the simulation model will be seen as accurate for a study deeper into different possibilities for the use of the reflective panels. However, there should be noted that the simulations will probably give slightly less optimistic results than the measurements, with a slightly lower increase of the speech intelligibility and lower increase of the speech privacy compared to the situation without a panel, and the results of the STI at one meter from the table should be neglected.

5.3 Reflective panels in the case study

In the previous paragraph an ODEON model for simulating the effects of placing reflective panels above the tables on the speech intelligibility and speech privacy is validated by a comparison to the measured data. The simulations give slightly less optimistic results than the measurements, which should be kept in mind. In this paragraph an optimization of the design of these panels will be simulated and there will be looked into the possibilities of the use of these panels in the case study and the effects on the speech intelligibility and speech privacy.

Method

For the optimization of the design of the reflective panels, the same simulation model and set up as in the previous paragraph is used (see Figure 5.17). Also the same SPL of the source and ambient noise is used. The highest measured altitude from a reflective panel above the table is 82 cm. The tables in the restaurant have a height of 75 cm, resulting in a height of the panels of 157 cm. In a prefarable situation the panels will have a higher altitude so people will not look on the top of a large amount of reflective panels. This visual barrier can also be overcome by changing the material of the panels to glass. Another improvement for the usability of the panels will be minimizing the size, to prevent that people will bump their head to the panels. These improvements will be tested in the model in order to gain insight into the effects on the STI. Next to that, there will be looked into the effects of the panels with a reduced table size, since most tables in the restaurant will be smaller than the measured tables.

Results

Table 5.11 shows the results and a comparison of the STI when the panels have a higher altitude. The situation with the panel at a height of 90 cm above the table has the highest STI values at the table. Resulting in the best speech intelligibility at the table. However, people will still be bumping their heads against the panels, thus a panel with a higher altitude is preferable. The panel with a height of 110 cm above the table gives STI values which differ less than 0.03 with the panel with a height of 90 cm, which is not a noticeable difference. The panel with a height of 120 cm above the table gives STI values which differ more than 0.03 with the panel with a height of 90 cm. Therefore this panel will not be preferred. This can also been seen in Figure 5.22 and Figure 5.23, which show the results of the STI for the different receiver and source positions. The height of the panel with a height of 110 cm above the table will be 185 cm above the ground, which is higher than most people’s heads. This panel will overall be chosen as best option.

Table 5.11 *STI results and comparison for the simulations with panels at different altitudes*

STI ($L_{N,A}$ = 64 dB(A))	A q = 90 cm	B q = 100 cm	C q = 110 cm	D q = 120 cm	E Without reflective panel	A minus E	B minus E	C minus E	D minus E
S1R1	0.36	0.34	0.34	0.33	0.23	0.13	0.11	0.11	0.10
S1R2	0.22	0.21	0.22	0.23	0.14	0.08	0.07	0.08	0.09
S1R3	0.05	0.05	0.05	0.05	0.01	0.04	0.04	0.04	0.04
S1R1 minus S1R2	0.14	0.13	0.12	0.10	0.09	0.05	0.04	0.03	0.01
S1R1 minus S1R3	0.31	0.29	0.29	0.28	0.22	0.09	0.07	0.07	0.06
S2R4	0.37	0.36	0.35	0.34	0.26	0.11	0.10	0.09	0.08
S2R5	0.23	0.22	0.22	0.22	0.18	0.05	0.04	0.04	0.04
S2R6	0.05	0.06	0.06	0.06	0.07	-0.02	-0.01	-0.01	-0.01
S2R4 minus S2R5	0.14	0.14	0.13	0.12	0.08	0.06	0.06	0.05	0.04
S2R4 minus S6R6	0.32	0.30	0.29	0.28	0.19	0.13	0.11	0.10	0.09

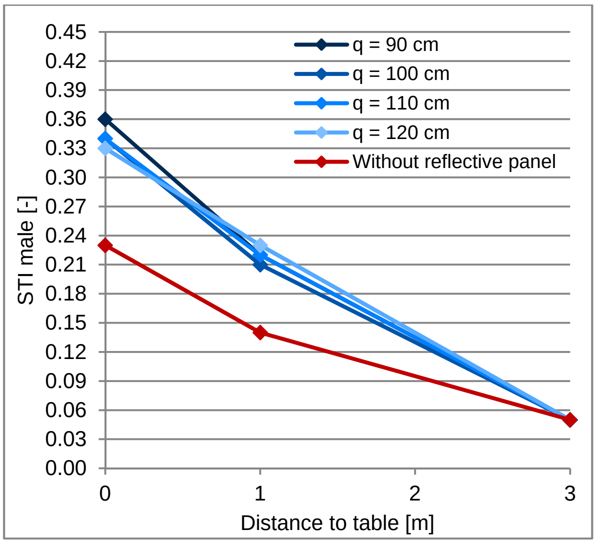

Figure 5.22 *STI results for the simulations with panels at different altitudes for R1, R2 and R3 and S1*

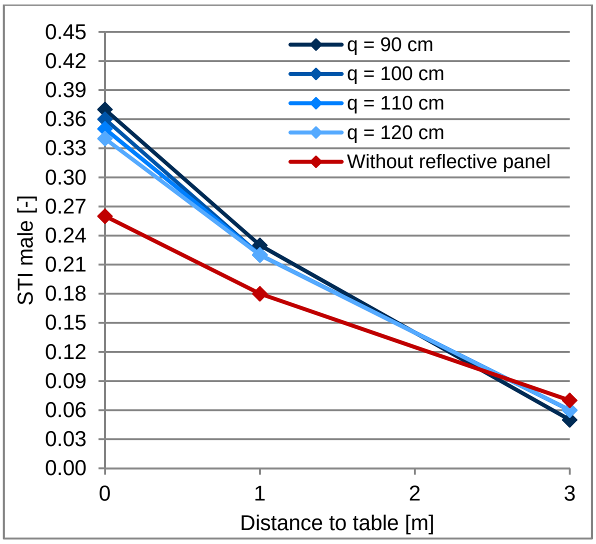

Figure 5.23 *STI results for the simulations with panels at different altitudes for R4, R5 and R6 and S2*

Table 5.12 shows different situations for a panel with a height of 110 cm above the table with a reduced panel size as shown in Figure 5.24. With reducing the size of the panels, the speech intelligibility decreases a bit compared to the situation with a bigger panel as shown in Table 5.11, but these differences are lower than the just noticeable difference (JND = 0.03). The speech privacy increases a bit, but also this difference is lower than 0.03. The situations where the panel is reduced with a ring of 30 cm gives the best results for the speech intelligibility and the speech privacy. However, the differences are very small and lower than the just noticeable difference. This is also shown in Figure 5.25 and 5.26.

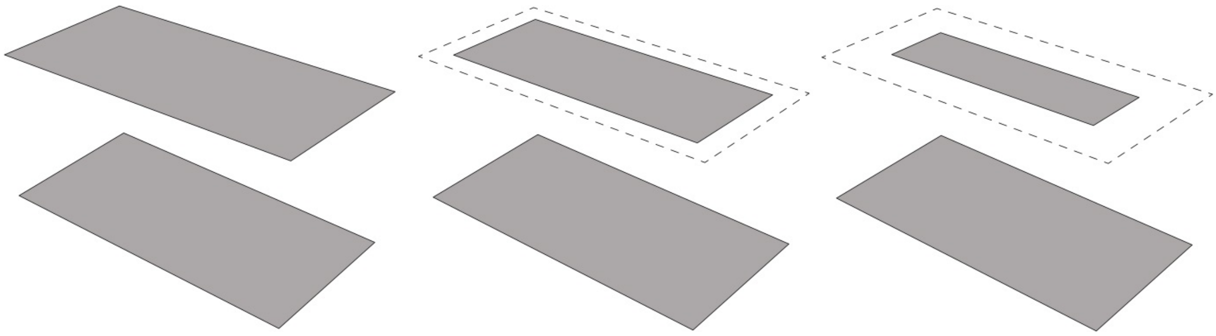

Figure 5.24 *Reducing the size of the panel by removing rings*

Table 5.12 *STI results and comparison for the simulations with panels of different sizes at a height of 110 cm above the table*

STI ($L_{N,A}$ = 64 dB(A))	A q = 110 cm - 10 cm ring	B q = 110 cm - 20 cm ring	C q = 110 cm - 30 cm ring	D q = 110 cm - 40 cm ring	E Without reflective panel	A minus E	B minus E	C minus E	D minus E
S1R1	0.33	0.33	0.33	0.32	0.23	0.10	0.10	0.10	0.09
S1R2	0.20	0.19	0.19	0.19	0.14	0.06	0.05	0.05	0.05
S1R3	0.05	0.04	0.04	0.04	0.01	0.04	0.03	0.03	0.03
S1R1 minus S1R2	0.13	0.14	0.14	0.13	0.09	0.04	0.05	0.05	0.04
S1R1 minus S1R3	0.28	0.29	0.29	0.28	0.22	0.06	0.07	0.07	0.06
S2R4	0.35	0.35	0.35	0.34	0.26	0.09	0.09	0.09	0.08
S2R5	0.21	0.21	0.21	0.21	0.18	0.03	0.03	0.03	0.03
S2R6	0.05	0.06	0.05	0.05	0.07	-0.02	-0.01	-0.02	-0.02
S2R4 minus S2R5	0.14	0.14	0.14	0.13	0.08	0.06	0.06	0.06	0.05
S2R4 minus S6R6	0.30	0.29	0.30	0.29	0.19	0.11	0.10	0.11	0.10

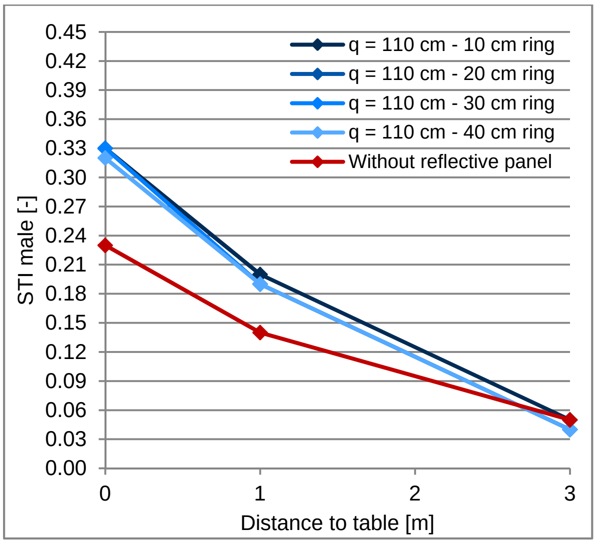

Figure 5.25 *STI results for the simulations with panels of different sizes at a height of 110 cm above the table for R1, R2 and R3 and S1*

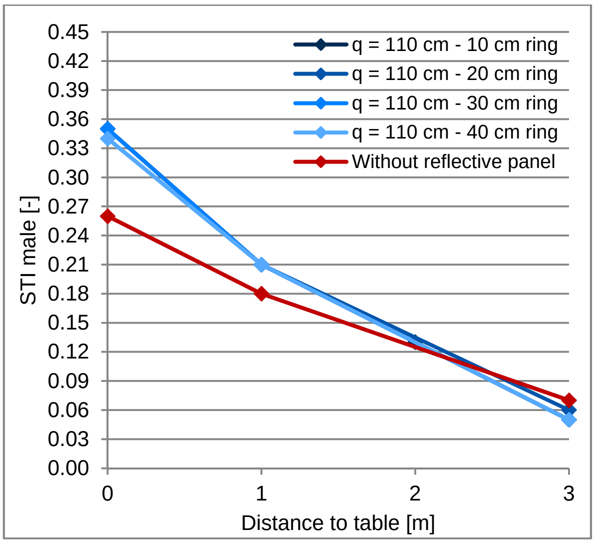

Figure 5.26 *STI results for the simulations with panels of different sizes at a height of 110 cm above the table for R4, R5 and R6 and S2*

Table 5.13 shows the results and a comparison of the STI between the situations with a panel and without a panel for the simulations with a reduced table size. In this case the table is 0.7 m to 1.4 m, which is the size of a table for four persons. The simulations are conducted along both sides, as shown in Figure 5.27. Table 5.13 shows that for these small distances the panel barely influences the STI. Along the 0.7 m side, the differences are lower than 0.03, resulting in no noticeable differences, which is also shown in Figure 5.28. Along the 1.4 m side the differences are just noticeable and the panel with a reduced size of 10 cm along the sides gives the best results for the speech intelligibility and speech privacy, this is shown in Figure 5.29.

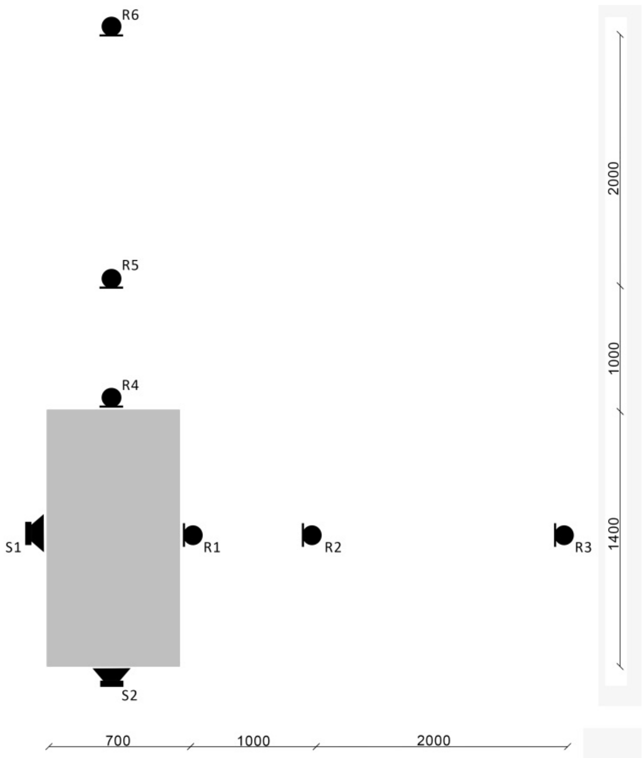

Figure 5.27 *simulation setup with a table size of 0.7 m to 1.4 m*

Table 5.13 *STI results and comparison for the simulations with a table size of 0.7 m to 1.4 m*

STI ($L_{N,A}$ = 64 dB(A))	A q = 110 cm	B q = 110 cm - 10 cm ring	C q = 110 cm - 20 cm ring	D q = 110 cm - 30 cm ring	F Without reflective panel	A minus F	B minus F	C minus F	D minus F
S1R1	0.57	0.57	0.57	0.57	0.56	0.03	0.03	0.03	0.03
S1R2	0.26	0.25	0.25	0.25	0.24	0.04	0.04	0.03	0.02
S1R3	0.11	0.11	0.11	0.11	0.11	0.02	0.02	0.01	0.02
S1R1 minus S1R2	0.15	0.15	0.16	0.17	0.16	-0.01	-0.01	0.00	0.01
S1R1 minus S1R3	0.37	0.37	0.38	0.37	0.36	0.01	0.01	0.02	0.01
S2R4	0.41	0.41	0.41	0.41	0.38	0.01	0.01	0.01	0.01
S2R5	0.26	0.26	0.25	0.24	0.22	0.02	0.01	0.01	0.01
S2R6	0.04	0.04	0.03	0.04	0.02	0.00	0.00	0.00	0.00
S2R4 minus S2R5	0.31	0.32	0.32	0.32	0.32	-0.01	0.00	0.00	0.00
S2R4 minus S6R6	0.46	0.46	0.46	0.46	0.45	0.01	0.01	0.01	0.01

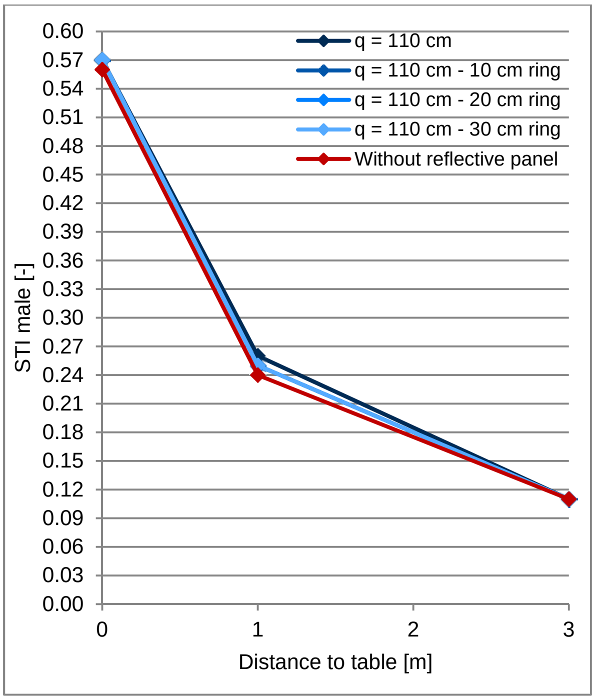

Figure 5.28 *STI results for the simulations with a table size of 0.7 m to 1.4 m, simulated along the 0.7 m side for R1, R2 and R3 and S1*

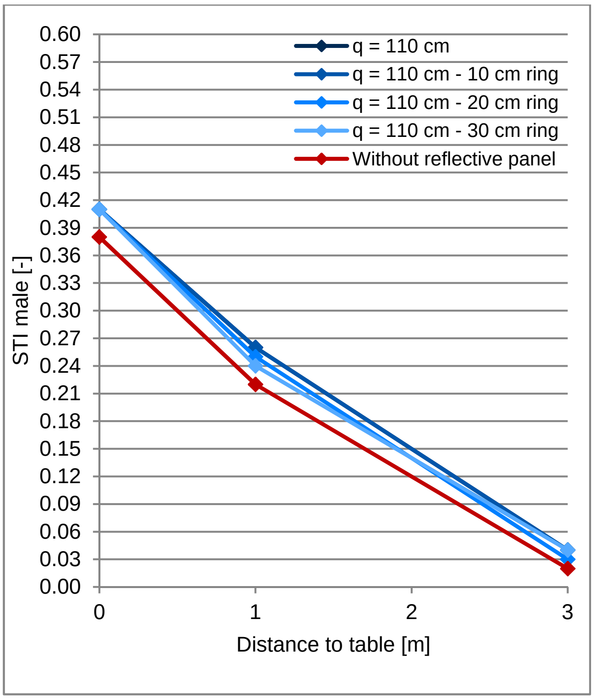

Figure 5.29 *STI results for the simulations with a table size of 0.7 m to 1.4 m, simulated along the 1.4 m side for R4, R5 and R6 and S2*

Table 5.14 shows the results and a comparison of the STI between the situations with a panel and without a panel for the simulations with a table size of 0.7 to 2.1 m. The simulations are conducted along the 2.1 m side, as shown in Figure 5.30. Table 5.14 shows there are significant differences for the speech intelligibility and the speech privacy between the situation without a panel and the situations with panels. Figure 5.31 shows the panel with a reduced size of 30 cm along the sides gives the best results for the speech privacy and only slightly lower results for the speech intelligibility than the whole panel and the panel with a reduced size of 10 cm along the sides.

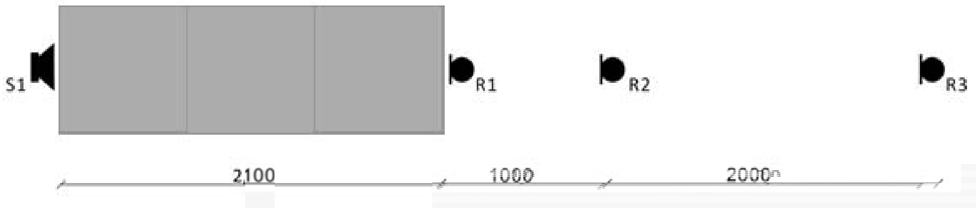

Figure 5.30 *simulation setup with a table size of 0.7 m to 1.4 m*

Table 5.14 *STI results and comparison for the simulations with a table size of 0.7 m to 2.1 m, simulated along the 2.1 m side*

STI ($L_{N,A}$ = 64 dB(A))	q = 110 cm A	q = 110 cm - 10 cm ring B	q = 110 cm - 20 cm ring C	q = 110 cm - 30 cm ring D	Without reflective panel F	A minus F	B minus F	C minus F	D minus F
S1R1	0.33	0.33	0.32	0.32	0.27	0.06	0.06	0.05	0.05
S1R2	0.21	0.21	0.20	0.19	0.16	0.05	0.05	0.04	0.03
S1R3	0.05	0.04	0.03	0.02	0.01	0.04	0.03	0.02	0.01
S1R1 minus S1R2	0.12	0.12	0.12	0.13	0.11	0.01	0.01	0.01	0.02
S1R1 minus S1R3	0.28	0.29	0.29	0.30	0.26	0.02	0.03	0.03	0.04

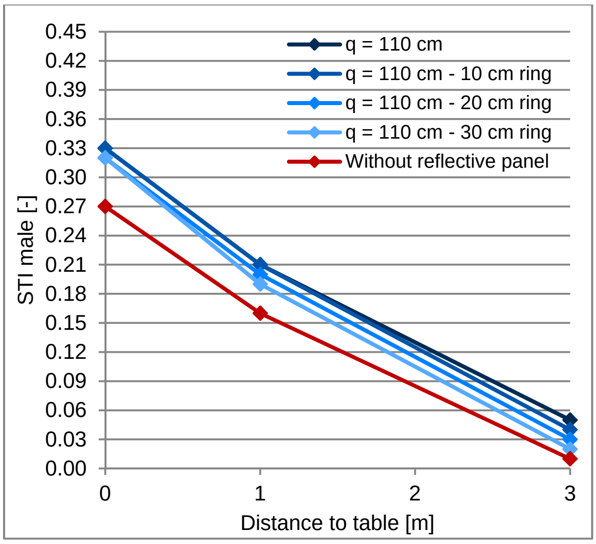

Figure 5.31 *STI results for the simulations with a table size of 0.7 m to 2.1 m, simulated along the 2.1 m side for R1, R2 and R3 and S1*

When the material of the panels is changed to glass, the simulations give approximately the same STI values. The use of glass will thereby be preferred because of aesthetic reasons.

Conclusion

Placing the panels at a height of 110 cm above the table is seen as the best option, because it gives sufficient values concerning the speech intelligibility at the table and speech privacy at the surroundings from the table and the height of the panel will result in a situation where people will not be bumping their heads against the panel. Reducing the panel size, results in some cases in an increasing speech privacy, but this effect is barely noticeable. However a reduced panel size is preferred because of aesthetic reasons. For smaller tables the effects of the panels are barely noticeable, thus there is no need in placing panels above tables for four or two people. With larger tables, like for six or eight people, the effects are significant.

For future research it can be interesting to do simulations with other kind of panels. Hereby there can be thought of different shapes, materials, dimensions and heights. Next to that, there can be thought of the effect of different shapes of, for example, the ceiling, wall or even decoration at the table.

6 Redesign case study

6.1 Redesign case study

In Chapter 4,it is concluded that for this research the acoustic capacities of the case study, calculated for the different areas with Rindels simplified equation given in Chapter 2, will be seen as correct. However, this equation for calculating the acoustic capacity of the room uses an assumption of a diffuse sound field. In the current case study this will not be accurate. The results given by this method are thereby a rough aproximation. In this Chapter a redesign will be made of the case study. The ambient noise caused by the multiple talkers present in the restaurant will be simulated by adding a speech source in the simulation model for every speaker.

Method

In the redesign the capacity of 120 people, which is prescribed in the original program of requirements, will be kept. The original design will be improved by placing the wooden floor on joists, placing Filzfelt Aro shingles at the side walls at a height of 0.75 m to 2.1 m and placing Filzfelt Akustika absorption at the ceiling, as described in 'Situation C' in Table 2.5. For this situation the acoustic capacity does not meet the requirements and is 82 persons, calculated with Rindels simplified equation for the different areas (Table 2.8). This will be neglected, but the ratio of persons per area will be used for the redesign. This results in the required seats per area as shown in Table 6.1. Hereby the seating arrangement from the original design should be changed.

Table 6.1 *Required seats per area in the redesign, derived by the ratio of the acoustic capacity per area, calculated with Rindels simplified equation for the different areas for Situation C*

	Area 1	Area 2	Area 3	Area 1+2+3
N_{max} Situation C	44	22	16	82
Percentage (%)	53	27	20	100
Seats per area redesign	62	34	24	120

In paragraph 5.3 is concluded that it is not necessary to place panels above smaller tables for two or four people. With large tables (for more than four people), the effects on the speech intelligibility and speech privacy are significant. Placing the panels at a height of 110 cm above the table with a reduced panel size is preferred. These insights will also be included in the redesign.

When a new seating arrangement is made, the best sizes for the panels can be derived by using the same method as in Chapter 5. The ODEON model of the restaurant will be used with the new seating arangement and the other improvements mentioned before. A reflective panel will be placed above every large table (for more than four people) at a height of 110 cm above the table. The sources will be placed at the shortest edge of the tables and the three receivers (at the table, 1 m from the table and 3 m from the table) at the other side of the tables. The recommended maximum ambient noise level ($L_{N,A}$) for sufficient quality of verbal communication is 71 DB(A). Thereby a raised voice with a SPL of 75.5 dB(A) is sufficient. The power octave band spectrum for the ambient noise and speech source are shown in Table 6.2. The used spectrum for the ambient noise is derived from the speech power octave band spectrum shown in Table 3.1.

Table 6.2 *Sound power octave band spectrum for the ambient noise used in Dirac*

Frequency (Hz)	63	125	250	500	1000	2000	4000	8000	A-weighted
$L_{N,A}$ (dB)	47.6	57.6	67.9	71.6	65.6	58.4	51.9	47.0	71.0
SPL source (dB)	52.1	62.1	72.4	76.1	70.1	62.9	56.4	51.5	75.5

When the preferred panels are placed above the tables, a speech source for every talker in the restaurant will be placed in the simulation model. Hereby a group size of g = 3.5 will be used and the number of talkers (sources) per area will be calculated. These sources will be placed randomly around the tables at a height of 1.2 m and in front of the heads of the geometries of the persons. A receiver grid will be placed at a height of 1.2 m. The receiver grid shows the parts of the restaurant with the higher and lower ambient noise levels. The A-weighted sound pressure level at the receiver, taken from the grid response as the 50% percentile, gives an indication if the acoustic capacity of the restaurant is exceeded or not. This is exceeded when the SPL is higher than 68 dB(A) (derived from Formula 1 and $L_{S,A,1m}$ = 66,5 dB(A) with a raised voice[7]). 'Rasti.SO8' speech sources will be used with sound spectrum as shown in Table 6.2

Results

Figure 6.1 shows the redesign of the seating arrangement of the case study. The required seats per area as shown in Table 6.1 is used and all seats at the different tables have a minimum distance of 1.5 m to each other to improve the speech privacy. There are four large tables (for more than four persons) where panels will be placed above the tables. The preferred size of the panels will be determined by the STI values at the table and further from the table. Whereby high STI values are preferred at the table, because of a good speech intelligibility, and low STI values are preferred further from the table, because of good speech privacy. The receiver positions and source positions for the different tables are shown in Figure 6.2.

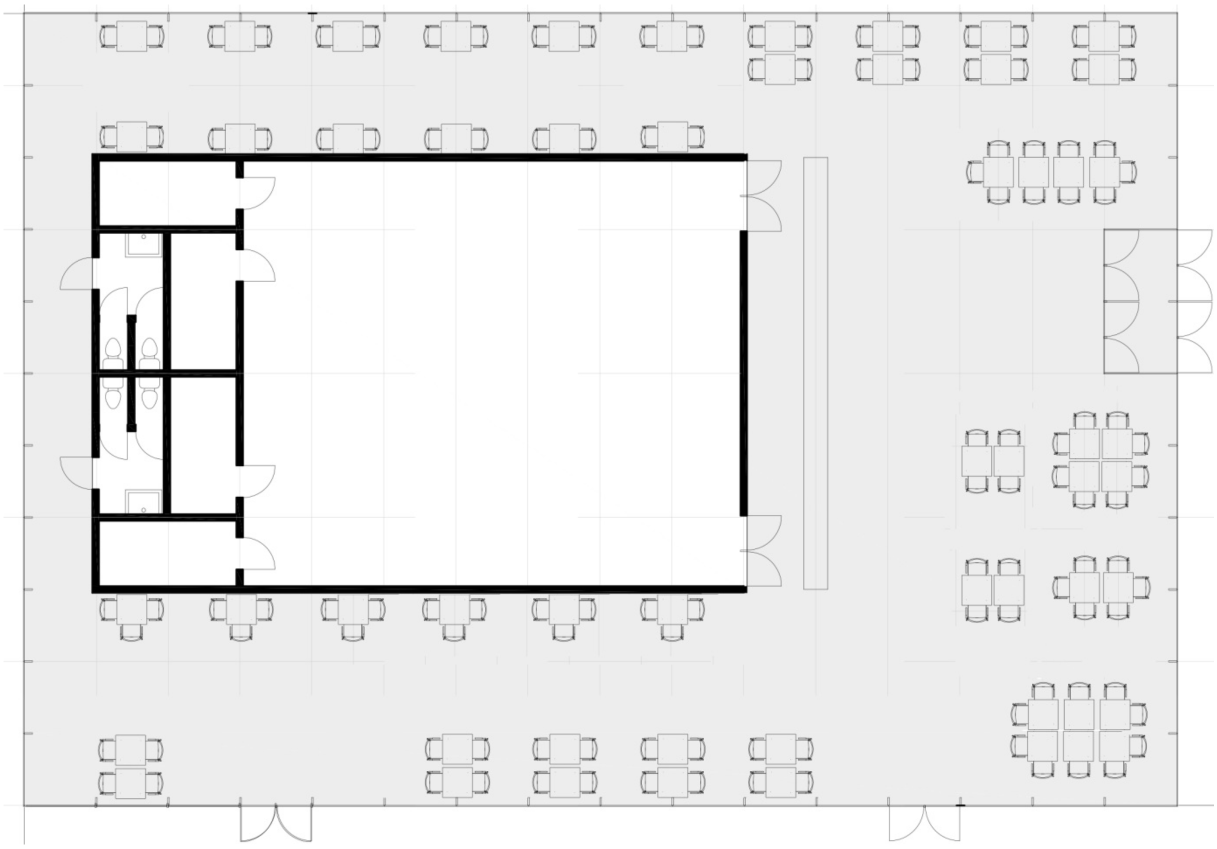

***Figure 3.1** Floorplan of the restaurant with a redesign of the seating arrangement*

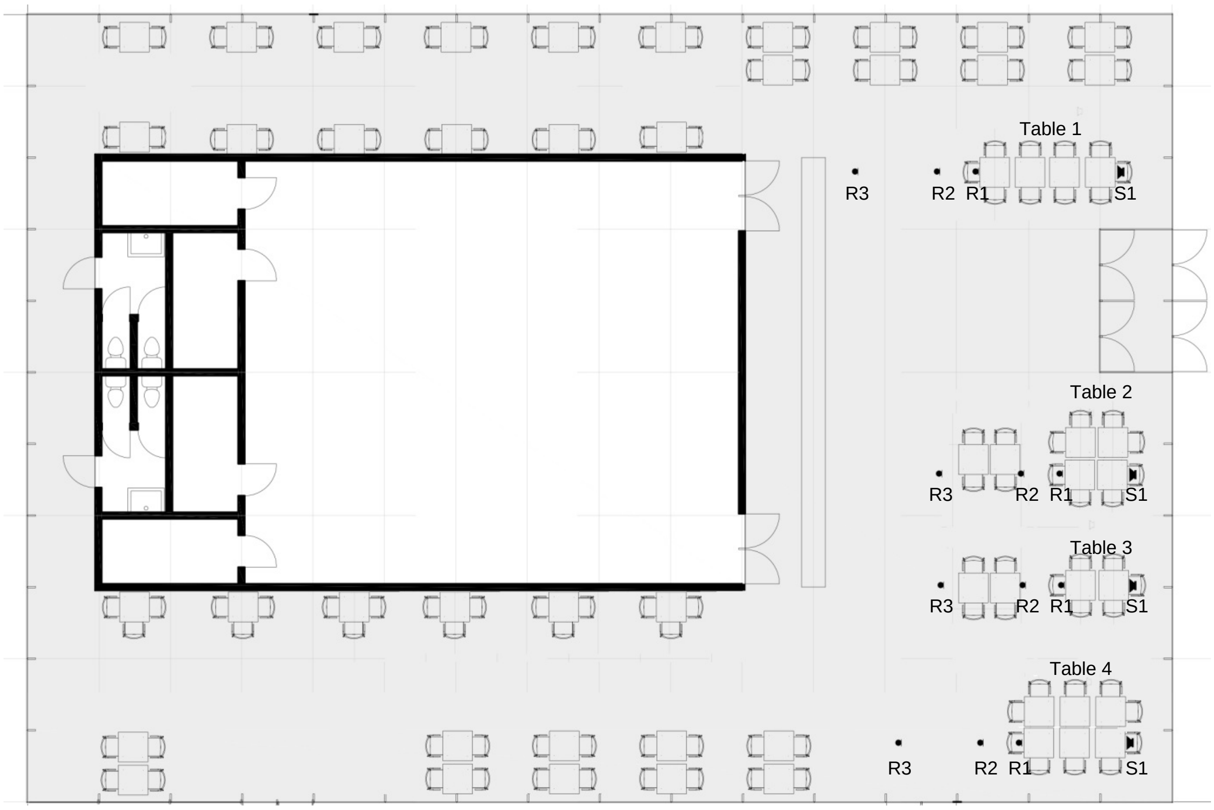

***Figure 4.2** Floorplan of the restaurant with the receiver positions and source positions at the tables with panels*

Table 6.3 shows the results and a comparison of the STI for the simulations with panels of different sizes at a height of 110 cm above table 1 (shown in Figure 6.2). The STI values give a bad quality of the speech (lower than 0.30) at the table. Which means that the speech is unintelligible for that distance. However, placing a panel still improves the speech intelligibility and speech privacy. Panel D, which is reduced with 30 cm at both sides from the long edge and 10 cm at both sides from the short edge will be used in the redesign.

Table 6.3 *STI results and comparison for the simulations with panels of different sizes at a height of 110 cm above table 1*

STI ($L_{N,A}$ = 71 dB(A))	A q = 110 cm	B q = 110 cm - 10 cm ring	C q = 110 cm - 20 cm ring	D q = 110 cm - 30 cm from the long edge at both sides and – 10 cm from the short edge at both sides	E Without reflective panel	A minus E	B minus E	C minus E	D minus E
S1R1	0.06	0.05	0.05	0.05	0.01	0.05	0.04	0.04	0.04
S1R2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S1R3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S1R1 minus S1R2	0.06	0.05	0.05	0.05	0.01	0.05	0.04	0.04	0.04
S1R1 minus S1R3	0.06	0.05	0.05	0.05	0.01	0.05	0.04	0.04	0.04

Table 6.4 shows the results and a comparison of the STI for the simulations with panels of different sizes at a height of 110 cm above table 2 (shown in Figure 6.2). The STI values give a bad quality of the speech (lower than 0.30) at the table, which means that the speech is unintelligible for that distance. However, placing a panel still improves the speech intelligibility and speech privacy. The panel which is not reduced in size gives the highest values for the STI at the table. However, a reduced panel size is preferred because of practical and aesthetic reasons. Thereby, panel B, which is reduced with a ring of 10 cm, will be used in the redesign.

Table 6.4 *STI results and comparison for the simulations with panels of different sizes at a height of 110 cm above table 2*

STI ($L_{N,A}$ = 71 dB(A))	q = 110 cm A	q = 110 cm - 10 cm ring B	q = 110 cm - 20 cm ring C	q = 110 cm - 30 cm ring D	Without reflective panel E	A minus E	B minus E	C minus E	D minus E
S1R1	0.15	0.13	0.12	0.12	0.07	0.08	0.06	0.05	0.05
S1R2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S1R3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S1R1 minus S1R2	0.15	0.13	0.12	0.12	0.07	0.08	0.06	0.05	0.05
S1R1 minus S1R3	0.15	0.13	0.12	0.12	0.07	0.08	0.06	0.05	0.05

Table 6.5 shows the results and a comparison of the STI for the simulations with panels of different sizes at a height of 110 cm above table 3 (shown in Figure 6.2). The STI values give a fair quality of the speech (see Table 1.2) at the table. Which means that the speech is intelligible for this distance. Placing a panel improves the speech intelligibility and speech privacy. The panel which is not reduced in size gives the highest values for the STI at the table. However, a reduced panel size is preferred because of practical and aesthetic reasons. Thereby, panel B, which is reduced with a ring of 10 cm, will be used in the redesign.

Table 6.5 *STI results and comparison for the simulations with panels of different sizes at a height of 110 cm above table 3*

STI ($L_{N,A}$ = 71 dB(A))	q = 110 cm A	q = 110 cm - 10 cm ring B	q = 110 cm - 20 cm ring C	q = 110 cm - 30 cm from the long edge at both sides and – 10 cm from the short edge at both sides D	Without reflective panel E	A minus E	B minus E	C minus E	E minus E
S1R1	0.55	0.53	0.52	0.52	0.50	0.03	0.01	0.00	0.00
S1R2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S1R3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S1R1 minus S1R2	0.55	0.53	0.52	0.52	0.50	0.03	0.01	0.00	0.00
S1R1 minus S1R3	0.55	0.53	0.52	0.52	0.50	0.03	0.01	0.00	0.00

Table 6.6 shows the results and a comparison of the STI for the simulations with panels of different sizes at a height of 110 cm above table 3 (shown in Figure 6.2). The STI values give a bad quality of the speech (lower than 0.30) at the table. Which means that the speech is unintelligible for that

distance. However, placing a panel still improves the speech intelligibility and speech privacy. The panel which is not reduced in size gives the highest values for the STI at the table. However, a reduced panel size is preferred because of practical and aesthetic reasons. Thereby, panel C, which is reduced with a ring of 20 cm, will be used in the redesign.

Table 6.6 *STI results and comparison for the simulations with panels of different sizes at a height of 110 cm above table 4*

STI ($L_{N,A}$ = 71 dB(A))	A q = 110 cm	B q = 110 cm - 10 cm ring	C q = 110 cm - 20 cm ring	D q = 110 cm - 30 cm ring	E Without reflective panel	A minus E	B minus E	C minus E	D minus E
S1R1	0.17	0.15	0.15	0.13	0.04	0.13	0.11	0.11	0.09
S1R2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S1R3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S1R1 minus S1R2	0.17	0.15	0.15	0.13	0.04	0.13	0.11	0.11	0.09
S1R1 minus S1R3	0.17	0.15	0.15	0.13	0.04	0.13	0.11	0.11	0.09

Figure 6.3 shows the results of th SPL at the receiver grid when a speech source is placed for every talker in the restaurant (34 speech sources). Around the bar, around the doors and in the corridor are low sound pressure levels. At the spots where the sources are placed, the sound pressure levels have a maximum of 71.3 dB(A). The A-weighted sound pressure level at the receiver, taken from the grid response as the 50% percentile, is 66.3 dB(A). This means the acoustic capacity of the restaurant is not exceeded with 120 people and if necessary the amount of seats in the restaurant can be increased. Next to that, it can be concluded that the acoustic capacities of the case study calculated for the different areas with Rindels prediction formula are too low.

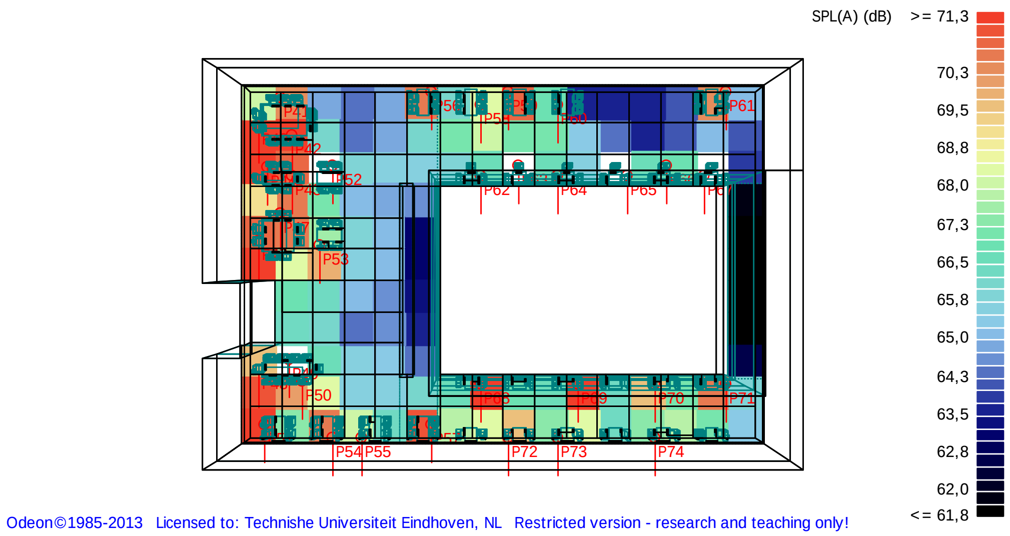

Figure 6.3 *SPL dB(A) ath the receiver grid with 34 speech sources*

Conclusion

When looking at the low STI values derived from the simulations at the large tables, there can be concluded that some distances at the tables are too big to obtain intelligible speech with an ambient noise level of $L_{N,A}$ = 71 dB(A). However in al situations, placing the panels above the tables will improve the speech intelligibility and speech privacy.

The A-weighted sound pressure level as a result of individual placed speech sources for 120 persons (34 speakers) is lower than the maximum A-weighted sound pressure level. Which means that the acoustic capacity of the restaurant is not exceeded with 120 people and, if necessary, the amount of seats in the restaurant can be increased.

If this last prediction method is seen as the most trustworthy of the prediction methods described in this report, it can be concluded that none of the other prediction methods give accurate results for this case study.

7 Conclusion and further research

Rindels prediction formula gives significant different results for the acoustic capacity in the used case study of a restaurant with a concrete volume placed in the middle of the space, compared to Rindels computer-based prediction model for multi-talkers environments. A possible reason is that the assumption of a diffuse sound field can't be made for this case study. while the prediction formula relies on this assumption and the computer-based model uses a transfer function at this assumption. An attempt is made to improve the situation by dividing the room in four rectangular areas. The results derived by this method combined with Rindels prediction formula result in the most trustworthy returns, excluding the method where the SPL in the restaurant is simulated by placing speech sources for every talker in the restaurant. However, the latter method is quite time consuming. From the results derived by this method it can be concluded that the acoustic capacity is not exceeded in the redesign with 120 people in the restaurant.

For further research it can be interesting to look into the adjusted computer-based method and to make an attempt to improve it. Also, the accuracy of the methods can be tested by doing measurements in restaurants and comparing these results with the results derived by the prediction methods. Next to that, simulating the case study with wave-based software can give new insights.

From the results from the experimental research it can be concluded that the speech intelligibility increases significantly at the table, by placing a reflective panel above a table. The differences between the STI values at the table and further from the table also increase by placing a reflective panel above the table. This means that the speech privacy at the surroundings from the table increases. These effects accumulate even more when the ambient noise increases. The measurements and simulations give similar results at the table and at three meters from the table for the situations with a panel. The use of the room acoustics software ODEON will be seen as accurate for a study deeper into different possibilities for the use of the reflective panels. However, there should be noted that the simulations will probably give slightly less optimistic results than the measurements, with a slightly lower increase of the speech intelligibility and lower increase of the speech privacy compared to the situation without a panel, and the results of the STI at one meter from the table should be neglected.

Apart from the effect on the speech intelligibility and the speech privacy, the usability and the aesthetics of the panels should be taken into account so people will not be bumping their heads against the panels and will not have a bad view over the top of the large amount of reflective panels.

For further research it can be interesting to also do measurements and simulations with other kind of panels. Different shapes, materials, dimensions and heights are possible. Next to that, there can be thought of the effect of different shapes of, for example the ceiling, wall or even decoration at the table. In addition, it can be a useful research to look more thoroughly into the formula which describes the STI and to try to calculate the most optimal situation.

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Annex

Annex I Results case study Rindels prediction formula

Table I.I *Reverberation time (T_{20}) in the restaurant, derived by conducting eight simulations on different spots in the area, and acoustic capacity N_{max}, derived by Rindels prediction formula for the different areas*

Frequency (Hz)		63	125	250	500	1000	2000	4000	8000	Avg $_{500,\ 1000}$
Original situation	Area 1	2.61	2.80	2.54	2.51	2.66	2.67	1.79	0.96	2.59
	Area 2	2.47	2.66	2.41	2.43	2.58	2.58	1.69	0.89	2.50
	Area 3	2.27	2.46	2.24	2.26	2.44	2.46	1.55	0.81	2.35
Situation A	Area 1	1.99	2.08	2.14	2.33	2.59	2.67	1.79	0.96	2.46
	Area 2	1.88	1.97	2.04	2.25	2.51	2.58	1.69	0.89	2.38
	Area 3	1.71	1.79	2.00	2.09	2.37	2.46	1.55	0.81	2.23
Situation B	Area 1	1.56	1.59	1.52	1.51	1.62	1.62	1.21	0.73	1.56
	Area 2	1.46	1.49	1.44	1.42	1.52	1.53	1.16	0.69	1.47
	Area 3	1.31	1.34	1.16	1.03	1.15	1.23	0.93	0.54	1.09
Situation C	Area 1	1.49	1.52	1.28	1.22	1.30	1.30	1.05	0.61	1.26
	Area 2	1.44	1.47	1.26	1.14	1.25	1.25	0.95	0.60	1.20
	Area 3	1.33	1.36	1.14	1.05	1.15	1.19	0.90	0.54	1.10
Situation D	Area 1	1.49	1.52	1.23	1.08	1.04	1.16	0.95	0.60	1.06
	Area 2	1.43	1.46	1.14	0.96	1.00	1.00	0.87	0.60	0.98
	Area 3	1.31	1.34	1.05	0.86	0.88	0.92	0.76	0.53	0.87
Situation E	Area 1	1.87	1.91	1.61	1.51	1.60	1.60	1.25	0.72	1.55
	Area 2	1.82	1.85	1.55	1.44	1.54	1.56	1.18	0.67	1.49
	Area 3	1.70	1.74	1.47	1.27	1.34	1.38	1.10	0.62	1.30

Table I.II *Reverberation time (T_{20}) of the entire restaurant for the different situations derived by the 'Global estimate' function and acoustic capacity N_{max}, derived by Rindels prediction formula*

Frequency (Hz)	63	125	250	500	1000	2000	4000	8000	Avg $_{500,\ 1000}$
Original situation	2.56	2.77	2.52	2.50	2.67	2.68	1.78	0.98	2.59
Situation A	1.95	2.04	2.12	2.33	2.60	2.69	1.78	0.98	2.47
Situation B	1.50	1.53	1.33	1.18	1.19	1.22	1.00	0.62	1.19
Situation C	1.48	1.52	1.17	0.99	1.02	1.07	0.89	0.58	1.01
Situation D	1.47	1.50	1.13	0.88	0.89	0.93	0.79	0.54	0.89
Situation E	1.87	1.92	1.55	1.32	1.36	1.38	1.13	0.68	1.34

Annex II Results case study Rindels computer-based prediction model

Table II.I shows the ambient noise level and the acoustic capacity for the different situations, areas and speech spectrums calculated with Rindels computer-based prediction model as explained in the method in Chapter 3. With an ambient noise level of 71 dB a raised speech spectrum is sufficient, as shown in Table 3.1.

Table II.I *Ambient noise levels and acoustic capacity N_{max} for the different situations and areas*

	Area	Area 1				Area 2				Area 3			
	Vocal effort	Normal	Raised	Loud	Shout	Normal	Raised	Loud	Shout	Normal	Raised	Loud	Shout
	$L_{W.A.1}$ (dB)	68.4	75.5	82.6	91.0	68.4	75.5	82.6	91.0	68.4	75.5	82.6	91.0
	N	62	62	62	62	41	41	41	41	26	26	26	26
	N_s (g = 3.5)	18	18	18	18	12	12	12	12	7	7	7	7
Original situation	$L_{N.A.1}$ (50%) (dB)	53.1	60.3	67.5	76.0	54.9	61.9	69.1	77.6	56.2	63.4	70.7	79.0
	ΔL (dB)	22.2	15.2	8.2	-0.1	20.4	13.2	6.2	-2.1	17.8	10.8	3.9	-4.6
	$L_{N.A}$ (dB)	75.3	75.5	75.7	75.9	75.3	75.1	75.3	75.5	74.0	74.2	74.6	74.4
	$L_{N.A.Areas}$ (dB)	65.8	65.8	65.8	65.8	66.0	66.0	66.0	66.0	66.1	66.1	66.1	66.1
	N_{max}	31	31	30	29	20	21	20	20	15	15	14	14
Situation A	$L_{N.A.1}$ (50%) (dB)	53.3	60.5	67.6	76.0	55.1	61.7	68.8	77.2	55.7	62.9	70.1	78.5
	ΔL (dB)	22.4	15.4	8.3	-0.1	20.6	13.0	5.9	-2.5	17.3	10.3	3.3	-5.1
	$L_{N.A}$ (dB)	75.7	75.9	75.9	75.9	75.7	74.7	74.7	74.7	73.0	73.2	73.4	73.4
	$L_{N.A.Areas}$ (dB)	65.7	65.7	65.7	65.7	65.9	65.9	65.9	65.9	66.0	66.0	66.0	66.0
	N_{max}	30	29	29	29	20	22	22	22	17	17	16	16
Situation B	$L_{N.A.1}$ (50%) (dB)	48.4	55.3	62.2	70.7	51.2	58.1	65.1	73.4	52.9	59.9	66.9	75.3
	ΔL (dB)	17.5	10.2	2.9	-5.4	16.7	9.4	2.2	-6.3	14.5	7.3	0.1	-8.3
	$L_{N.A}$ (dB)	65.9	65.5	65.1	65.3	67.9	67.5	67.3	67.1	67.4	67.2	67.0	67.0
	$L_{N.A.Areas}$ (dB)	60.3	60.3	60.3	60.3	61.4	61.4	61.4	61.4	61.9	61.9	61.9	61.9
	N_{max}	106	111	116	113	55	57	59	60	37	38	39	39
Situation C	$L_{N.A.1}$ (50%) (dB)	47.9	55.0	61.9	70.3	50.7	58.0	64.7	73	52.1	59.1	66.2	74.5
	ΔL (dB)	17.0	9.9	2.6	-5.8	16.2	9.3	1.8	-6.7	13.7	6.5	-0.6	-9.1
	$L_{N.A}$ (dB)	64.9	64.9	64.5	64.5	66.9	67.3	66.5	66.3	65.8	65.6	65.6	65.4
	$L_{N.A.Areas}$ (dB)	59.9	59.9	59.9	59.9	60.9	60.9	60.9	60.9	60.9	60.9	60.9	60.9
	N_{max}	119	119	125	125	62	59	65	66	45	46	46	47
Situation D	$L_{N.A.1}$ (50%) (dB)	48.0	55.0	62.1	70.4	50.9	57.9	65.0	73.3	52.6	59.7	66.7	75.1
	ΔL (dB)	17.1	9.9	2.8	-5.7	16.4	9.2	2.1	-6.4	14.2	7.1	-0.1	-8.5
	$L_{N.A}$ (dB)	65.1	64.9	64.9	64.7	67.3	67.1	67.1	66.9	66.8	66.8	66.6	66.6
	$L_{N.A.Areas}$ (dB)	59.3	59.3	59.3	59.3	59.8	59.8	59.8	59.8	61.0	61.0	61.0	61.0
	N_{max}	117	120	120	123	60	61	61	63	40	40	41	41
Situation E	$L_{N.A.1}$ (50%) (dB)	48.1	55.1	62.1	70.4	50.8	57.9	64.9	73.3	52.4	59.5	66.5	74.9
	ΔL (dB)	17.2	10.0	2.8	-5.7	16.3	9.2	2.0	-6.4	14.0	6.9	-0.3	-8.7
	$L_{N.A}$ (dB)	65.3	65.1	64.9	64.7	67.1	67.1	66.9	66.9	66.4	66.4	66.2	66.2
	$L_{N.A.Areas}$ (dB)	65.4	65.4	65.4	65.4	65.3	65.3	65.3	65.3	64.6	64.6	64.6	64.6
	N_{max}	101	103	106	108	54	54	56	56	39	39	40	40

Annex III Results experimental research

A-weighted SPL from the speech source (SPL at 1 m = 60,0 dB(A)) at the receiver positions

$L_{p,A,S}$ [dB]	q = 27 cm	q = 54.5 cm	q = 82 cm	Without reflective panel	q = 75.5 cm to 36 cm	q = 103 cm to 63 cm
S1R1	64.1	62.4	62.2	56.0	59.7	58.1
S1R2	55.5	55.4	55.5	53.2	54.5	53.3
S1R3	51.6	51.6	51.7	49.4	50.1	49.5
S2R4	63.0	61.0	62.2	56.3	61.0	-
S2R5	55.9	54.6	55.4	53.2	55.2	-
S2R6	53.2	52.4	52.8	51.0	52.1	-
S1R4	61.9	59.8	58.4	57.0	59.8	58.4
S1R5	54.8	53.8	54.7	53.3	53.7	54.0
S1R6	51.4	51.5	50.5	50.4	52.3	50.6
S2R1	62.0	59.1	58.5	57.3	58.1	-
S2R2	53.9	53.0	53.1	53.0	53.3	-
S2R3	49.7	50.2	49.7	50.3	49.5	-

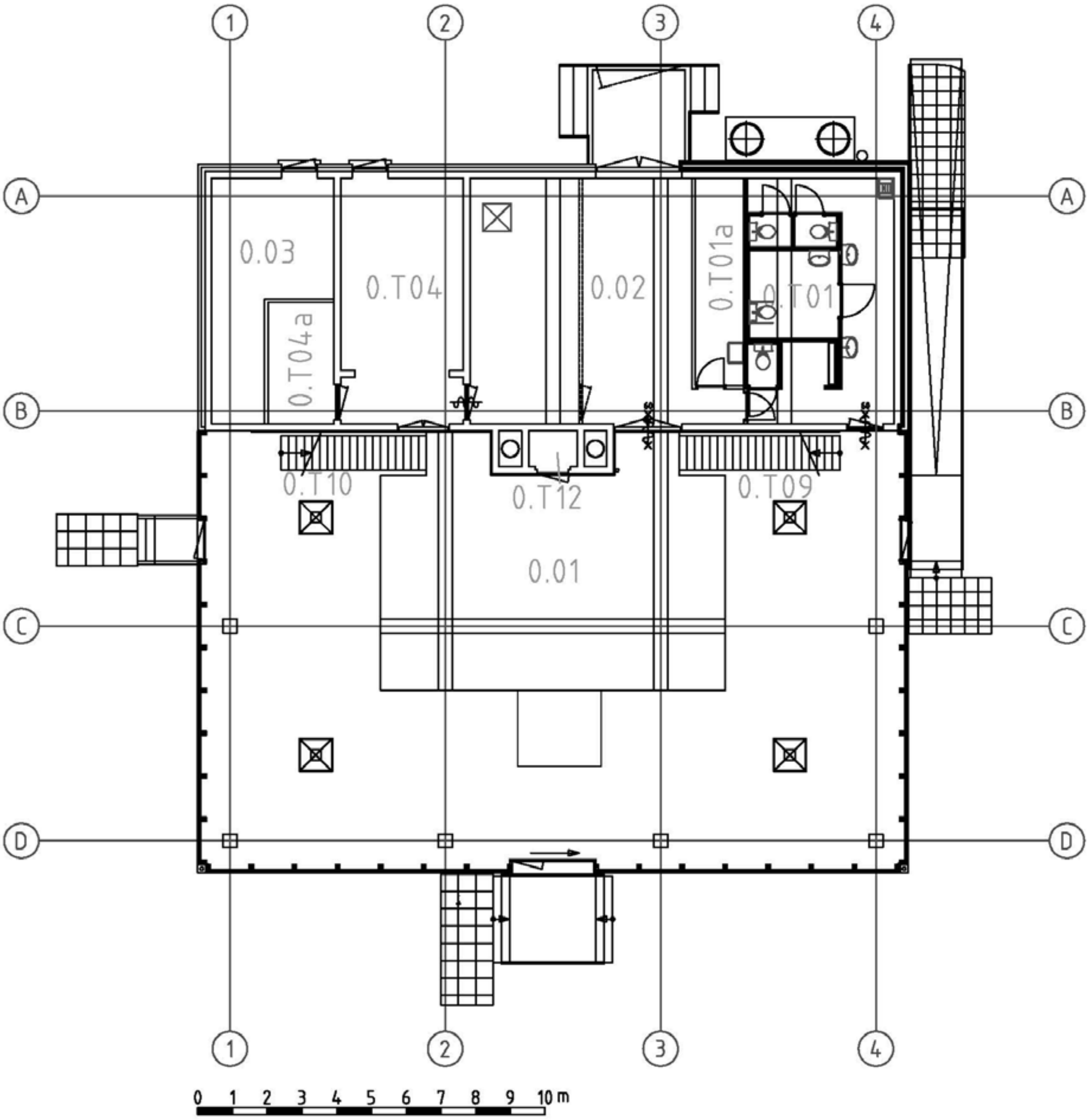
STI results and comparison for the measurements without ambient noise (SNR = 100 dB)

STI (SNR = 100 dB)	A q = 27 cm	B q = 54.5 cm	C q = 82 cm	D Without reflective panel	E q = 75.5 cm to 36 cm	F q = 103 cm to 63 cm	A minus D	B minus D	C minus D	E minus D	F minus D
S1R1	0.96	0.93	0.93	0.83	0.92	0.86	0.13	0.10	0.10	0.09	0.03
S1R2	0.83	0.81	0.83	0.75	0.76	0.75	0.08	0.06	0.08	0.01	0.00
S1R3	0.74	0.72	0.72	0.69	0.70	0.67	0.05	0.03	0.03	0.01	-0.02
S1R1 minus S1R2	0.13	0.12	0.10	0.08	0.16	0.11	0.05	0.04	0.02	0.08	0.03
S1R1 minus S1R3	0.22	0.21	0.21	0.14	0.22	0.19	0.08	0.07	0.07	0.08	0.05
S2R4	0.93	0.90	0.93	0.84	0.91	-	0.09	0.06	0.09	0.07	-
S2R5	0.80	0.76	0.79	0.76	0.79	-	0.04	0.00	0.03	0.03	-
S2R6	0.75	0.72	0.73	0.70	0.75	-	0.05	0.02	0.03	0.05	-
S2R4 minus S2R5	0.13	0.14	0.14	0.08	0.12	-	0.05	0.06	0.06	0.04	-
S2R4 minus S6R6	0.18	0.18	0.20	0.14	0.16	-	0.04	0.04	0.06	0.02	-
S1R4	0.93	0.91	0.88	0.85	0.89	0.89	0.08	0.06	0.03	0.04	0.04
S1R5	0.77	0.75	0.77	0.73	0.74	0.75	0.04	0.02	0.04	0.01	0.02
S1R6	0.68	0.67	0.68	0.65	0.68	0.68	0.03	0.02	0.03	0.03	0.03
S1R4 minus S1R5	0.16	0.16	0.11	0.12	0.15	0.14	0.04	0.04	-0.01	0.03	0.02
S1R5 minus S1R6	0.25	0.24	0.20	0.20	0.21	0.21	0.05	0.04	0.00	0.01	0.01
S2R1	0.94	0.91	0.87	0.85	0.87	-	0.09	0.06	0.02	0.02	-
S2R2	0.77	0.75	0.73	0.72	0.72	-	0.05	0.03	0.01	0.00	-
S2R3	0.68	0.67	0.66	0.66	0.65	-	0.02	0.01	0.00	-0.01	-
S2R1 minus S2R2	0.17	0.16	0.14	0.13	0.15	-	0.04	0.03	0.01	0.02	-
S2R1 minus S2R3	0.26	0.24	0.21	0.19	0.22	-	0.07	0.05	0.02	0.03	-

STI results and comparison for the measurements with recommended maximum ambient noise level for sufficient quality of verbal communication ($L_{N,A}$ = 64.5 dB(A))

STI (($L_{N,A}$ = 64.5 dB(A))	A q = 27 cm	B q = 54.5 cm	C q = 82 cm	D Without reflective panel	E q = 75.5 cm to 36 cm	F q = 103 cm to 63 cm	A minus D	B minus D	C minus D	E minus D	F minus D
S1R1	0.42	0.36	0.38	0.17	0.33	0.24	0.25	0.19	0.21	0.16	0.07
S1R2	0.15	0.13	0.17	0.06	0.09	0.08	0.09	0.07	0.11	0.03	0.02
S1R3	0.06	0.04	0.04	0.04	0.04	0.04	0.02	0.00	0.00	0.00	0.00
S1R1 minus S1R2	0.27	0.23	0.21	0.11	0.24	0.16	0.16	0.12	0.10	0.13	0.05
S1R1 minus S1R3	0.36	0.32	0.34	0.13	0.29	0.20	0.23	0.19	0.21	0.16	0.07
S2R4	0.34	0.3	0.26	0.2	0.28	-	0.14	0.10	0.06	0.08	-
S2R5	0.11	0.08	0.1	0.07	0.08	-	0.04	0.01	0.03	0.01	-
S2R6	0.04	0.04	0.04	0.04	0.04	-	0.00	0.00	0.00	0.00	-
S2R4 minus S2R5	0.23	0.22	0.16	0.13	0.20	-	0.10	0.09	0.03	0.07	-
S2R4 minus S6R6	0.30	0.26	0.22	0.16	0.24	-	0.14	0.10	0.06	0.08	-
S1R4	0.35	0.27	0.22	0.19	0.22	0.28	0.16	0.08	0.03	0.03	0.09
S1R5	0.08	0.06	0.06	0.06	0.06	0.09	0.02	0.00	0.00	0.00	0.03
S1R6	0.04	0.03	0.03	0.04	0.03	0.04	0.00	-0.01	-0.01	-0.01	0.00
S1R4 minus S1R5	0.27	0.21	0.16	0.13	0.16	0.19	0.14	0.08	0.03	0.03	0.06
S1R5 minus S1R6	0.31	0.24	0.19	0.15	0.19	0.24	0.16	0.09	0.04	0.04	0.09
S2R1	0.35	0.31	0.38	0.18	0.31	-	0.17	0.13	0.20	0.13	-
S2R2	0.14	0.09	0.14	0.07	0.11	-	0.07	0.02	0.07	0.04	-
S2R3	0.06	0.05	0.06	0.04	0.06	-	0.02	0.01	0.02	0.02	-
S2R1 minus S2R2	0.21	0.22	0.24	0.11	0.20	-	0.10	0.11	0.13	0.09	-
S2R1 minus S2R3	0.29	0.26	0.32	0.14	0.25	-	0.15	0.12	0.18	0.11	-

Annex IV Floorplan Gaslab



Annex V Used equipment

Description	Brand	Type/name	Photo
Sound source	Brüel & Kjaer	Echo Speech Source Type 4720	
Microphone	Brüel & Kjaer	Type 2671	
USB Audio Interface	Acoustics Engineering	Triton