MASTER

The effect of the acoustics of a cinema on the reproduction of the acoustics of a movie soundtrack

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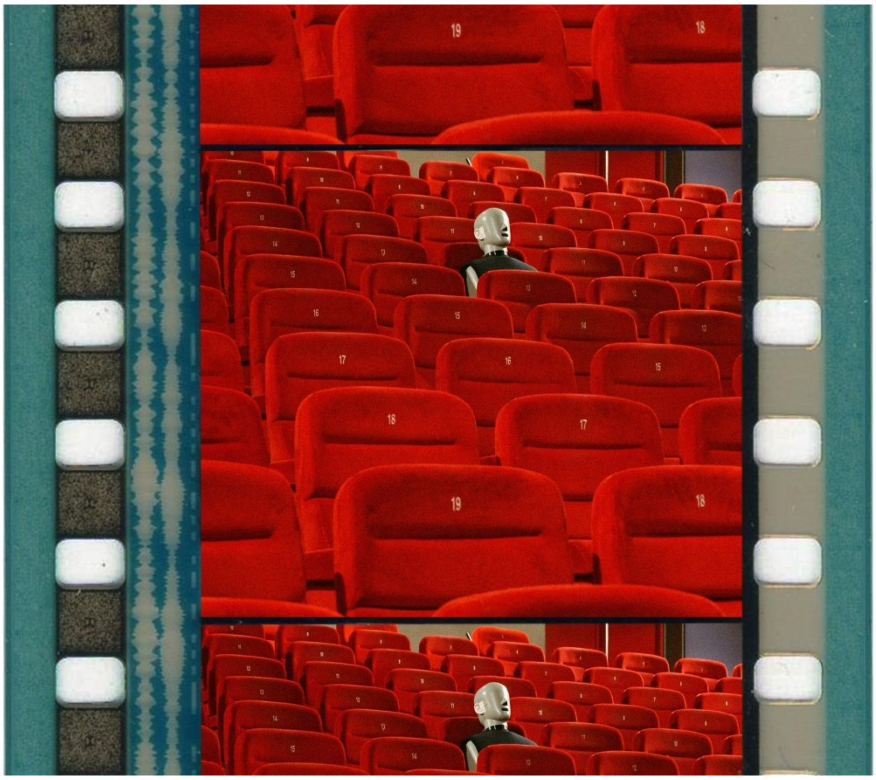
The Effect of the Acoustics of a Cinema on the Reproduction of the Acoustics of a Movie Soundtrack



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Correction sheet

The following textual content needs to be changed:

Acknowledgements. Page 43:

Replace '*disinterested cooperation*' with '*great voluntary cooperation*'.

The following figures replace the existing figures in the report without consequences for the textual content.

Chapter 2. Page 21:

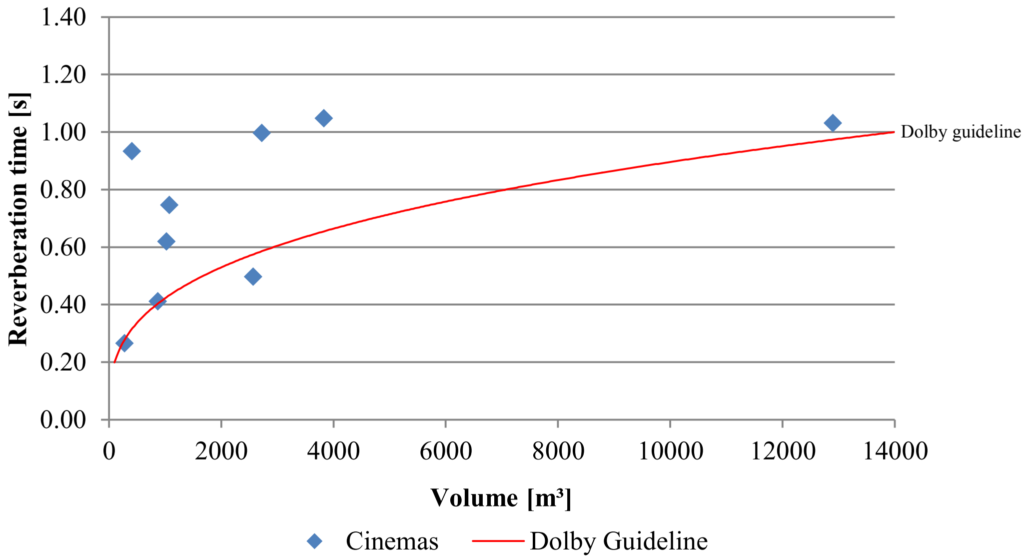


Figure 2.3 *Reverberation time related to cinema volume compared to the Dolby guidelines advice*

Chapter 3. Page 32:

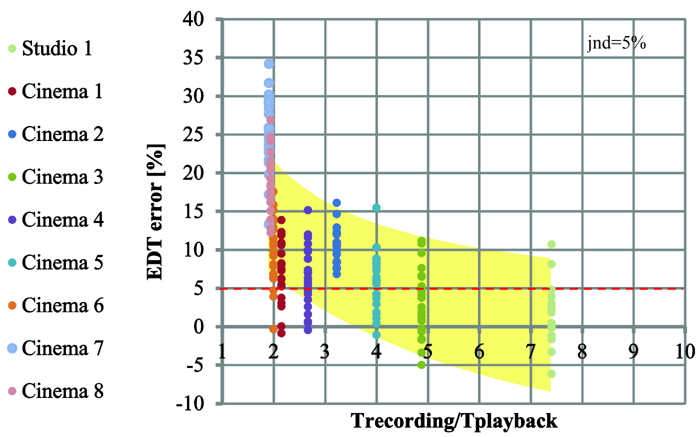


Figure 3.5 *Difference between EDT recording and EDT playback, the yellow zone indicates the trend for the 95% interval*

Appendix A. Page xx:

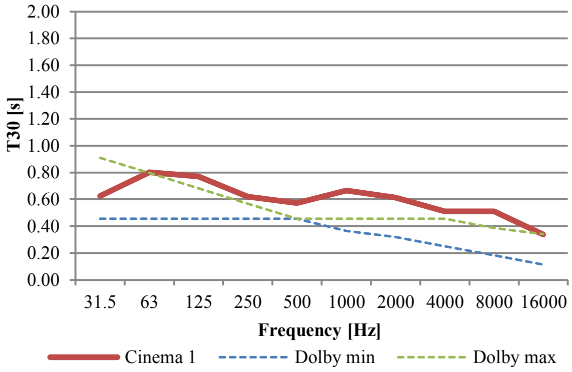


Figure 5.3 *Cinema 2 reverberation ISO 3382*

Summary

Hak and Wenmaekers introduced a new measurement method to objectively examine the reproduction quality of playback rooms based on the reproduction of a specific recording. In this method, the recording room acoustics are compared to the room-in-room acoustics (recording room in playback room) with the jnd as allowable error.

To extent the research on this new method, large playback rooms have been measured as part of a graduation project. Nine cinemas over a wide range of volumes are examined. Also different cinema loudspeaker combinations and receiver locations are assessed.

Nowadays, more and more classical concerts and operas are broadcasted in cinemas. This is one of the reasons that the reproduction quality of a concert hall recording is used as reference.

The reproduction quality is investigated for different parameters using a Head And Torso Simulator. The energy related parameters T_{30} and EDT are assessed, as well as the energy ratio parameter C_{80}, the energy modulation related parameter MTI and the spaciousness related parameter IACC. Also crosstalk is taken into account.

The results show that the reproduction error for these large playback rooms is in the range that is introduced by Hak and Wenmaekers. More specific: most of the measurements are on the positive side of the estimated error curves. In cinemas, the best reproduction quality related to the researched parameters is found when using only the front loudspeakers and when seated at the center line of the cinema. Depending on the parameter, it is better to sit at the front row or at the back row.

List of abbreviations and symbols

RIR	Room-In-Room
ADC	Analog to Digital Convertor
DAC	Digital to Analog Convertor
DCP	Digital Cinema Package
DSP	Digital Signal Processor
HATS	Head And Torso Simulator
HVAC	Heating Ventilation Air Conditioning
IR	Impulse Response
jnd	Just-noticeable difference
LFE	Low Frequency Effects

A	Total absorption	[m²]
C_{80}	Clarity parameter, energy ratio of 0-80 ms and 80-∞ ms	[dB]
EDT	Early Decay Time	[s]
IACC	Inter Aural Cross-correlation Coefficient	[-]
IACF	Inter Aural Cross-correlation Function	[-]
INR	Impulse response to noise ratio	[dB]
M(F)	See MTF	
MTF	Modulation Transfer Function	[-]
MTI	Modulation Transfer Index	[-]
p	Sound Pressure	[Pa]
Q	Source Directivity	[-]
r_k	Critical distance	[m]
SPL	Sound Pressure Level	[dB]
STI	Speech Transmission Index	[-]
T_{20}	Reverberation time calculated from the -5 to -25 dB range	[s]
T_{30}	Reverberation time calculated from the -5 to -35 dB range	[s]
T_{60}	Reverberation time calculated from the -5 to -65 dB range	[s]
T	See T_{60}	
$T_{playback}$	Reverberation time of the playback room	[s]
$T_{recording}$	Reverberation time of the recording room	[s]
V	Volume	[m³]

Contents

Introduction

Recordings of music, speech or other sounds have acoustical properties, such as reverberation, definition and clarity. When these sounds are played back in a listening room through its sound system, in this research a cinema, the acoustical properties of the room and the sound system affect the perceived acoustics of the recording. For example, when a concert hall recording is played back in a cinema, the acoustical properties of the recording are influenced by room acoustics and loudspeaker position. Due to this influence, it might be difficult to have the original acoustical properties accurately reproduced.

In film industry, a lot of money is spent on superb picture and sound quality to give the audience the experience that they are not in the cinema but really in the story. To ensure that this quality is brought to the audience, multiple guidelines have been introduced. However, most guidelines are about the equipment part of the reproduction, overlooking the importance of acoustical design.
Also, over the years different sound formats have been introduced, with different (multi)channel possibilities. With nowadays and future modern digital surround sound formats, the director has the possibility to origin high quality sounds from every possible direction. This possibility is used to give the audience a quick auditory spatial impression of the scene on screen instead of using a relatively long establishment shot [1, 2]. Formerly the acoustics of a cinema was designed such that it contributed to the ambience of the soundtrack, while with modern digital surround sound the (acoustical) ambiance is created on the soundtrack [1; Appendix A], the acoustical information is recorded on the soundtrack. With modern digital cinema projectors, it is now possible to live broadcast operas from a concert hall at the other side of the world. To satisfy the visitors of these operas in the cinemas, it is important to accurately reproduce the acoustics of the concert hall.
So changes in acoustical properties of the recordings by room acoustics of the cinemas are undesirable. Cinemas should be acoustically designed to prevent this
Where the quality of the video reproduction mostly depends on the equipment, for audio reproduction the room acoustics play a large role. Contrary to concert hall acoustics, guidelines for cinema acoustics are very limited and not much research on this topic has been done.

This research is an extension of earlier research. Previously, the general effect of acoustics on reproduction quality has been investigated by Hak and Wenmaekers [3]. In that paper a new measurement technique has been introduced in order to judge the acoustical reproduction quality of a playback room based on the playback of a specific recording in that room. This general research on the effect of room acoustics on the perceived acoustics of reproduced sound has been followed up by a study on sound control rooms. In the research on sound control rooms [4, 5], this specific type of room is examined.
This graduation research handles a different type of room using the same measurement technique: cinemas. Where the sound control rooms didn't deviate much in geometry and size, the cinemas in this research show a rather wide variety in volume. Also multiple listener positions are taken into account.

Preliminary to this research project, a literature study has been performed on cinemas in the Benelux to support the measurements for this graduation research project. In this literature study a relation is made between cinema history, audio equipment and cinema acoustics to make an introduction to the design strategy and the equipment use of modern cinemas. The measured reverberation time of eight

cinemas have been compared to acoustical design guidelines to get an impression of nowadays cinema acoustics.
This study can be found in Appendix A.

The structure of this report is as follows:
At first, the new measurement technique to investigate reproduction quality will be explained. The second chapter discusses the method of how the cinemas have been investigated and will also show a description of those cinemas.
In chapter three, the results will be presented and discussed. This report finishes with the conclusion, recommendations and the acknowledgement. The appendices of this report include the literature study, extensive cinema description, the measurement plan, the measurements quality assessment, the resulting graphs and an overview of the calculated errors.

Chapter 1: Reproduction

The effect of acoustics of a playback room on an original recording can be described by a situation everybody can recognize. Imagine being in a reverberant bathroom listening to the radio. No matter what type of music is on this radio, all of the music sounds reverberant because of the long reverberation time of the bathroom. The other way around, if a recording is made in a reverberant church for example, and it is played back in a less reverberant living room, the reverberation of the original recording is better reproduced. The playback room, in combination with the used sound system affects the recorded acoustics.

In the introduction it has already been mentioned that a new measurement method is introduced by Hak and Wenmaekers [3] to examine the acoustical reproduction quality of a playback room. One of the advantages of this method is that the acoustics of the recording that is being reproduced is part of this examination. Not the physical properties of the room, but the purpose of the room is objectively examined.
This method can be explained in three steps:

1. In the recording room, an acoustical impulse response is measured for a typical reference situation. For example in a concert hall with the source on the stage and the receiver positioned at a seat of the audience.

2. The impulse response of the recording room is played in the playback room. The impulse response of the recording room is affected by the acoustics of the playback room. This affected impulse response is recorded on the listener position. This recorded impulse response represents the perceived acoustics for this specific scenario.

3. Acoustical parameters for both the original recording room impulse response and the affected impulse response are calculated and compared to each other. The just-noticeable difference is used as allowable error.

In the next sections, different aspects of this method are discussed in more detail. Results of the earlier research are shown at the end of this chapter.

1.1. Impulse response

For the quantification of the acoustical properties of a room, the impulse response is used. The acoustical impulse response is the characteristic energy decay for a specific combination of source and receiver. Theoretically, this source produces an infinite, ideal impulse, a Dirac delta function (δ function) as shown in Figure 1.1.

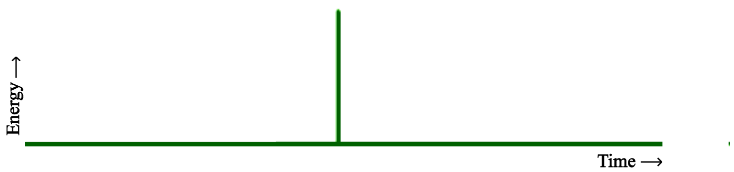


Figure 1.1 *Dirac delta function*

This impulse travels through the enclosure, the building. At a certain moment the direct sound followed by the reflections arrive at the receiver position. This registration of all reflections forms the impulse response. Different parameters influence the registered impulse response:

- Directivity of the source
- Geometry and materialization of the room
- Temperature and humidity of the room
- Directivity of the receiver

Also, the impulse response is source position, receiver position and frequency dependent. An example of a concert hall impulse response is shown in Figure 1.2.

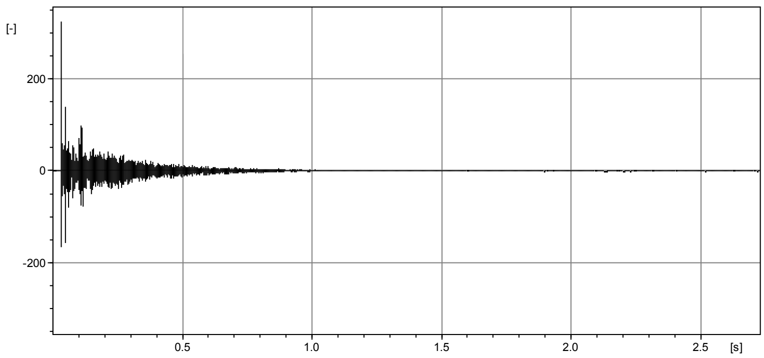


Figure 1.2 *Impulse response of a concert hall*

1.2. Room-in-room impulse response

The acoustical information of a recording can be characterized as the impulse response of the recording room. When this recording room impulse response is played in the playback room the affected impulse response is a room-in-room impulse response.
The recording room impulse response is affected by the playback room impulse response. Only for a Dirac delta function impulse response of an anechoic playback room, the room-in-room impulse response is exactly the same as the recording room impulse response. In practice, the playback room impulse response always affects the recording room impulse response. Depending on the characteristics of both impulse responses, the effect is noticeable or not.
Besides that the decay characteristics of the impulse response is affected, also the buildup of the impulse is changed. The room-in-room impulse response is smoothed relative to the original impulse responses. Figure 1.3 illustrates the convolution of two impulse responses ($h_1(t)$ and $h_2(t)$) resulting in a smoothed room-in-room impulse response ($h_{12}(t)$).
This smoothing effect occurs because the impulse generated by the source is not a Dirac delta function but already an impulse response. With a Dirac delta function, the direct sound to the receiver is the first sound to arrive and results in the start peak of the impulse response. All the reflections arrive later and have less intensity than the direct sound, this forms the complete impulse response. For a room-in-room impulse response, direct sound can still be recorded when the reflections already arrive at the receiver position. A buildup of direct and indirect sound is registered at this position, possibly exceeding the first peak of the direct sound only.

Figure 1.3 *Smoothing of a RIR impulse response [4]*

1.2.1. Effect of the reproduction equipment on the impulse response

For room acoustical measurements standardized equipment is used. For example the Brüel & Kjær OmniPower Sound Source Type 4292 omni-directional sound source. By using standardized equipment, reproducible measurements are made possible and measurements can be compared to each other.
However, for the playback room measurements the equipment and location of this equipment of this room are to be used. In this way not the average physical properties are measured, but the specific impulse response of a practical transmission path (loudspeaker – audience) is measured.

In cinemas, a lot of equipment is used to play the soundtrack of a movie [Appendix A]. Some of this equipment uses DSP's to modify the sound signal. The effects applied by these DSP's are spectrum and delay related. Spectrum related changes of the signal do not influence the acoustical properties of the resulting impulse response as long as spectral differences within one bandwidth are relatively small. The applied delays on the surround channels influence the measurements when the surround channels are used in the measurements. This is the typical behavior of the sound system and therefore is part the reproduction research. For the subwoofers, the Low Frequency Effects channel, phase related DSP's may be applied, but this channel is not used in the acoustical measurements.

The directivity and location of the loudspeakers is of more importance to the impulse response. Where omnidirectional sources tend to be omnidirectional for all frequencies, cinema loudspeakers show a more common directivity of typical loudspeakers. In the lower frequencies, the loudspeakers are omnidirectional, but the higher the frequency, the smaller the radiated sound beam becomes. Also the loudspeakers are located flat to the wall, further increasing the impact of the directivity. The different locations of the listener/spectator relative to the loudspeaker can show large acoustical differences, especially in the higher frequencies.

1.2.2. Convolution

In theory, to get the room-in-room impulse responses, the impulse response of the recording room is played in the playback room. In practice, this comes with some disadvantages. Audio equipment, and more specific the loudspeakers of the audio chain, can show some difficulties when reproducing the impulse responses, due to the instantaneously high load. Distortion of the signal may occur. Most important disadvantage is the lack of flexibility due to the specific reproduction signals.
Both disadvantages can be eliminated by convolution. Convolution is a mathematical operation in which two signals are convolved with each other, resulting in a third signal. Acoustically spoken, the impulse response of the recording room can be convolved with the impulse response of the playback room, resulting in the room-in-room impulse response of both rooms.
In this way, the usual measurement methods can be used to obtain both impulse responses. And room-in-room impulse responses can be generated without the need of specific room-in-room measurements. Compared to the method of playing the recording room impulse response, the room-in-room impulse response will be of higher quality, as will be expressed in a higher INR [6] of the convolved room-in-room impulse response.

The convolution y of signal s and system impulse response h can be written as:

$$y(t) = (s * h)(t) = \int_{-\infty}^{\infty} s(t) \cdot h(t-\tau) d\tau \qquad (1.1)$$

With Equation 1.1, the room-in-room impulse can be defined as:

$$h_{12}(t) = \partial(t) * h_1(t) * h_2(t) \qquad (1.2)$$

Where:

$h_{12}(t)$ = room-in-room impulse response of room 1 and room 2
$\partial(t)$ = Dirac delta function (ideal impulse)
$h_1(t)$ = impulse response room 1
$h_2(t)$ = impulse response room 2

1.3. Just-noticeable difference

The just-noticeable difference (jnd) is a way to describe whether a small change (to acoustics) is perceived as a change by the majority of the observants.

In acoustics, the jnd is presented as a single value. Where this is the most practical way of handling the jnd, in reality the jnd depends for example on timing, frequency and the reverberance of the sound field. It is not a static number.
The introduced research method uses the jnd as a tool to determine to what extent the difference between the recording room impulse response and the room-in-room impulse may be perceived. If the difference (error) is smaller than the jnd, the vast majority of the visitors of the playback room will experience the same acoustics as they will in the recording room. When the error is equal to the jnd, the majority of the visitors may perceive a difference between both impulse responses in a direct comparison. In practice the visitors won't have this direct comparison, they will only experience the room-in-room acoustics. With this in mind, reproduction assessment based on the jnd is a reproducible, reliable method based on extensive research on the jnd.

1.4. Results of earlier work

Diffuse field investigation

The introduced new method of researching room in room acoustics is already applied to two different cases. In the first case, a set of 11 existing different diffuse field impulse responses are mutually convolved [3]. Because $h_1(t) * h_2(t) = h_2(t) * h_1(t)$, this set results in 66 different room in room impulse responses. For these convolved responses, the errors relative to the 'recording room', which can be both h_1 and h_2, is plotted in a diagram with on the x-axis the ratio of reverberation time of the recording room and the playback room: $T_{recording}/T_{playback}$. Figure 1.4 shows this diagram for the decay related parameter $T_{20,}$ Figure 1.5 shows the diagram for the energy ratio related parameter C_{80} (clarity), and finally, Figure 1.6 shows this diagram for the energy modulation related parameter MTI (Modulation Transfer Index). For the T_{20} and C_{80} errors, mean values for the 500 Hz and 1000 Hz octaves are shown, for the MTI error, the 500 Hz and 2000 Hz octaves are combined. All graphs show the relevant jnd.

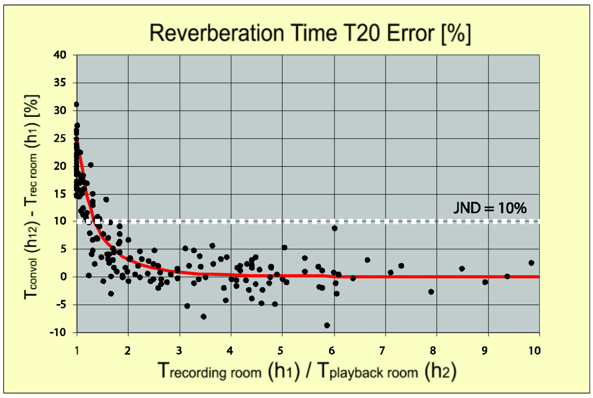


Figure 1.4 *Reverberation time T20 error [%][3]*

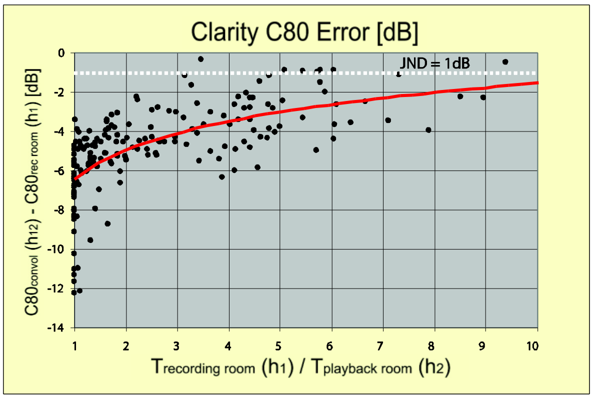


Figure 1.5 *Clarity C_{80} error [dB] [3]*

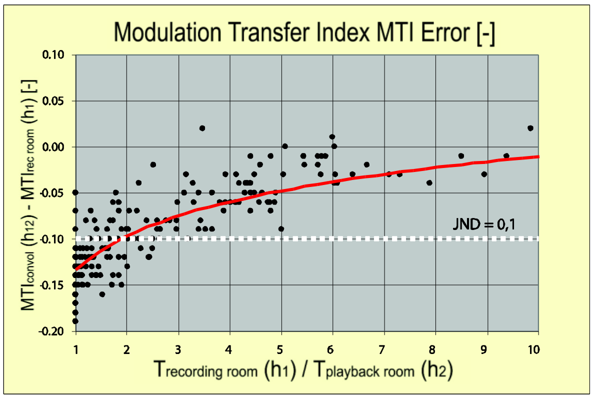


Figure 1.6 *MTI error [-][3]*

Based on these graphs it was concluded that for the judgment of the energy decay rate of a recording of a diffuse field in a playback room with a diffuse field, the playback room is allowed to have as much as half this decay rate.

Under the same conditions, the auditive judgment of the C_{80} is only possible in playback rooms with decay rate higher than 8 times the decay rate of the recording room. Practically, this means judgment in a dry sound control studio, or the use of headphones [5, 7].

The decay rate of the playback for the judgment of energy modulations, which are related to speech intelligibility, should be at least four times smaller than that of the recording room.

Sound control room investigation

The second study was performed on recordings played back in a direct field environment, in sound control rooms. Four binaural impulse responses are used as recording room impulse response. These impulse responses are recorded in the Muziekgebouw Eindhoven [8] with a Head and Torso Simulator instead of an omnidirectional microphone [9]. Two of the impulse responses are recorded in the large symphonic music hall (Figure 1.7) and two in the smaller hall for chamber music (Figure 1.8). In both halls an impulse response is measured at the critical distance (R1) removed from the omnidirectional source and the second in the diffuse field of the hall (R2).

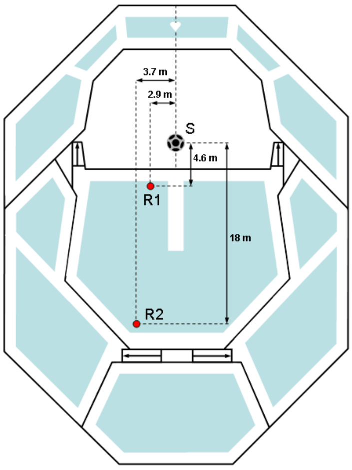


Figure 1.7 *Symphonic music hall [4]*

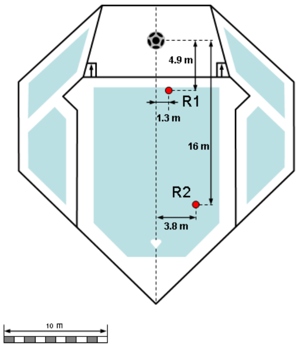


Figure 1.8 *Chamber music hall [4]*

These impulse responses are convolved with the measured impulse responses of six sound control rooms and a headphone (pure free field measurement), using a Head and Torso Simulator and the loudspeaker set-up of the sound control rooms itself (direct field).

For these measurements, not only Reverberation Time, Clarity and the Modulation Transfer Index is assessed, also the spaciousness related parameter Inter Aural Cross Correlation is studied. The results are shown in Figures 1.9 through 1.16.

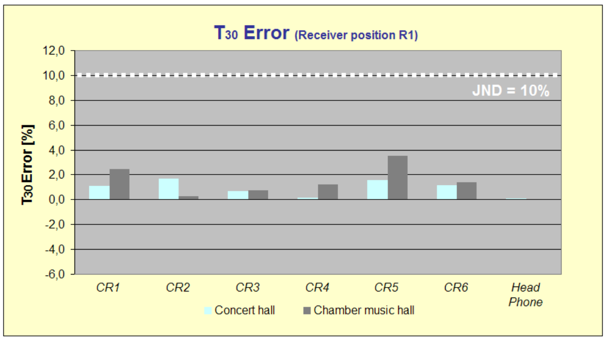


Figure 1.9 T_{30} *error on position R1 [4]*

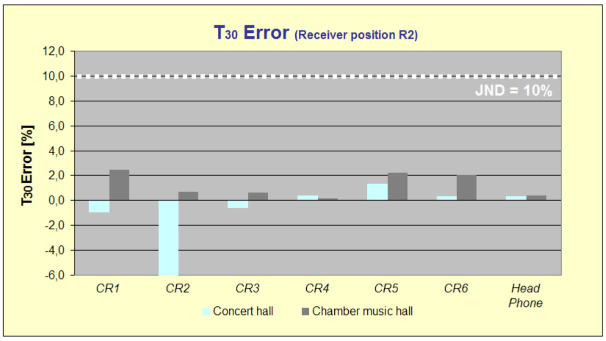


Figure 1.10 T_{30} *error on position R2 [4]*

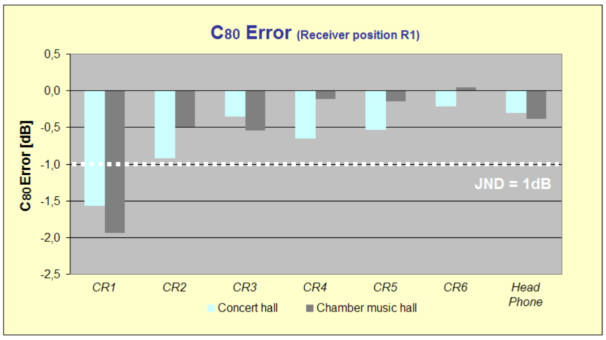


Figure 1.11 C_{80} *error on position R1 [4]*

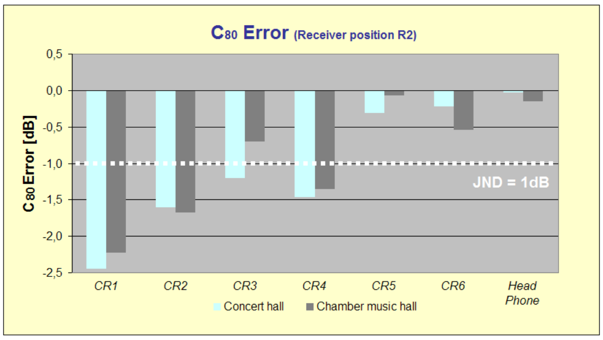


Figure 1.12 C_{80} *error on position R2 [4]*

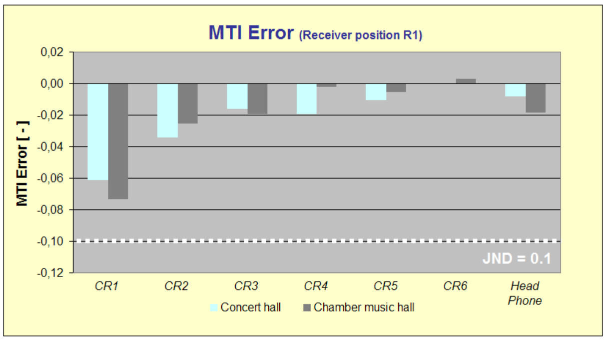


Figure 1.13 *MTI error on position R1 [4]*

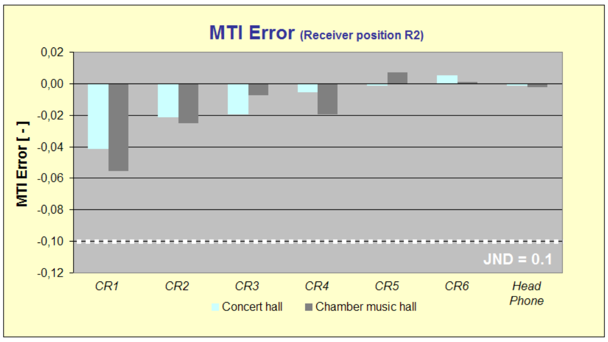


Figure 1.14 *MTI error on position R2 [4]*

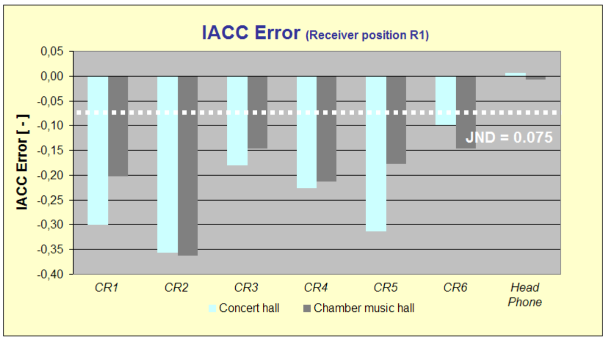


Figure 1.15 *IACC error on position R1 [4]*

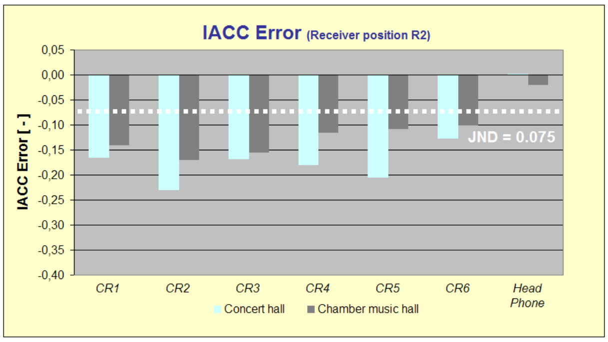


Figure 1.16 *IACC error on position R2 [4]*

Based on these results, the conclusion was drawn that:

- The sound control rooms are suitable for the evaluation of the reverberation in concert hall recordings.
- Only the sound control rooms with a reverberation time below 0.15s are suitable for the assessment of clarity, which corresponds to the diffuse field investigation of [3].
- Speech intelligibility can be adequately evaluated in the sound control rooms.
- Most likely, the assessment of spaciousness related to the IACC has to be judged by headphones, however more research on this topic is recommended.

Hypothesis based on previous research

Based on the diffuse field investigation and the sound control room study, a hypothesis for the investigated cinemas in Appendix A is formed. This hypothesis is based on a recording room impulse response used in the sound control room study, symphony hall position R2, and the reverberation data of the ISO reverberation measurements in the cinemas. On this basis, in Table 1.1 the $T_{recording}/T_{playback}$ ratio is shown, followed by the expected errors based on [3].

Table 1.1 $T_{recording}/T_{playback}$ *and expected errors for nine cinemas*

	T_{30}[1] [s]	$T_{recording}/T_{playback}$[2]	T_{30} error	C_{80} error	MTI error
Studio 1	0.27	7.55	-2 to 1 %	-1 to -4 dB	-0.00 to -0.09
Cinema 1	0.93	2.14	-1 to 4 %	-3 to -6 dB	-0.05 to -0.12
Cinema 2	0.62	3.23	0 to 5 %	-3 to -5 dB	-0.03 to -0.10
Cinema 3	0.41	4.87	0 to 2 %	-1 to -4 dB	-0.01 to -0.07
Cinema 4	0.75	2.68	-2 to 3 %	-3 to -5 dB	-0.05 to -0.10
Cinema 5	0.50	4.03	-2 to 2 %	-2 to -5 dB	-0.03 to -0.06
Cinema 6	1.00	2.01	0 to 7 %	-3 to -6 dB	-0.05 to -0.13
Cinema 7	1.05	1.91	0 to 9 %	-3 to -7 dB	-0.06 to -0.15
Cinema 8	1.03	1.94	0 to 8 %	-3 to -6 dB	-0.05 to -0.14

[1] *mean* T_{30} *for 500 and 1000 Hz octaves, data according to ISO 3382-1*

[2] $T_{recording}$ *being* T_{30} *for 500 and 1000 Hz octaves for the symphony hall, which is 2.00s.*

The expectations show that for all cinemas it is expected that the reverberation time error is smaller than the jnd for this parameter. In none of the cinemas, Clarity can be auditively judged, clear differences are to be expected on the quantity of the error.

No clear relation with the IACC error was found. In this research on cinemas new relations to the IACC may be reveal because more variables, like different volumes and seating positions, will be taken into account. Based on the sound control room study, it is to be expected that all cinemas will exceed the jnd in relation to the IACC error.

Reproduction errors compared to the sound control studios will be larger, because of the longer reverberation time of the cinemas and the listeners position is further away from the loudspeakers. Because of this, the acoustics of the cinemas have more influence on the reproduction quality than sound control studio acoustics have.

Chapter 2: Method

This research study focusses on large reproduction rooms: cinemas. Eight cinemas and a studio are selected on their volume to investigate the full range of available sizes of cinemas in the Netherlands. The study is performed equal to the sound control room study [5], the audio equipment of the cinemas are used as measurement source and a Head and Torso Simulator is placed at the audiences position(s) as receiver position for the measurement of the impulse responses.
This chapter will describe the selection criterion and the properties of the used recording room impulse response and where and how the playback room impulse responses of the cinemas are measured. Also an impression of the transmission path of this virtual room-in-room response is given. The chapter concludes with an overview and description of the parameters which are assessed on the reproduction error.

2.1. Recording room impulse responses

For cinemas, acoustical properties of played sounds can be divided into three categories: music, speech and movie sound effects. For this latter, because of the artificial character of the sounds, no realistic impulse response is available to use as input to the reproduction test.
Because there is no standard way of recording speech, it is hard to obtain a relevant impulse response for this situation. Also, the playback of dialogue in cinemas isn't standardized, which makes it difficult to formulate an impulse response measurement method for the playback room.
Music is widely used in movies, music is chosen by the director to create a specific ambiance in the movie. A lot of soundtracks consist of symphonic music. This study will focus on the reproduction of a concert hall impulse response, in the hypothetical case that the recording of the sound track takes place in the concert hall. Also nowadays (live) recorded concerts are broadcasted to cinemas all around the world, the concert hall experience needs to be reproduced in the cinema. In section 2.2 is explained how the relevant recording room and playback room impulse responses will be measured and used.

Figure 2.1 *Muziekgebouw Eindhoven [4]*

The recording room impulse response used in this study is the binaural impulse response used in [5] of the symphonic music hall at position R2 (diffuse field). The advantage of this impulse response is that it is a well-documented, qualitative good binaural impulse response. This binaural impulse response is recorded with the same Head and Torso Simulator as is used in this study. A direct comparison to the results of [5] is possible.
The specifications of the hall are shown in Table 2.1, Table 2.2 shows the from the binaural impulse response derived acoustical properties of the hall. Figure 2.1 gives an impression of this concert hall.

Table 2.1 *Specifications of symphonic music hall [5]*

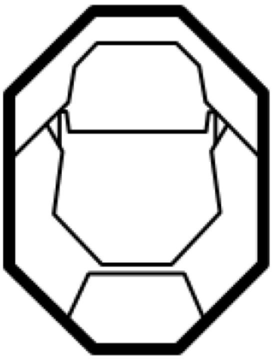
Floor plan	
Volume [m³]	14400
Number of seats	1250
Stage area [m²]	200

Table 2.2 *Properties of binaural impulse response*

T_{30} [s][1]	2.00
C_{80} [dB] [1]	-0.28
MTI [-][2]	0.47
IACC [-][1]	0.50

[1] Averaged over 500 Hz and 1000 Hz octaves
[2] Averaged over 500 Hz and 2000 Hz octaves

2.2. Playback room impulse responses

Playback rooms

Different cinemas in the Benelux are measured to obtain the desired data. The cinemas are selected on their seating capacity because of the strong relation with the volume of the hall. Cinemas are chosen from 100 seats (small) up to 1000 seats (very large). In the Benelux, Cinemas with more than about 500 seats mostly are a combination of cinema and a theatre. The acoustical design is in most cases a compromise between a short reverberation time (large cinema, +/- 0.6s [10]) and a longer reverberation time (theatre, +/-1.2 s [11]). An overview of the cinema properties are presented in Table 2.3. Detailed information on all cinemas can be found in Appendix B. Figure 2.2 shows an impression of one of the cinemas, cinema 3. The numbering of the cinemas is based on the seating capacity. The critical distance is calculated with Equations 2.1 and 2.2.

Figure 2.2 *Interior of a measured cinema*

$$T_{60} = \frac{V}{6A} \text{ [s]} \qquad (2.1)$$

Where
T_{60} = reverberation time [s]
V = room volume [m³]
A = total absorption [m²]

$$r_k = \sqrt{\frac{Q \cdot A}{16\pi}} \qquad (2.2)$$

Where
r_k = critical distance [m]
Q = source directivity [-] (in this case 1 is taken as reference directivity)

Table 2.3 *Properties of the measured cinemas*

	Seats	Floor surface [m²]	Volume [m³]	T_{30}[1] [s]	C_{80}[1] [dB]	Background noise LAeq [dB(A)]	r_k [m]
Studio 1	20	82	275	0.27[2]			1.85
Cinema 1	100	103	410	0.93	9.86	32.5	1.21
Cinema 2	100	200	1023	0.62	8.36	34.6	2.34
Cinema 3	120	166	872	0.41	14.40	30.7	2.65
Cinema 4	150	200	1076	0.75	11.05	32.2	2.19
Cinema 5	350	428	2568	0.50	13.25	34.2	4.14
Cinema 6	280	407	2724	1.00	9.24	32.4	3.01
Cinema 7	530	435	3828	1.05	5.02	34.0	3.48
Cinema 8	1000	1165	12896	1.03	4.50	32.0	6.44

[1] *Mean value of ISO 3382 [12] measurements 500-1000 Hz.*

[2] *T_{30} based on earlier research*

According to the Dolby guidelines [10], the reverberation time of a cinema is a function of volume. In Figure 2.3, the reverberation time and volume of the cinemas are shown as well as the Dolby advice. This graph shows that in practice this relation is absent.

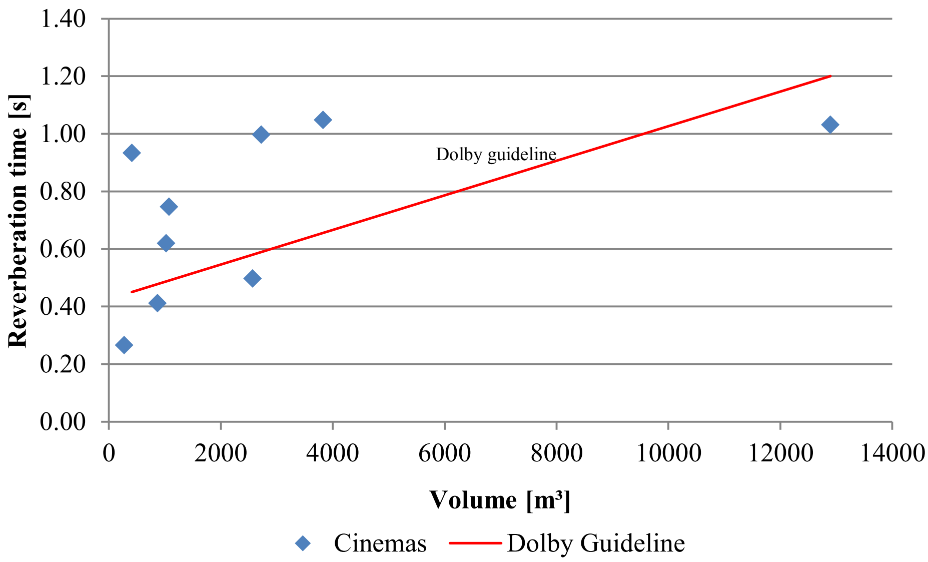


Figure 2.3 *Reverberation time related to cinema volume compared to the Dolby guidelines advice*

It is remarkable that the studio is the only of these 9 researched objects where flutter echoes are absent, for all other cinemas these flutter echoes are clearly audible.

Measurement principle

All cinemas except cinema 2 and studio 1 are equipped with modern digital servers and processors. These cinemas are measured asynchronous through the cinema audio equipment. In this way, the complete installed cinema audio configuration is used.

Asynchronous measurements are measurements of which the Digital to Analog Converter (DAC) and Analog to Digital Converter (ADC) work independent of each other, they both have a different clock generator. This is the case when the DAC of the test signal source and the ADC of the receiver are not the same device. Because of real small deviations of the different clock generators, relatively large

measurement errors can occur [13]. The measurement software Dirac uses a method to correct for these clock differences.
Measurements are synchronous when both DAC and ADC use physically the same clock generator

Cinema 2 is measured by connecting the measurement equipment directly to the audio processor. The processor spreads the test signal over the different channels. In this particular cinema the processor showed unexpected behavior. It is not certain that all channels were played on the right level and with the correct spectrum especially a difference between the front and surround loudspeakers was audible. By switching amplifiers on and off, it was possible to make the desired loudspeaker combinations. This is a synchronous measurement.

Studio 1 is also measured on a synchronous way by plugging the measurement equipment directly into the mixing desk. On this desk the desired channels were selected for each measurement. After this desk, the signal is fed to the cinema processors. The test signal is still handled like it is a movie soundtrack in a cinema by applying equalization and delay corrections.
An e-sweep [14] of about 10,92s (2^{19} audio samples = $\frac{2^{19}}{48000\ Hz}$ s) is used as measurement signal. An e-sweep is used because it includes more energy in the lower frequencies, compensating for the low frequent noise of the HVAC systems. Also the error due to the asynchronous measurement is smaller [13]. For the asynchronous measurements, this signal is as uncompressed PCM track placed in a DCP file [15, Appendix A] to be played by the cinema movie server. The content of this DCP file can be found in Appendix C. For the synchronous measurements, this e-sweep is generated by internally by the measurement software Dirac. In both situations the signal is amplified by the cinemas audio equipment and reproduced by the chosen loudspeakers in the cinema.
With both the asynchronous and synchronous measurements, deconvolution techniques are used [16] to obtain the impulse response out of the recorded sweep signal. The asynchronous recorded sweeps were afterwards deconvolved to an impulse response. With the synchronous measurements the software is able to immediately deconvolve during the recording of the sweep. The software exactly knows what signal is brought in the room because it is generated by itself.

Schematic room-in-room response

For a better understanding of the room-in-room impulse response sound paths, Figure 2.4 shows how this route from recording room source to playback room receiver works.

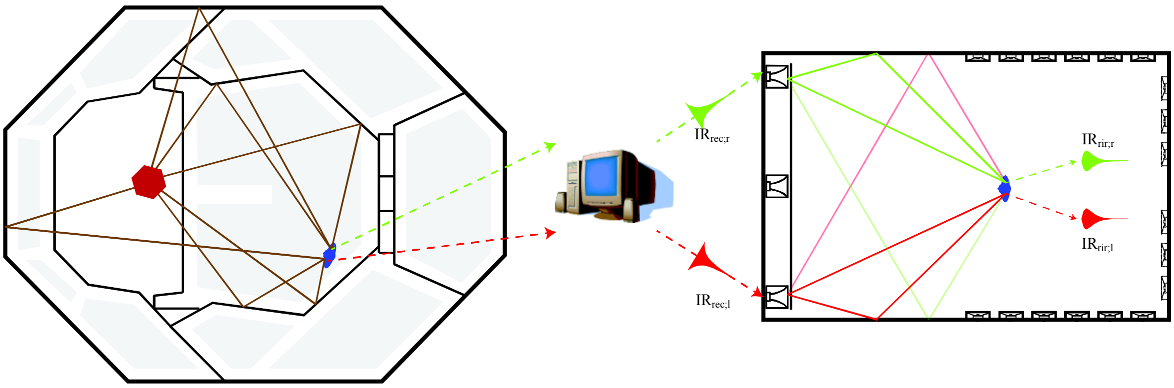


Figure 2.4 *Theoretical schematic response from recording room source to playback room receiver*

The omnidirectional source transmits its sweep (hexagon, red), building up a soundfield in the concert hall (brown rays). The HATS (blue) receives this sweep. Deconvolution of this sweep by computer software results in an impulse response for the left ear ($IR_{rec;l}$) and for the right ear ($IR_{rec;r}$). Theoretically $IR_{rec;l}$ is played through the left loudspeaker in the cinema and $IR_{rec;r}$ through the right one. The registered sound of the right ear is $IR_{rir;r}$ and for the left ear $IR_{rir;l}$.

In practice, new impulse responses are measured with the e-sweep originating from both the left and right loudspeaker at the same time. At the receiver position (HATS, blue), $IR_{play;l}$ and $IR_{play;r}$ are registered.

Left ear: Convolving $IR_{rec;l}$ with $IR_{play;l}$ results in $IR_{rir;l}$.

Right ear: Convolving $IR_{rec;r}$ with $IR_{play;r}$ results in $IR_{rir;r}$.

Also the effect of crosstalk in the cinema is visible: sound from the left loudspeaker (“$IR_{rec;l}$”) influences the right ear of the HATS and vice versa. Where theoretically $IR_{rec;l}$ reaches the right ear, in the current method of convolution, the complete $IR_{play;r}$ is convolved with $IR_{rec;r}$. In this way all the sound on the right ear is treated as coming from the right loudspeaker. Crosstalk is measured as a level difference over both ears, when using one side of a loudspeaker combination at a time. Crosstalk has a negative influence on the reproduction quality, this is indirectly incorporated in acoustical parameter errors. No direct relation to the reproduction error is described. The amount of crosstalk for each individual situation is measured to investigate the relation between crosstalk, cinema, receiver location and loudspeaker source. With increased crosstalk, sound localization becomes more difficult, which also is part of the reproduction.

Source – receiver combinations

Cinemas have multiple audio channels present. Where Figure 2.4 showed the most fundamental setup of only the front left and front right channel, in cinemas more combinations are possible. Due to the different locations, this might give different reproduction quality results. Figure 2.5 shows a typical setup for a 5.1 equipped cinema.

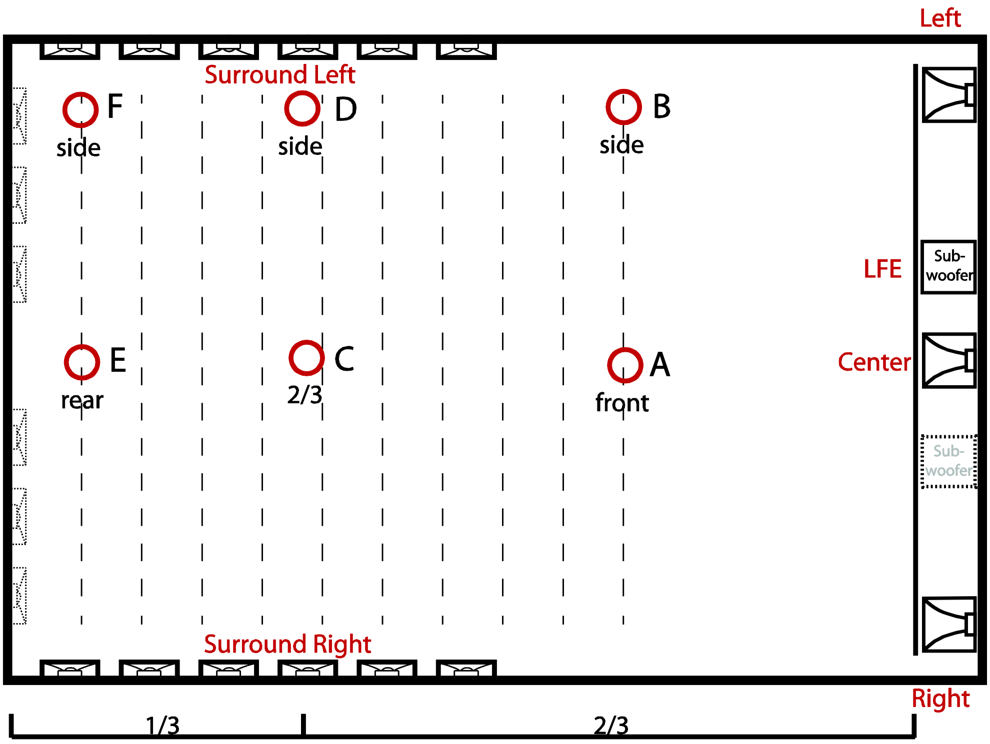


Figure 2.5 *Typical equipment for a 5.1 cinema and six receiver positions*

Three loudspeaker combinations with a left and a right sound playback can be made, as shown in Table 2.4.

Table 2.4 *loudspeaker combinations*

Combination	Left	Right	Surround Left	Surround Right
Front	✓	✓		
Surround			✓	✓
Both	✓	✓	✓	✓

As mentioned in Appendix A, the surround channels may have a time delay relative to the front loudspeakers to compensate for the sound travel distance difference. For the sake of documentation, these delays are measured according to the procedure in Appendix C and the results can be found in Appendix B. For the loudspeaker combination 'Front', delays play no role in the measurements. For the combinations 'Surround' and 'Both', natural and artificial delays may have influence on the reproduction quality. With simultaneously using multiple loudspeakers (Figure 2.6), it is important all loudspeakers are connected in the same phase state. If this is not the case for one loudspeaker, this loudspeaker is in opposite phase, resulting in exactly the opposite movement of the loudspeakers driver membrane. This can cause

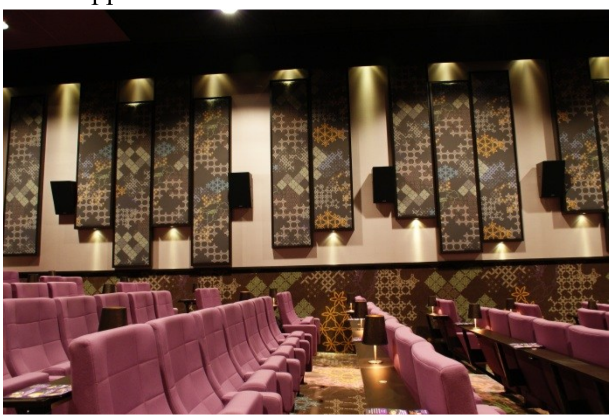


Figure 2.6 *Multiple surround speakers*

measurement errors because of interference. Phase measurements are performed according to the procedure in Appendix C to check whether phase differences are present or not. The results in Appendix B show that cinema 5 and cinema 7 both have one loudspeaker in opposite phase.

As already mentioned, a Head and Torso Simulator (HATS) is used to perform the impulse response measurements (Figure 2.7). When using a HATS, results will be different compared to measurements performed with an omnidirectional microphone according to ISO 3382-1 [9, 12] because of different loudspeaker location and directivity and different recording position and directivity. For this reproduction study it is more important to measure the perceived acoustics by taking the directivity of the human ears into account. Also the spaciousness related parameter IACC demands the use of the HATS.
Another advantage of the use of this HATS is that for the recording room impulse response exactly the same HATS is used. So both recording room and playback room impulse responses are recorded with the same directivity, making a comparison more realistic.

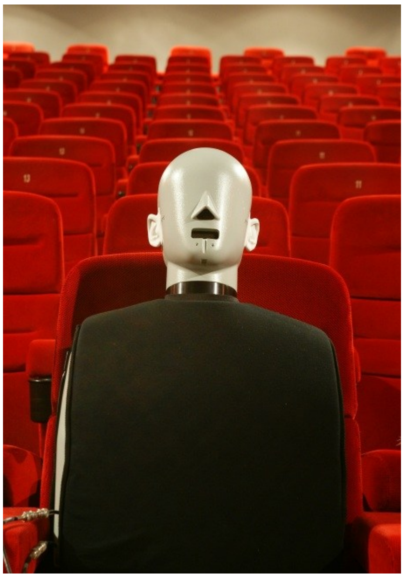


Figure 2.7 *Head and Torso Simulator*

Figure 2.5 also shows the measurement positions for the HATS. The six positions are chosen because of their specific locations. Positions A, C and E are chosen in the *center line* of the cinema, the distance between the left and the right loudspeaker channels is about equal. Positions B, D and F are on the far *side* of the row, on these locations, the imbalance between the left and right loudspeaker channels is the largest.
Positions A and B are situated in the front row of the cinema, the relative displacement of the front loudspeakers is the largest and the distance to the loudspeakers is the smallest. Positions C and D are positioned at 2/3rd of the cinema length from the screen. On this distance, the sweetspot of the cinema is located, because of cinema alignment instructions [Appendix A, 10]. Also in the mixing studio, the sound engineer is located at 2/3rd of its studio, so basically movies are mixed for this listener's position.
The back row of the cinema shows the opposite of the front row, relative displacement of the front loudspeakers is the smallest here. Also this row is as far away from the front loudspeakers as possible, making the impact of the hall on the impulse response measurement probably the largest.
At measurement positions B, D and F, the side positions of the rows, the head of the HATS is rotated so that the nose is pointing towards the center of the screen (Figure 2.9) where for the position on the center line the HATS is looking forward (Figure 2.8). The body of the HATS isn't rotated.

For Studio 1, the seating area is completely different compared to the cinemas plans. In the studio the sound engineers position is the most important. This position is equal to position C. Also a position on a couch behind the engineer is chosen: position C'. In the back of the studio, two rows with seats are present. Position E and F are chosen like in all other cinemas.

All measurements in these cinemas took place according to the measurement procedure of Appendix C. And all specific measurement positions can be found in Appendix B.

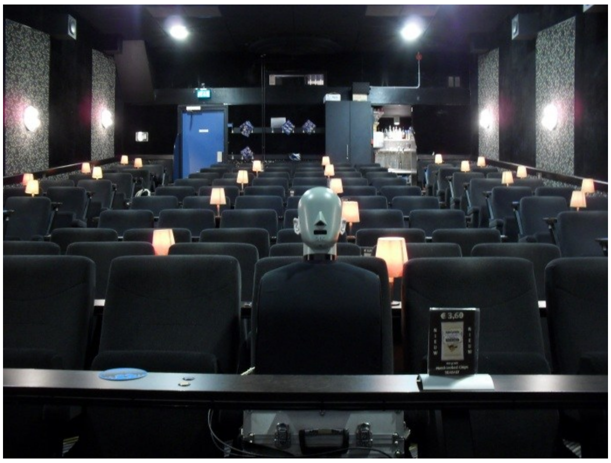


Figure 2.8 *HATS looking forward*

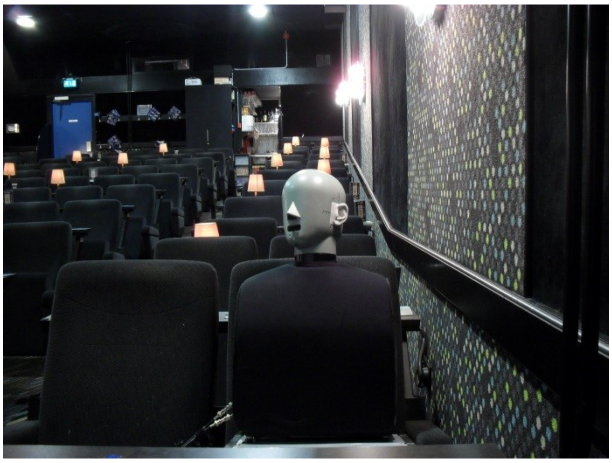


Figure 2.9 *Head of HATS rotated towards screen*

2.3. Parameters

Acoustical properties of a room can be described with standardized parameters (ISO 3382-1) based on impulse responses. In this study, these acoustical properties of the cinemas are not directly investigated. These properties are indirectly involved in the reproduction error based on these parameters, the playback room impulse response is only convolved with the original recording room impulse response. To understand the importance of the used different reproduction errors, in this section the parameters are explained.

The chosen parameters can be divided in four categories: Decay range related, energy time ratio related, signal modulation related and spaciousness related. With these different types of parameters, a wide range of defined acoustical properties is covered.

Decay range

Two parameters related to the decay of the squared impulse response are used. The first is the reverberation parameter T_{30} which is used to determine T_{60}. T_{30} evaluates the decay range of -5 dB to -35 dB with an advised headroom of 10 dB to the noise floor. This parameter gives the physical reverberation of the cinema. The second is the Early Decay Time which is a better estimator for the perceived reverberance. The EDT is evaluated over the range 0 to -10 dB.

These parameters are calculated from the squared impulse responses by backwards integration [17] based on Equation 2.3.

$$L(t) = 10lg\frac{\int_t^\infty p^2(t)dt}{\int_0^\infty p^2(t)dt} \text{ [dB]} \qquad (2.3)$$

Where *L(t)*is the equivalent of the squared pressure.

Energy ratio

The parameter C_x (Clarity) describes the ratio between early (0 - x ms) and late (x - ∞ ms) arriving sound. For speech the C_{50} related to D_{50} is used. In this study C_{80} [18] is used, which is more relevant to music clarity. This parameter is obtained by Equation 2.4.

$$C_{80} = 10lg\frac{\int_t^{80ms} p^2(t)dt}{\int_{80ms}^\infty p^2(t)dt} \text{ [dB]} \qquad (2.4)$$

Signal modulation

The Speech Transmission Index is used as indicator for speech intelligibility [19]. This STI is the weighted average of Modulation Transfer Indices [20]. The MTI(f) is an average of 14 Modulation Transfer Functions m(F) [21] (Equation 2.6). The MTF m(F) describes the modulation depth caused by the total transmission chain, from microphone to receiver, to the signal. 14 Modulation frequencies F in the range from 0.63 to 12.5 Hz are used in Equation 2.5.

$$m(F) = \frac{\int_{-\infty}^{\infty} p^2(t) \cdot e^{-j2\pi Ft} dt}{\int_{-\infty}^{\infty} p^2(t) dt} \text{ [-]} \qquad (2.5)$$

$$MTI(F) = \frac{\sum_{n=1}^{14} m(F_n)}{14} \text{ [-]} \qquad (2.6)$$

Spatial impression

All previous parameters are basically monaural parameters. For a spatial impression, the Inter Aural Cross-correlation Coefficient over 0 to 80 ms is used. This interval corresponds to the early reflections. The IACC is calculated with use of the Inter Aural Cross-correlation Function in Equation 2.7.

$$IACF_{t_1,t_2}(\tau) = \frac{\int_{t_1}^{t_2} p_l(t) \cdot p_r(t+\tau) dt}{\sqrt{\int_{t_1}^{t_2} p_l(t) dt \cdot \int_{t_1}^{t_2} p_r(t) dt}} \text{ [-]} \qquad (2.7)$$

Where $p_l(t)$ is the impulse response measured at the left ear and $p_r(t)$ is the impulse response measured at the right ear of the HATS. The IACC is calculated using Equation 2.8.

$$IACC_{t_1,t_2} = |IACF_{t_1,t_2}(\tau)|_{max} \quad \text{for -1ms} < \tau < \text{+1 ms} \qquad (2.8)$$

The Impulse response to Noise Ratio

The INR is used as an indicator of impulse response quality [6]. A study on the measurements is done, extensive results can be found on Appendix D. Table 2.5 shows the calculated minimum INR values over the 500 Hz and 1000 Hz octaves.

Table 2.5. *Minimum and average INR for 500Hz and 1000 Hz octaves*

	Minimum INR	Average INR
Recording room IR	58 dB	58 dB
Playback room IR	53 dB	67 dB
Room-in-room IR	43 dB	56 dB

Averaging

Because of the use of the HATS, for each source/receiver combination, two impulse responses are recorded (left and right ear). For the sake of clarity, the calculated parameters of these impulse responses are averaged. This averaging takes place in different ways. For T_{30}, EDT and C_{80}, just both results are averaged. For the MTI however, just averaging the results will underestimate the perceived speech intelligibility. Already a simple but effective method is taking the best results of each ear per octave, the so called best-ear method [22]. The IACC is already a parameter in which both ears are involved.

According to ISO 3382-1 [12] the parameters are averaged over the mid-frequency octaves 500 Hz and 1000 Hz, except for the MTI. For the MTI, the 500 Hz and 2000Hz octaves are averaged. These octaves are the most important for speech intelligibility, as is shown with the RASTI. The difference with the RASTI calculation is that in this study the modulation transfer functions are calculated for all modulation frequencies and that the average of the octaves is unweighted.

Just-noticeable difference

Table 2.6 shows the values used for the jnd in this research. The values are common used values, except for the jnd of the MTI. A common used value for the jnd of the MTI is 0.1 [-], where this is taken from the jnd of the STI. It is expected by Hak that a value of 0.065 is more suitable for single MTI values.

Table 2.6 *Overview of jnd values*

Parameter	Octaves	jnd
T_{30}	500; 1000	10 %[1]
EDT	500; 1000	5 %[2]
C_{80}	500; 1000	1 dB[2]
MTI	500; 2000	0.065[3]
IACC 0-80ms	500; 1000	0.075[2]

[1] Estimated, based on [13]
[2] ISO 3382-1 [12]
[3] Estimated by C.C.J.M. Hak

Chapter 3: Results and discussion

The results will be separately shown and discussed. In different sections the reproduction error of cinema averages, location averages and loudspeaker combination averages will be shown and discussed. This is followed by a study on crosstalk. This chapter concludes with reviewing these results relative to the general research on reproduction errors of Hak and Wenmaekers [3].
All results are averages of the 500 Hz and 1000 Hz octaves and for the MTI data 500 Hz and 2000 Hz octaves and the jnd values are according to Table 2.6. Average values are absolute averages, negative errors are treated the same as positive errors. For C_{80}, MTI and IACC, the value is preserved to their negative nature. All graphs can be found in Appendix E, the relevant measurement results can be found in Appendix F.
In the graphs, the cinemas are sorted on their $T_{recording}/T_{playback}$ value, which is in this case is in order of reverberation time (T) because only one recording room is used. Figure 3.1 shows the reverberation time of the cinemas in increasing order.

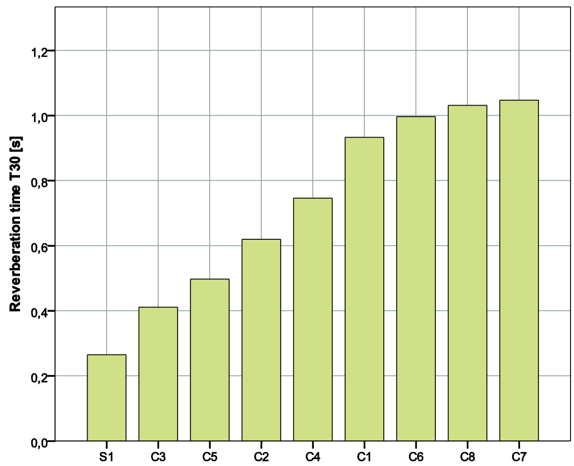
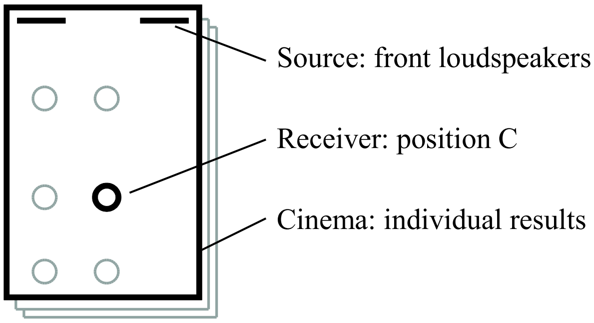
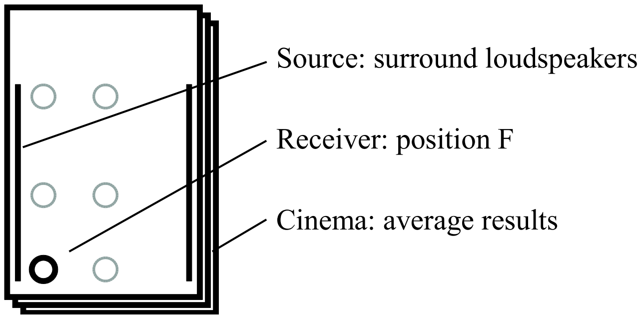
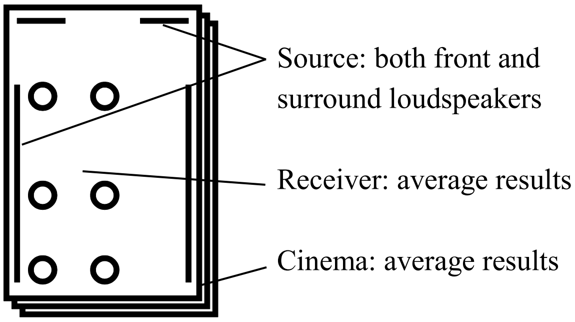


Figure 3.1 *Cinema reverberation time ISO 3382-1 T_{30}*

Every graph is accompanied by a visual representation of the involved variables, as explained in the following example legends:







The black lines represent the loudspeaker combination that is used in the measurement: front loudspeakers left and right, surround loudspeakers left and right and both front and surround loudspeakers combined left and right.

The bold circles represents the involved measurement receiver position(s). For example, only one bold black circle and five grey circles means that the exact value of the bold position is shown in the graph. When multiple positions are indicated by a bold circle, the shown values in the graph are averaged over these bold positions.

Whether the values shown in the graph are individual or averaged cinema values is indicated by the type of enclosure of the legend. If the legend shows one black outline and two smaller grey outlines, the shown values are individual cinema results. When the legend shows multiple thick black outlines, the results are averaged over all measured cinemas for the marked source-receiver combination.

For the graphs in which the cinema results are averaged, the standard error (SE) of the mean is shown by the whiskers on the graph. Also in all graphs the relevant jnd value is shown.

3.1. Previous research

In this section, the measurement data is projected on the results of the earlier research performed by Hak and Wenmaekers [3]. This may lead to a refinement of the target curves of the reproduction error or to a better understanding of the physical properties that have influence on this curve. For each cinema, the results for each location per loudspeaker combination are shown (for each Cinema 24 results, for the Studio 16 results).

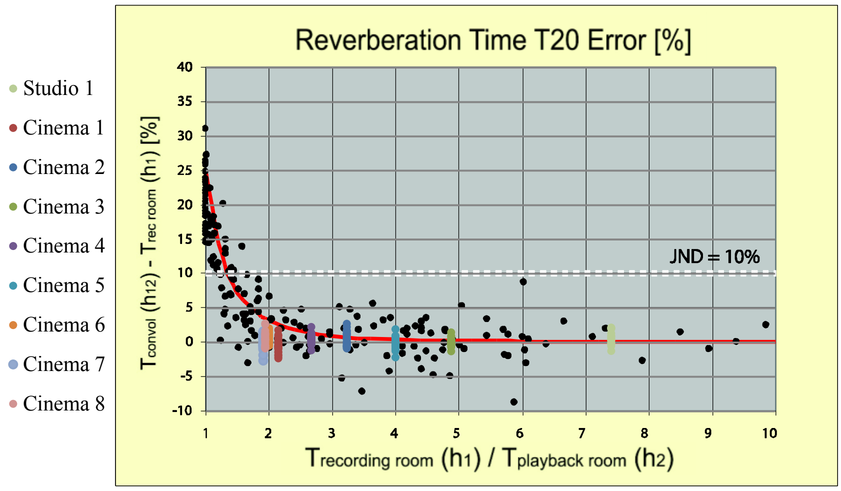


Figure 3.2 *Difference between T_{30} recording and T_{30} playback*

It is already shown that the T_{30} error for the different cinemas is very low. For a T/T value higher than 3, the results match the target curve (Figure 3.2). The cinemas with a lower T/T value, the results are lower than expected, related to this target curve. The dispersion per cinema is for all cinemas about the same.

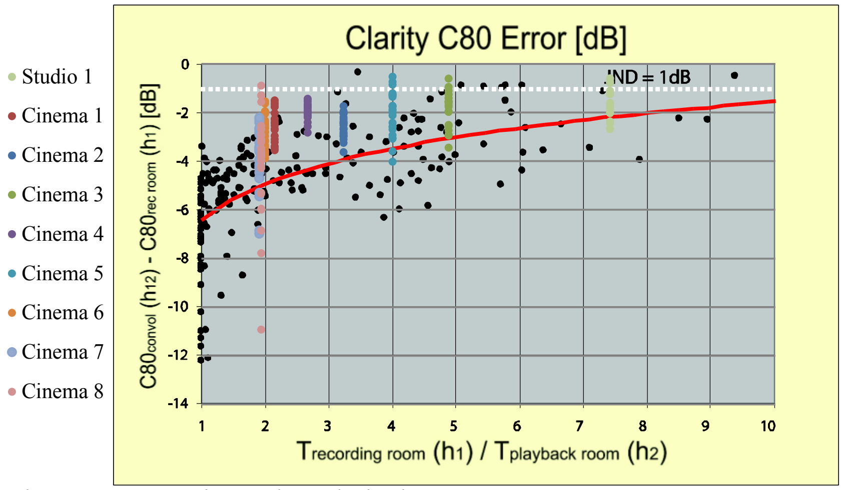


Figure 3.3 *Difference between C_{80} recording and C_{80} playback*

The C_{80} results are quite different from the expected curve. Values are overall better, being closer to the jnd error of 1 dB. As visible, for four cinemas, at least one location/loudspeaker combination does not exceed the jnd error. Cinema 8 show a very large dispersion, with a point within the jnd error and also a point of eleven times this jnd error. Also cinema 7 shows a wide spread, but not as wide as Cinema 8.

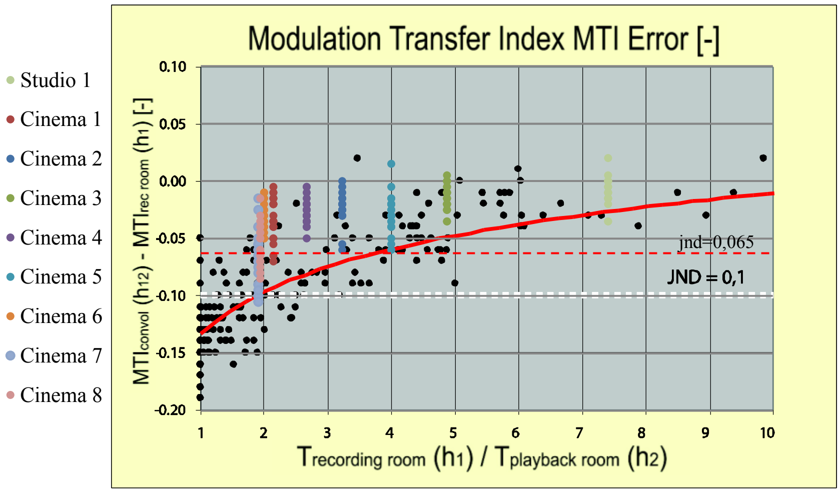


Figure 3.4 *Difference between MTI recording and MTI playback*

Also for the MTI error (Figure 3.4) results are better than expected according to the red curve. Almost all results lie between this curve and an error of 0.00. The change of allowed error (0.1 to 0.065) leads to much room-in-room responses of the original research to be exceeding the jnd error.

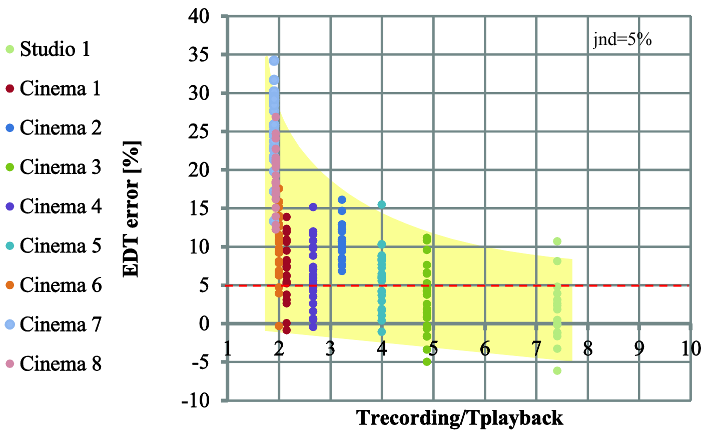


Figure 3.5 *Difference between EDT recording and EDT playback*

For the EDT error no such graph is available to project the results on. In Figure 3.5 the results are plotted in the same way. Differences in EDT error between cinemas are quite large. Also for cinemas with a low T/T, the spread of individual results is quite large.

Overall, a relation of EDT error to T/T can be seen as indicated by the yellow zone. More rooms need to be examined to make this relation more clear.

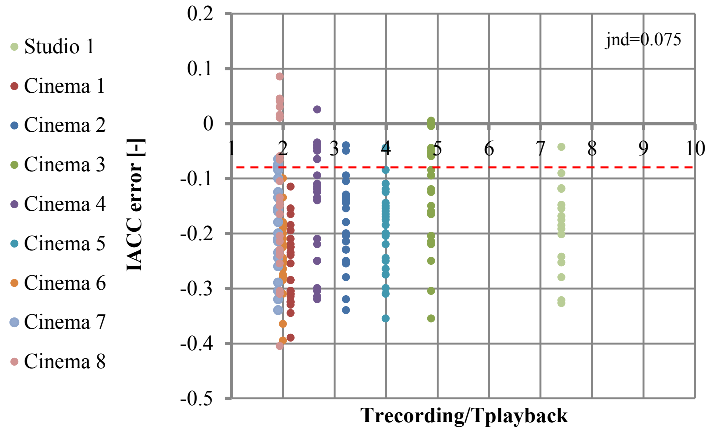


Figure 3.6 *Difference between IACC recording and IACC playback*

For the IACC error, the same graph is made. Figure 3.6 shows all data of the IACC error. The IACC error does not show a clear correlation with T/T. Also the dispersion is quite the same for all cinemas.

3.2. Cinema comparison

A comparison between the cinemas is made based on the most fundamental reproduction principle: front loudspeakers (left and right) and one receiver position. This receiver position is choosen to be the mix engineers position at 2/3rd distance from the screen, in the middle of the row. This is position C.

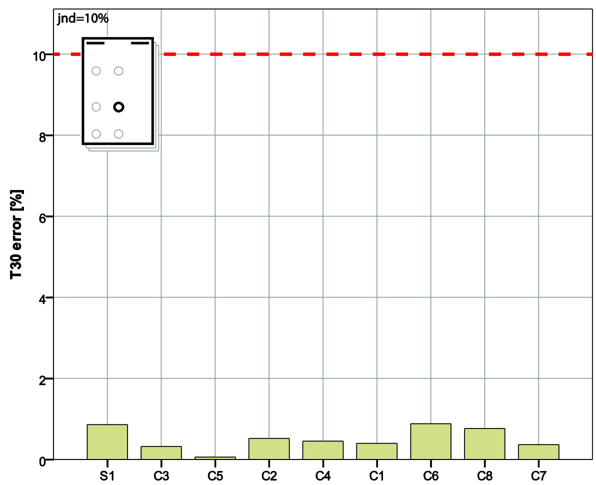


Figure 3.6 *T_{30} error with cinema; front loudspeakers; position C; 500; 1000 Hz averaged; two channel averaged*

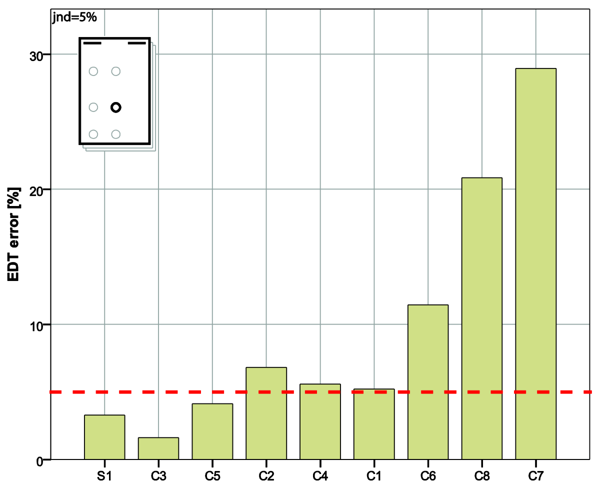


Figure 3.7 *EDT error per cinema; front loudspeakers; position C; 500, 1000 Hz averaged; two channel averaged*

Figure 3.6 shows that the T_{30} error is very small for all cinemas, relative to the jnd error of 10%. With an increase of T, a really small but not significant increase of T_{30} error is visible.
In Figure 3.7 the EDT error graph shows a clear increase of EDT with an increasing T. Where for this position most cinemas have values within the jnd error or slightly above it, cinemas 6, 7 and 8 show a significant increase in EDT error up to almost six times the jnd value.

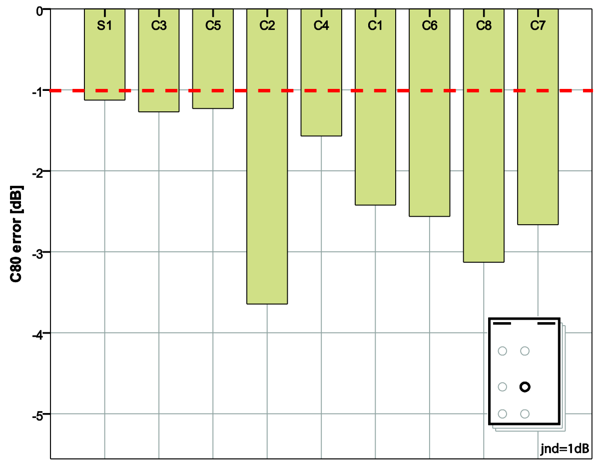


Figure 3.8 *C_{80} error per cinema; front loudspeakers; position C; 500, 1000 Hz averaged; two channel averaged*

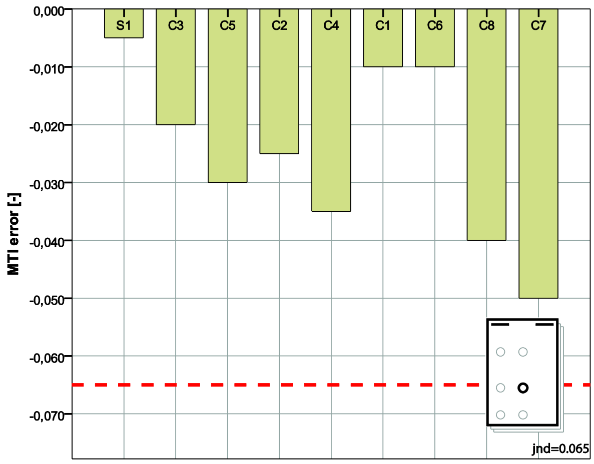


Figure 3.9 *MTI error per cinema; front loudspeakers; position C; 500, 2000 Hz averaged; best ear averaged*

As expected, the C_{80} error for all cinemas is exceeding the jnd error (Figure 3.8). Studio 1 shows the best result, with an error close to the jnd error. On individual level there are a few loudspeaker – location combinations of Studio 1 in which the C_{80} error is even smaller than the jnd error of 1 dB. Also Cinema 3 and 5 are close to the jnd error. The correlation of the C_{80} error to T is visible, with Cinema 2 as quite a large exception exceeding the jnd error by far and with the Cinema 7 C_{80} error a little lower than expected.

For this position, all MTI errors stay within the allowed jnd error (Figure 3.9). Also, a correlation between MTI error and T is visible. However, Cinemas 1 and 6 are exceptions to this correlation, with low MTI error values.

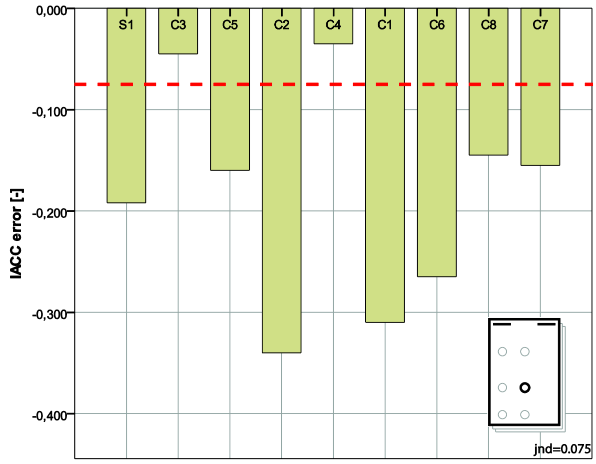


Figure 3.10 *IACC error per cinema; front loudspeakers; position C; 500, 1000 Hz averaged*

From Figure 3.10 no relation between the IACC error and T of the cinemas is found. It is not clear how the IACC error relates to the cinema properties. There is also no clear correlation found between volume and IACC error and critical distance and IACC error.

Regarding the absolute error, most cinemas exceed the jnd error. Cinema 3 and Cinema 4 show an IACC error within the allowed error. Errors of five times the allowed error are found as well.

Noticeable is Studio 1, which performed quite good in the previous charts. This studio shows a relative large IACC error.

Related to the sound control rooms [4], the average IACC error per cinema is relatively low. Where the IACC error is just slightly higher, the T/T values are multiple times lower.

3.3. Loudspeaker combinations and receiver position

In this research, three different loudspeaker combinations are used for the reproduction measurements: front, surround and both front and surround. In Appendix E, Figures E.6 through E.10 show the graphs of the error per loudspeaker combination averaged over all positions and all cinemas. For the T_{30} error and the EDT error, no significant differences are found between the loudspeaker combinations. C_{80} error, MTI error and IACC error show a significant smaller error for the front loudspeaker combination than for the other two combinations.

Despite the apparent similarity between the EDT errors for the different loudspeaker combinations, when looking at the individual positions related to the loudspeaker combinations, significant differences can be found.

In Appendix E, Figures E.11 through E.40 represent the results for the positions in all cinemas averaged, relative to the loudspeaker combination. These figures will be discussed by acoustical parameter in this section. Relevant graphs will be shown here as well. After the discussion of the acoustical parameters, general trends in the graphs will be discussed.

T30 error

For all combinations and positions, the T_{30} error is significantly smaller than the allowed error of 10%. Absolute differences between the combinations and positions are too small to draw conclusions.

EDT error

For the EDT error, the graphs show a decreasing error from the front row to the back row. It is not a significant decrease, but most graphs show this trend.
Exception to this trend is Position C when using the surround loudspeakers (Figure 3.12). Where Figure 3.11 (Front loudspeakers) show the slight decrease to the back, the EDT error for Position C in Figure 3.12 is significantly smaller. For the EDT error, this is the only combination where the Standard Error crosses the allowed error line.
The differences in error between the center line and the side positions are quite small.

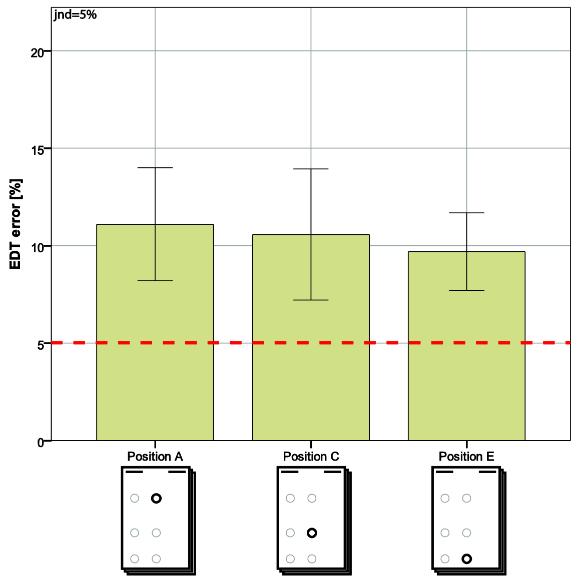


Figure 3.11 *EDT error with SE per center line position; all cinemas averaged; front loudspeakers; 500, 1000 Hz averaged; ears averaged*

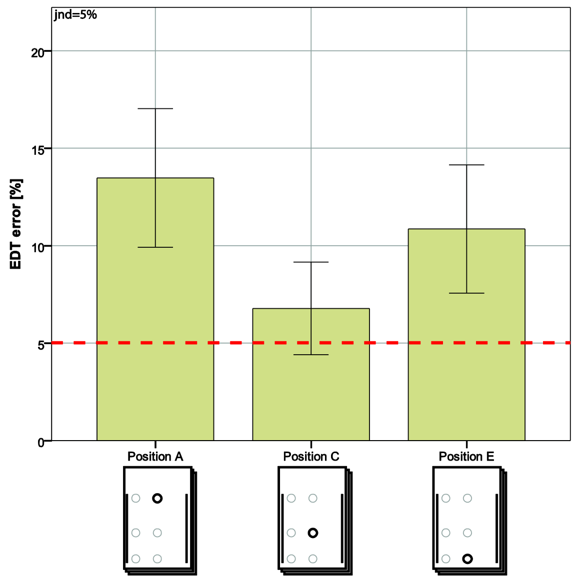


Figure 3.12 *EDT error with SE per center line position; all cinemas averaged; surround loudspeakers; 500, 1000 Hz averaged; ears averaged*

C_{80} error

When using only the front loudspeakers, the C_{80} error decreases from the front to the back. For the centreline, this is a significant decrease (Figure 3.13). Also for the C_{80} error, when using the surround loudspeakers, Position C shows a significant smaller error than the front and back position (A and E) (Figure 3.14).

For all positions except for Position C, the errors for the surround loudspeaker measurements are significantly higher than for the front loudspeaker measurements.

All average values exceed the 1dB allowed error.

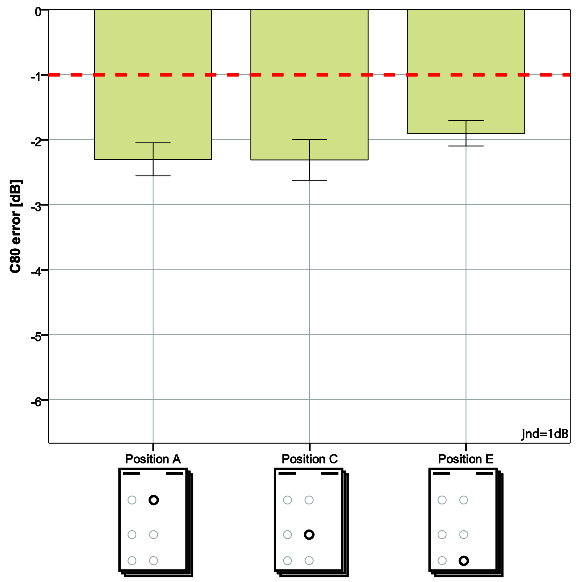


Figure 3.13 *C_{80} error with SE per center line position; all cinemas averaged; front loudspeakers; 500, 1000 Hz averaged; ears averaged*

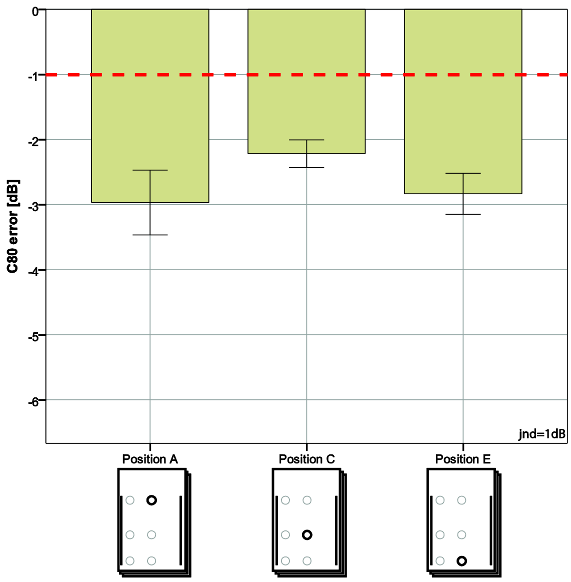


Figure 3.14 *C_{80} error with SE per center line position; all cinemas averaged; surround loudspeakers; 500, 1000 Hz averaged; ears averaged*

MTI error

For the MTI error, all graphs show the same pattern, the error on the front row is about the largest, being just larger than the error on the back row, the error on 2/3rd of the cinema (Position C, D) is clearly the smallest (Figure 3.15, 3.16). The error on Position C is about the same for the three different loudspeaker combinations.

MTI errors for all these situations do not exceed the jnd. The differences between the center line and side positions are quite small.

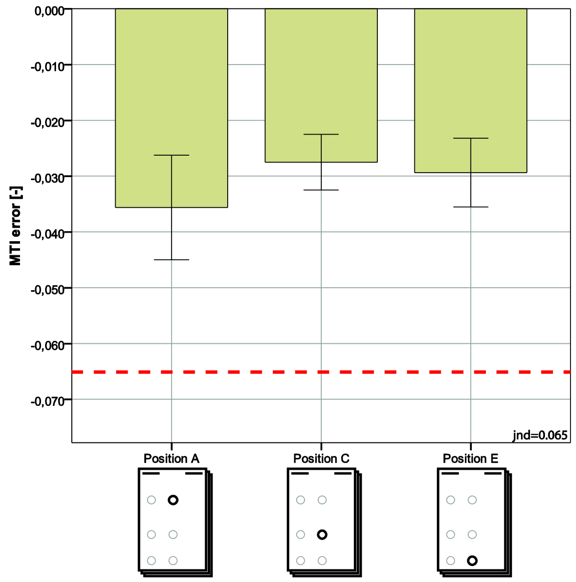


Figure 3. *MTI error with SE per center line position; all cinemas averaged; front loudspeakers; 500, 2000 Hz averaged; best ear averaged*

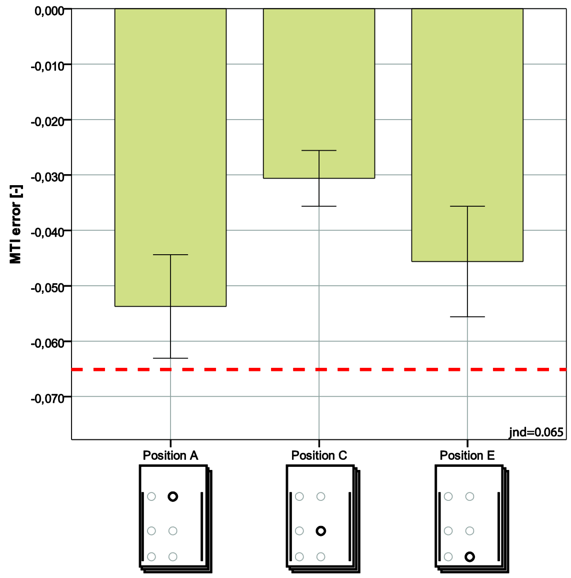


Figure 3.16 *MTI error with SE per center line position; all cinemas averaged; surround loudspeakers; 500, 2000 Hz averaged; best ear averaged*

IACC error

The characteristics for the IACC error are quite different from the other parameters, Position C is under no conditions the best position. In most situations, the smallest error is found at the front row, with the significant lowest value at Position A using the front loudspeakers (Figure 3.17). Exception to this is the center line for the surround loudspeaker combination, here the back row shows the smallest error (Figure 3.18).

The side positions show a slightly larger error than the center line positions.

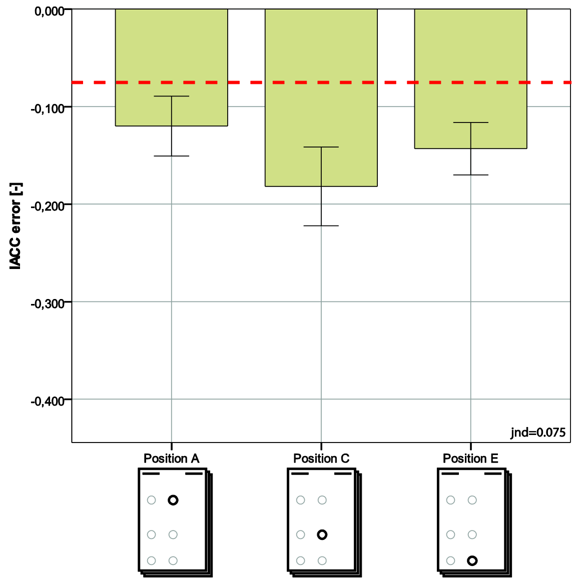


Figure 3.17 *IACC error with SE per center line position; all cinemas averaged; front loudspeakers; 500, 1000 Hz averaged*

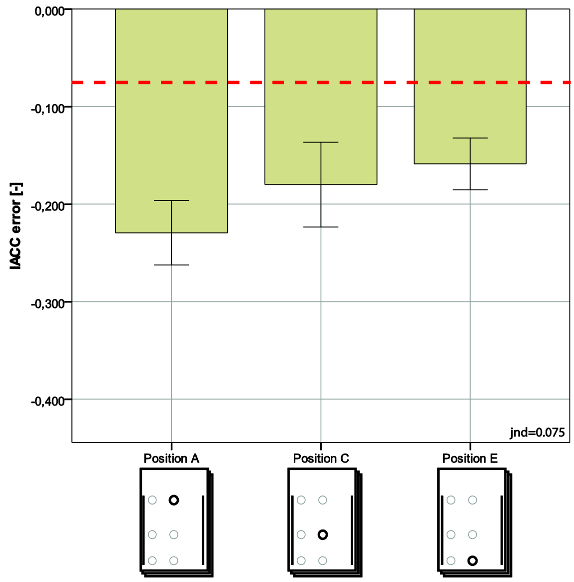


Figure 3.18 *IACC error with SE per center line position; all cinemas averaged; surround loudspeakers; 500, 1000 Hz averaged*

General

In general the results show that the differences in error between the positions are smaller when using the front loudspeakers than when using the surround loudspeakers or both of them.

When using the front loudspeakers, the smallest errors are found at the back row of the cinema, based on three measured positions. The central 2/3rd position shows larger errors than the back row. When using the surround loudspeakers only, the smallest errors are found at 2/3rd distance from the screen. Exception to this is the IACC, where the smallest errors can be found at Position A.
In general, the error values are lower on the center line positions than on the side positions.

3.4. Crosstalk

The crosstalk per position shows about the same characteristics for all three loudspeaker combinations. Figure 3.19 shows the crosstalk per side position and Figure 3.20 shows it for the center line positions. The blue bars show the level differences between the two ears when using only the left loudspeakers of the combinations, the red bars show the level differences between the two ears when using only the right loudspeakers of the combination. (SPL of the right ear minus SPL of the left ear)

For the center line positions, it is clearly visible that crosstalk increases from the front to the back. For the side positions, there is more crosstalk compared to the center line positions. Also, especially at Position F, there is the chance that for example the SPL caused by right loudspeaker is higher in the left ear than in the right ear, this might be caused by the applied rotation of the head of the HATS.

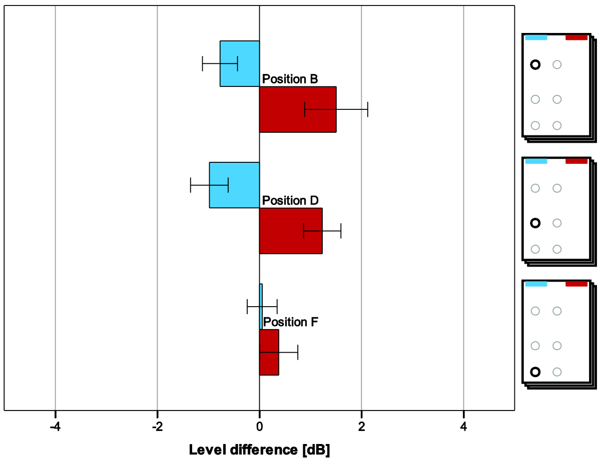


Figure 3.19 *Crosstalk per side position; right ear - left ear; all cinemas average; front loudspeakers; 500, 1000 Hz averaged; blue: left loudspeaker only, red: right loudspeaker only*

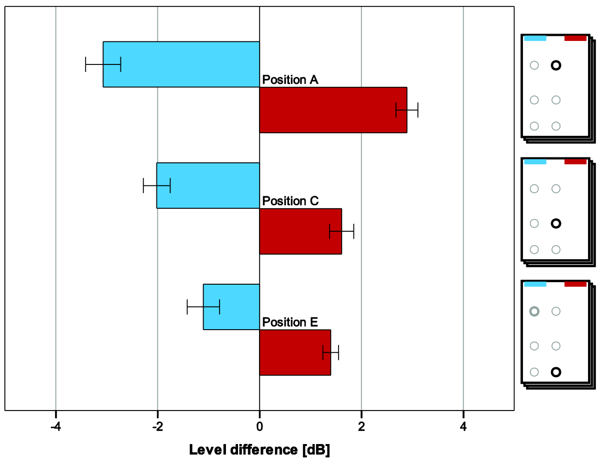


Figure 3.20 *Crosstalk per center line position; right ear - left ear; all cinemas average; front loudspeakers; 500, 1000 Hz averaged; blue: left loudspeaker only, red: right loudspeaker only*

Chapter 4: Conclusion

Nine cinemas of different sizes are investigated on their reproduction quality, using the audio equipment of the cinema. Different loudspeaker combinations and receiver positions are investigated. For a complete overview, also ISO 3382-1 reverberation time measurements are performed in these cinemas.

Dolby guideline

The reverberation times of the cinemas are compared to the Dolby guidelines corresponding to the volume of those cinemas. These guidelines allow longer reverberation times for larger halls. Unoccupied, six cinemas exceed the guideline with an exceeding reverberation time.

General results

The acoustical parameters EDT, C_{80} and MTI show a clear correlation to the reverberation time of the playback room (with a constant recording room). Other physical properties like volume and critical distance are only indirectly involved in the reproduction quality because of their relation to the reverberation time. For the T_{30} error, the values and the differences between them are too low to find a clear correlation. The achieved results are in the expected range of the theory introduced in [3], in general the cinemas performances are on the positive side of the trend line. The EDT error results of this research also show a relation to the reverberation time. For a more accurate relation to $T_{recording}/T_{playbback}$, this scatter plot can be extended with the impulse responses of [3]. The IACC error shows no relation to the reverberation time. Also no clear correlation of the IACC error to the measured physical properties of the cinemas is found. The cinemas perform relatively well on the IACC error, compared to the sound control rooms measured by Hak and Wenmaekers [4]. Like that study suggests, more research on this topic is required.

Cinema comparison

Because of the increasing reverberation time for larger cinemas due to the Dolby guidelines, smaller cinemas should show a smaller reproduction error than larger cinemas. Because of the fact that not all cinemas meet these guidelines, not all smaller cinemas have a smaller reproduction error than the larger ones. Differences in error between cinemas are large, for a parameter the error for one cinema can reach multiple times the allowed error where the error for another cinema doesn't exceed this allowed error.

Speaker combination and receiver position

The results of the different loudspeaker combinations show that for the smallest reproduction error only the front loudspeakers are to be used. As for the studied acoustical parameters, the reproduction error is greatly position dependent. The position for the smallest crosstalk is Position A, at the center line at the front. The worst case is at the back row at the side, Position F. The best situation for the reproduction of a concert hall recording in a cinema, related to the six measured positioned and the investigated parameters is when seated at Position E (back row, centerline) with only loudspeaker front left and front right, in a cinema with a low reverberation time. Which according to this research will be a small cinema, but not every small cinema. When the surround loudspeakers are used, Position C (2/3rd, centerline) is also a good position. This situation projected on Cinema 3 shows that all parameter errors stay within the allowed error, except for a slight exceedance of the C_{80} error.

Chapter 5: Recommendations

5.1. Supplementary research possibilities

To improve the knowledge on the reproduction quality in cinemas, the following items may be studied:

- Where the research is done in unoccupied cinemas, the audience may contribute to a lower reverberation time, improving the reproduction quality. So differences between occupied and occupied can be investigated.
- In the current research, six positions are investigated. More measured can provide more detailed information on the distribution of the reproduction quality inside the cinemas.
- The reproduction quality in this research is a combination of room acoustics and audio equipment. It might be useful to investigate the effect of only the audio equipment or only the room acoustics on the reproduction quality.

5.2. Future cinema design

This research showed that the reproduction quality for larger cinemas is worse than for smaller cinemas due to their longer reverberation time. For the sake of reproduction it is advised to acoustically design the cinemas at least to the Dolby guidelines, and preferably with a shorter reverberation time.

5.3. Future research

The research to reproduction quality just started. More knowledge in this field of acoustics is required. Based on this performed research project, the following recommendations for future research are formed:

- The relation between objectively measured errors related to the jnd and actual perceived reproduction experience of the audience.
- The relation of the receiver distance to the loudspeakers related to the reproduction error.
- Expand the dataset of the EDT error to create a more complete T/T diagram.
- Expand the dataset of the IACC error to find a relation between IACC error and a physical property of a room.

With use of the created dataset by this research on cinema reproduction quality, the following items may be studied:

- The same research can be performed on different types of recording rooms, like:
  - A speech recording studio
  - A Foley studio recording setup
  - The three other positions from the research of Hak en Wenmaekers [4, 5]
  - An opera house position, because a lot of cinemas broadcast operas
- The reproduction quality of a speech recording played by the center channel can be researched.
- Average ISO 3382-1 measurements can be compared to the same parameters measured with a HATS for nine cinemas on six locations and ten different loudspeaker combinations per location.

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Family and friends I want to thank for their interest in and support of this graduation project.
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Appendix A: Literature study

Contents

Introduction

Recordings of music, speech or other sounds have acoustical properties, such as reverberation, definition and clarity. When these sounds are played back in a listening room through its sound system, the acoustical properties and the sound system affect the perceived acoustics of the recording. For example, when a concert hall recording is played back in a cinema, the acoustical properties of the recording are influenced by speaker position and room acoustics. Due to this influence, it might be very hard to have the original acoustical properties accurately reproduced.

Hak and Wenmaekers [1] developed a new method to assess the room-in-room acoustics quality, the reproduction quality. This method is already applied to an extensive set of acoustical impulse responses. In the graduation research project on "The Effect of the Acoustics of a Cinema on the Reproduction of a Movie Soundtrack", cinemas are used as relatively large playback rooms to investigate the influence on the reproduction quality based on this new method.

In film industry, a lot of money is spent on superb picture and sound quality to give the audience the experience that they are not in the cinema but really in the story. To ensure that this quality is brought to the audience, multiple guidelines are introduced. However, most of the detailed information is about the equipment part of the reproduction, overlooking the importance of acoustical design.

Where the quality of the video reproduction mostly depends on the equipment, for audio reproduction the room acoustics play a very large role. Contrary to concert hall acoustics, guidelines for cinema acoustics are very limited and not much research on this topic has been done.

This report is an introduction to the graduation research project by providing information to support the measurements in the cinemas. This introduction report starts with an explanation of the new playback room examination method proposed by Hak and Wenmaekers [1]. Furthermore, cinema history related to audio and acoustics will be dealt with and nowadays design standards will be discussed to get an idea of the acoustical quality and design process of modern cinemas. Also the basic audio equipment of a modern cinema is introduced, this equipment will be used when performing the measurements in the cinemas.

In the graduation research project, 8 cinemas and a studio are subject to reproduction measurements. In this introduction report, standardized reverberation measurements of 8 of these cinemas will be compared to the discussed acoustical standards. Based on these results, a first estimation of reproduction quality based on the theorem of [1] will be done.

Chapter 1: New playback room examination method

Reproduction quality

The effect of acoustics of a playback room on an original recording can easily be described by a situation everybody will recognize. Imagine being in a bathroom and being listening to the radio. No matter what type of music is on this radio, all of the music is perceived very reverberant because of the (very) long reverberation time of the bathroom. The other way around, if a recording is made in a reverberant church for example, and it is played back in a recording studio, the reverberant field of the original recording is perfectly perceivable. The playback room, in combination with the used sound system affects the recorded acoustics.

In the introduction is already mentioned that a new method is proposed by Hak and Wenmaekers [1] to examine the acoustical quality of a playback room. The greatest advantage of this new method is that the acoustics of the recording that is being reproduced is part of this examination. Not the room itself, but the purpose of the room is examined.

This new method can be explained in three steps:

1. In the recording room, acoustical measurements have to be done. An acoustical impulse response measurement for a typical reference situation has to be performed. For example in a concert hall with the source on the stage and the receiver positioned at a seat of the audience.

2. The impulse response of the recording room is played in the playback room. The impulse response of the recording room thus is modified by the acoustics of the playback room. This reproduced impulse response is registered on the listener position. This recorded impulse response represents the perceived acoustics for this typical reproduction scenario.

3. Acoustical parameters for both the recording room impulse response and the perceived impulse response are calculated and compared to each other. The just-noticeable difference (jnd) is used as allowable error.

Diffuse field investigation

The proposed new method of researching room in room acoustics is already applied to a case in which a set of 11 existing different diffuse field impulse responses are mutually convolved [1]. For these convolved responses, the errors relative to the 'recording room', is plotted in a diagram with on the x-axis the ratio of reverberation time of the recording room and the playback room: $T_{recording}/T_{playback}$. Figure 1.1 shows this diagram for the decay related parameter $T_{20,}$ Figure 1.2 shows the diagram for the energy ratio related parameter C_{80} (clarity), and finally, Figure 1.3 shows this diagram for the energy modulation related parameter MTI (Modulation Transfer Index). For the T_{20} and C_{80} errors, mean values for the 500 Hz and 1000 Hz octaves are shown, for the MTI error, the 500 Hz and 2000 Hz octaves are combined. All figures show the relevant jnd.

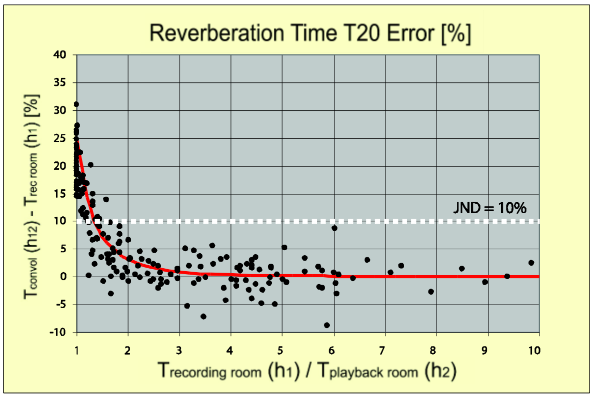

Figure 1.1 *Reverberation time T20 error [%] [1]*

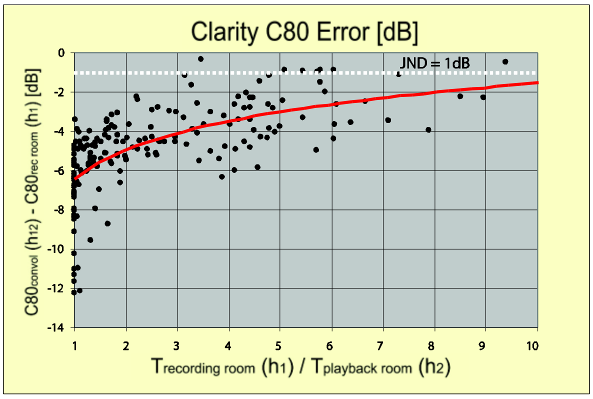

Figure 1.2 *Clarity C_{80} error [dB] [1]*

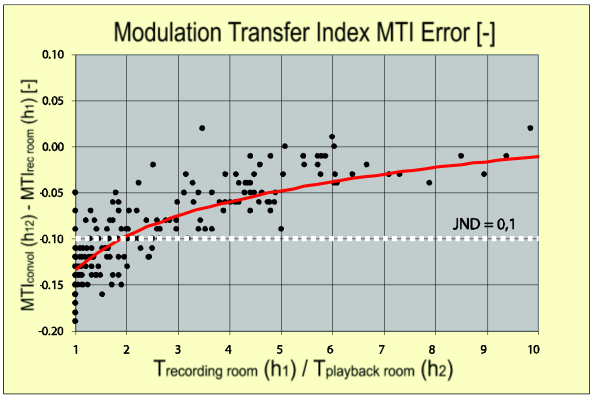

Figure 1.3 *MTI error [-] [1]*

Based on these figures is concluded that for the judgment of the energy decay rate of a recording of a diffuse field in a playback room with a diffuse field, the playback room is allowed to have as much as half this decay rate.

Under the same conditions, the auditive judgment of the C_{80} is only possible in playback rooms with decay rate higher than 8 times the decay rate of the recording room. Practically, this means judgment in a dry sound control studio, or the use of headphones [2, 3].

The decay rate of the playback for the judgment of energy modulations, which are related to speech intelligibility, should be at least four times smaller than that of the recording room.

The general conclusion is that for the Reverberation Time, Clarity and Modulation Transfer Index, the reproduction quality depends on the ratio between $T_{recording}$ and $T_{playback}$.

Chapter 2: Cinema Sound

Audio & acoustics

From the start of cinema audio history, acoustics play an important role in cinema design. However, this role changed drastically over the years. For four different periods, cinema audio and acoustics will be related to each other. The four different periods are formed based on specific events in these periods. These important events can be found in Appendix A.1.

Silent Era, 1895 - 1927

With the introduction of the projector, the history of cinema starts. In the beginning, there were only images on the film, there was no synchronized sound in movies. To make these silent movies more lively, live music or speech was performed in the cinema. For an attractive performance, the acoustics of the cinema were optimized for a good transmission and soundfield. In practice this means that for example the reverberation time is in the range of the reverberation time of a theatre.

Monophonic Era, 1927 - 1940

In the monophonic era, sound was mostly (re)produced by one speaker at a time. There was the possibility to switch to another speaker during the movie. Synchronised soundtracks were possible, but these tracks were not able to create an accurate ambiance due to the limited amount of speakers and the technical limitations of these speakers (limited power, limited frequency response). There was no need to treat the acoustics of the cinemas different than in the previous era. The acoustics of the cinema contributed to the ambiance of the sound track.

Experimental Surround Era, 1940 - 1987

At first, the change to multichannel sound started quite radically. Sound systems of 4+ channels and for example Fantasound with up to 96 speakers were experimented with. Multiple different sound systems were developed, but none of them succeeded to become a standard, due to technical difficulties. Than a vicious circle arose, due to the technical difficulties, the quality of the cinema wasn't that good where home entertainment reached a relative high level. The number of visitors decreased drastically. Because of this, cinemas did not have the opportunity to invest in a better system to attract visitors.

Finally Dolby came with its Dolby Spectral Recording system. This was a low cost and reliable system. Unfortunately, it wasn't the qualitative best system of the era. The system offered a standard left and right channel and a so called matrixed center channel, it was extractable from the left and right channel. Lateron a matrixed surround channel was added.

Due to the surround sound, theoretically it was to a certain level possible to recreate a soundfield. However, because of the different experiments and the lack of a standard, at first this ability wasn't used regularly. Also the (lack of) quality of the surround channels in the different systems were part of this. In this experimental period, the role of the acoustics changed. More and more the soundtrack took over the role of creating ambiance and spaciousness. To make full advantage of this, cinemas had to be acoustically 'dry'.

Digital Surround Sound Era, 1987 - present

Finally, in 1987, a standard for digital surround sound was introduced by the SMPTE. From this moment on, high quality, relatively low cost digital surround sound was possible in almost all cinemas. The advantage of this digital surround sound over the former formats is that all channels are completely discrete recorded and cover the full bandwidth of human hearing. This gives the directors the possibility and flexibility to place every kind of sound in every corner or place in the theatre (within the limitations of the amount of audio channels). With this technology it is possible to immerse the audience in the soundfield/ambience the director wishes them to be. To make optimal use of this possibility, acoustics of the cinema should not influence the soundtrack.

Although directors still are very careful with using surround sound in their productions, visitors more and more get accustomed to the complete soundscape in were they are placed. Greatly depending on the type of movie, aggressive use of surround sound becomes more common every day.

Influence of the development of sound on film

Sound in movies is not just an extra feature. Sound adds a complete new dimension to film. Sound can give an extra meaning to film. Depending on the sound accompanied with a scene, this scene can seem for example scary or happy or exciting or sad. So exactly the same video with a different soundtrack (or intentionally no soundtrack) can be experienced in a completely different way. In the modern way of filming, the soundtrack is as important as the image to the movie.

Historically, movie sound originated purely out of the diegetic space on screen. This means that only sounds are heard which can be allocated to something really happening on the screen. From this starting point, the audience slowly accepted a more freely use of the soundtrack. During the technical development of cinema audio, directors wanted to take the audio off the screen. This is what film critic Chion [4] calls the superfield. At first, sound was used to enlarge the visual area with a stable, balanced sound field around the screen. This superfield is a passive, continuous soundtrack which made it possible to audibly couple scenes with each other. Also extra information of a scenery good be given, supporting or even replacing the visual part of the movie. Still the audience was aware of being in a cinema instead of being at the scene itself.

Technical improvements of sound systems and a slowly adapted audience made it possible to establish complete new soundfields in the cinema. Digital surround sound makes it possible to recreate a complete auditory scenery. Kerins [5] calls this the ultrafield, an extension of Chions superfield. This is an extension because the auditory events take place outside the diegetic space but are more active than the former sounds form the superfield. The audience can get the feeling to be at the scenery itself instead of being in a cinema.

Another advantage of these modern possibilities can be found in the establishment shot. Formerly in movies, new scenes were introduced by an establishment shot, so the audience could see in what setting the scene takes place. By making use of the ultrafield and nowadays modern digital surround sound formats, the director has the possibility to origin high quality sounds from every possible direction. This possibility is used to give the audience a quick auditory spatial impression of the scene on screen instead of using a relatively long establishment shot. So by active listening to the soundtrack, the spectator is able to perceive the complete scenery, where the image of the movie only shows a small field of view on the scenery.

As mentioned in the previous section, to recreate complete auditory scenes, cinema acoustics may not influence the soundtrack. The creation of the auditory scene (acoustics) is completely recorded on the soundtrack. Cinemas should be acoustically designed to have no influence on the acoustical characteristics of the soundtrack.

Also, due to the introduction of 'digital' projection, a new type of event is introduced to cinemas. Because of the new type of projectors, it is possible to broadcast a live event happening for example at the other side of the world. At this moment (2012), it becomes more and more popular to broadcast operas live recorded for example in a concert hall in New York. Also with this type of event, it is very important to preserve the original acoustics.

By continuously improving the capabilities of a cinema sound system, the sound system is better able to recreate an accurate auditory scenery to completely immerse the audience into the movie scene. Not only cinema sound systems need improvements to achieve this, also recording and editing techniques and standards should be improved to obtain the best result.

During history, the role of the cinema to the sound changed. At first, the acoustics of the cinema played an essential role in the soundfield and ambiance of the soundtrack, later on the soundtrack took over this function completely.

Chapter 3: Modern equipment

In the nowadays Digital Surround Sound era, the audio equipment of a modern commercial cinema can be divided in two different sections, the so called a-chain and the b-chain. The a-chain consists of all equipment which handles line level signals. The b-chain is responsible for handling the amplification of the a-chain signal as well as the final playback. In Figure 3.1 a schematic representation of cinema equipment can be found. Both a-chain and b-chain will be used for the reproduction measurements in the cinemas.

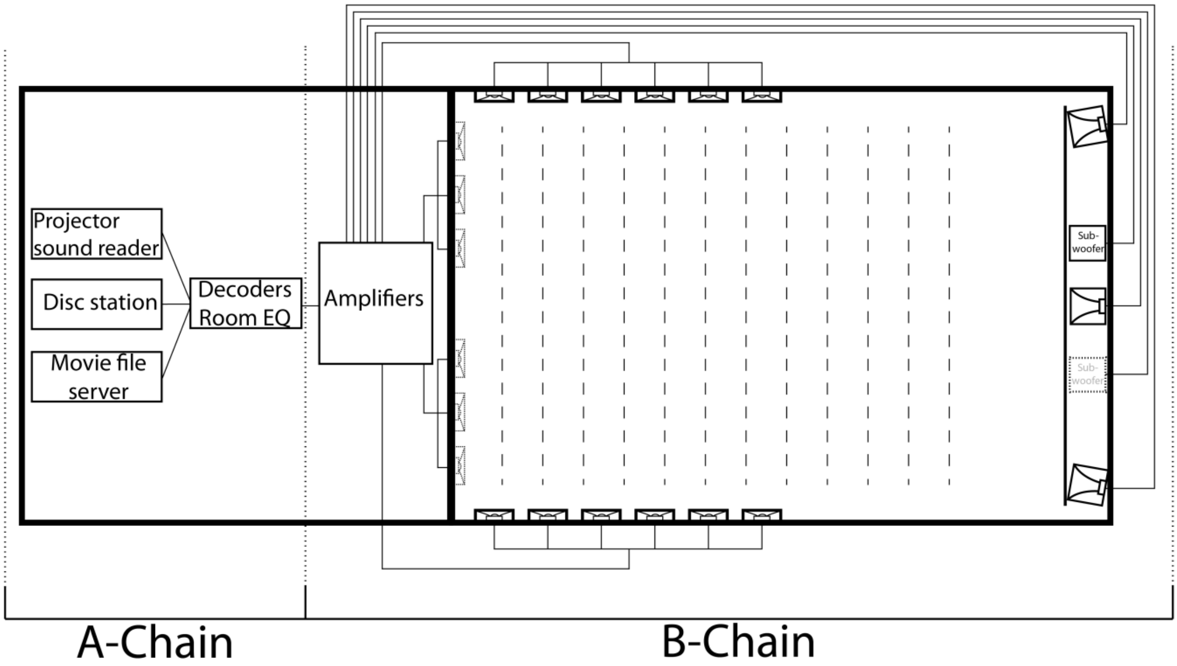

Figure 3.1 *Schematic overview of the A-chain and B-chain*

A-chain

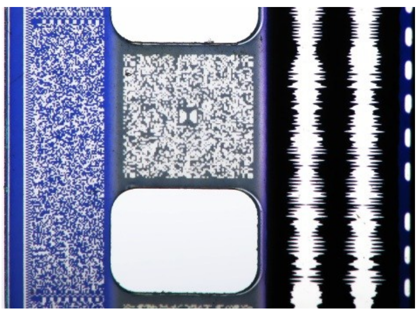

Figure 3.2 *Side of 35 mm film print featuring all four audio formats [6]*

In cinemas which still use 35 mm projectors, the a-chain starts at the projector. The sound is situated on the movie film. With an optical reader, the track is extracted from the film and converted into an electrical signal. From this reader, the signal is transported to the cinema sound processor where the sound level is selected and equalizing, surround matrixing effects, noise suppression and delays are applied. It is also possible that the optical reader extracts a digital Dolby SRD signal. This digital multichannel signal is decoded in the sound processor. Figure 2.2 shows the side of a film reel with from left to right: (1) rarely used optical digital Sony Dynamic Digital Sound data, (2) optical Dolby SR.D data blocks, (3) optical two channel Dolby Spectral Recording (SR), (4) DTS time code for synchronization with a DTS soundtrack on an external CD-drive.

In modern cinemas, 35 mm projectors aren't in use anymore. Both image and sound are stored on a movie file server. From this server, the video stream is sent to the digital projector, the digital audio stream is still sent to the sound processor. Sound level selection, equalizing and delays are still applied, but due to the digital source, there is no need for surround matrixing and noise suppression.

Where the old projector uses 35 mm film as video and sound medium, the modern digital file servers use a file standard of the Digital Cinema Initiatives (DCI) a Digital Cinema Package (DCP).

B-chain

The B-chain consists of the power amplifiers and the speakers. In modern cinemas, mostly 5.1 or 7.1 speaker systems can be found. 5.1 means five discrete full range channels (left, center, right, surround left, surround right) and a low frequency effects (LFE) subwoofer channel.7.1 adds another two surround (back) speakers to this configuration. The 7.1 configuration is found in several cinemas, but all configured in another way. Also sound engineers notify that there isn’t a proper standard for the use of the 7.1 configuration.

In practically all cinemas, the surround channels consist of more than one speaker per channel, as shown in Figure 3.1. In this way, for most of the audience, the surround sound is coming from the side walls rather than from the back corners. Also the LFE channel quite often is divided into two subwoofers to generate a more equal (low frequent) soundfield.

In the past, cinema brought us mono sound. Through a long journey, nowadays we have multichannel surround sound (5.1/7.1). What will the future bring? Will 5.1 be expanded to an optimal configuration of 12.2 [5] or lies the future in wave field synthesis, in which a complete soundfield is recreated.

Alignment of the A- and B-chain

In the past, sound levels and delay settings were optimized for one single position. This is the same position as the sound engineer of a mixing studio, at 2/3 from the screen, in the center of the screen. Due to the longer travel distance of the sounds coming from the front speakers, relative to the travel distance of the surround speakers to this central position, delays are applied to the surround channels. Where the surround channels consist of multiple speakers, it is possible to assign different delays to (groups of) these speakers.

Also on the 2/3 position sound levels are calibrated. With the Dolby Processor set to ‘7’ (-20 dBFs) and broadband pink noise on one of the front speakers, the sound pressure level on the 2/3 position is adjusted to 85 dB(c) and the level of the surround channels to 82 dB(c).

Digital Cinema Initiatives: Digital Cinema Package

In modern cinemas, digital techniques are used to transfer the movie onto the screen and to the B-chain. To support this development a standard file type is proposed by Digital Cinema Initiatives [7]. DCI’s Digital Cinema Package is worldwide accepted as the open standard of digital cinema medium.

The standard accepts a wide range of file formats, but the main specifications for sound and image can be found in Table 3.1 and 3.2. Popular movie file servers (Dolby, Doremi) are DCI compliant, so they are compatible with the DCP standard.

Table 3.1 *DCP audio specifications [7]*

File type	Uncompressed PCM
Bitrate	24 bit
Samplerate	48/96 kHz
Max. number of channels	12

Table 3.2 *DCP image specifications [7]*

Image resolution	2048x1080 2d/stereoscopic
Compression	JPEG2000
Color space	XYZ, 12 bit per channel
Framerate	24 fps

This standard makes it possible for everyone to create a video and play it back on original cinema equipment.

Chapter 4: Cinema standards

In order to make use of the full potential of the high quality of modern soundtracks, different standards are introduced as guidance to good cinema acoustics. The two most important standards are the ones of Dolby [8], and of THX [9]. Both Dolby and THX spend a lot effort on the equipment part of the audio reproduction and relatively little on acoustics. These guidelines are based on a general type of sound played back in cinemas. The research on the reproduction quality of cinemas will show whether these guidelines provide a good basis for a specific type of sound played back. This chapter will briefly show the guidelines which are only relevant for the acoustical design of cinemas.

Modern soundtracks are capable of producing a wide dynamic range, so both very soft and really loud sounds can be produced without touching the volume selector. To make full advantage of this, background noise needs to be quite low. However, recommendations to sound insulation and background levels will not be discussed, as this is not relevant to the reproduction part of the research.

Reverberation

According to Dolby Laboratories, reverberation has to be kept as low as possible. As mentioned in chapter 2 as well is in this guideline of Dolby, the 'acoustics' are already present on the soundtrack. Depending on cinema volume, Dolby advices a certain reverberation time at 500 Hz (Figure 4.1). In Figure 4.2, the value at 500 Hz is translated to a complete reverberation curve with upper and lower limits. Lower frequencies can have a larger reverberation time, higher frequencies will have a shorter reverberation time. Both the upper and lower limit are introduced to result in a balanced, natural reverberant field.

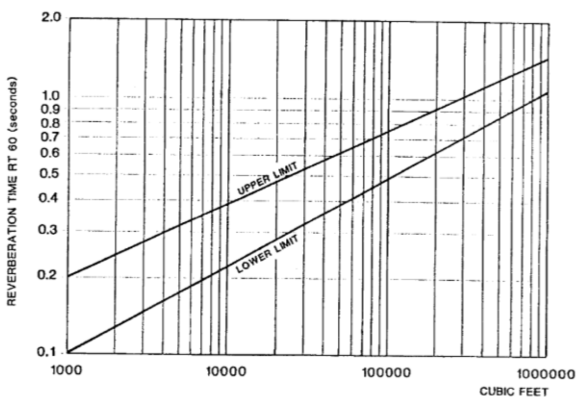

Figure 4.1 *Dolby advice RT60 at 500 Hz versus room volume [8]*

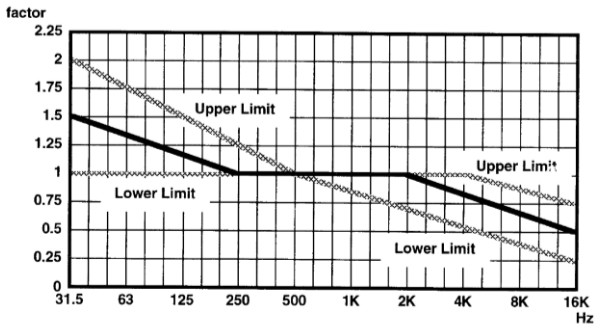

Figure 4.2 *Dolby RT 60 scaling curve based on 500 Hz [8]*

Where Dolby gives a quite accurate description of the reverberation curve, the THX guidelines are rather loose. Literally it says: "Depending on the size of the room, the acceptable range for reverberation should be from 0.5 to 2 seconds, never exceeding 2 seconds."

Both companies also advice to design a cinema in such a way that echoes and flutters are prevented. Also standing waves need to be controlled. According to Dolby, this can be achieved by adding the right material at the right position, no specific geometry or sound-reflecting surfaces are necessary. In the next section the materialization as proposed by Dolby is discussed.

Materialization

For the side walls, there is no specific description how to cover them, other than to avoid hard parallel surfaces. The absorption should be enough to conform the reverberation time prescription. More is written on the sound insulation properties of the walls.

For certain set-ups it is mandatory to have a good absorbing wall behind the screen to absorb echoes created in between the speakers and the (mostly acoustical transparent) screen.

The wall behind the audience should be totally absorbent, this prevents standing waves originating from the front speakers. Also annoying late reflections will be reduced by this absorbing surface.

It is advised to place carpet on floor whenever it is possible. Only in situations where it isn't possible to use carpet, hard flooring is acceptable.

The properly advise is given not to forget to take the absorption of the seats into account. It is recommended to have seats with about the same characteristics both in occupied and unoccupied state.

A great part of absorption will be allocated to the ceiling. The ceiling is able to absorb low frequencies to avoid excessive bass. An acoustical ceiling with a NRC rating 0.90 or higher is recommended.

Chapter 5: Cinemas in the Netherlands

To get an idea of the acoustics of the current cinemas in the Netherlands, ISO 3382-1 [10] reverberation measurements are performed in eight cinemas within a wide range of volume. Both the smallest and the largest commercial cinemas are investigated. Figure 5.1 shows the volume distribution of the different cinemas.

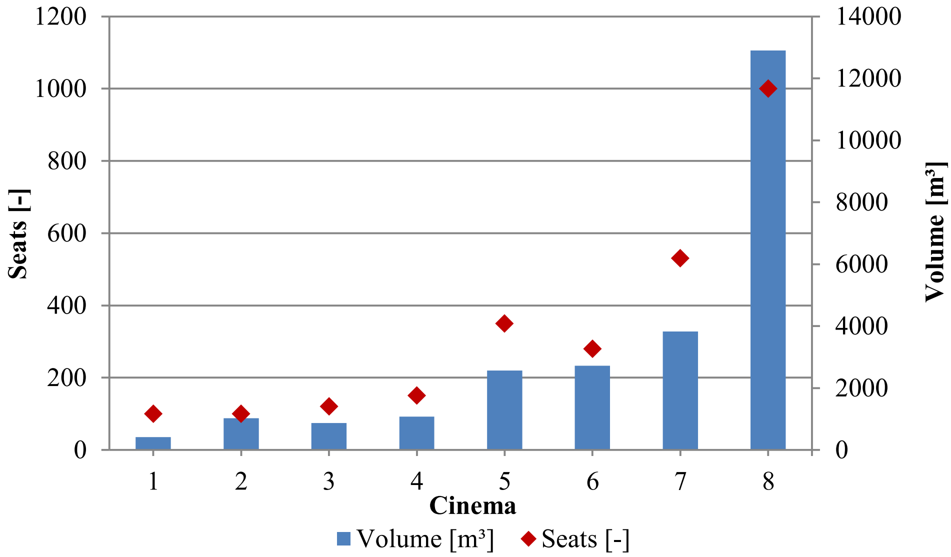

Figure 5.1 *Volume distribution measured cinemas*

The reverberation results can be compared to the Dolby guidelines. This comparison can be used in the reproduction research to relate reproduction quality to the Dolby acoustical guidelines.

In the Netherlands, cinemas with more than about 500 seats mostly are a combination of cinema and a theatre. The acoustical design is in most cases a compromise between a short reverberation time (large cinema, +/- 0,6s [8]) and a longer reverberation time (theatre, +/-1,2 s). Table 5.1 shows the characteristics of the measured cinemas, including the mean reverberation time for the 500 and 1000 Hz octaves. Figures 5.2 up to and including 5.8 show the reverberation data for the full octaves from 32.5 up to and including 16,000 Hz in the same figure as the upper and lower limits of the Dolby guidelines specific for its theatre volume. The measurement method can be found in Appendix A.2.

Table 5.1 *Cinema characteristics*

	Seats	Floor surface [m²]	Volume [m³]	T_{30} [1]	RT60 [2]
Cinema 1	100	103	410	0.93	0.35
Cinema 2	100	200	1023	0.62	0.46
Cinema 3	120	166	872	0.41	0.42
Cinema 4	150	200	1076	0.75	0.47
Cinema 5	350	428	2568	0.50	0.59
Cinema 6	280	407	2724	1.00	0.63
Cinema 7	530	435	3828 (+7312m³ flytower)	1.05	0.66
Cinema 8	1000	1165	12896	1.03	1.00

[1] *Mean value of ISO 3382 measurements 500-1000 Hz.*

[2] *500 Hz RT60 according to Dolby*

Measured reverberation time vs. Dolby Guidelines

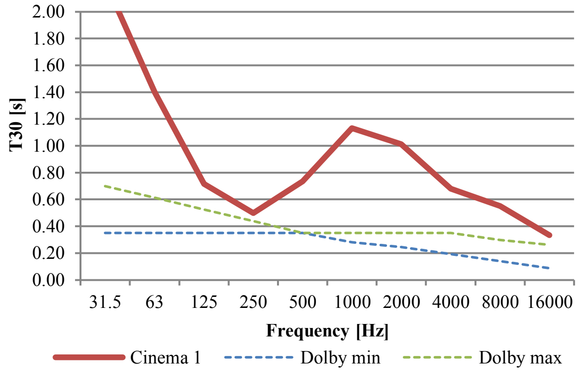

Figure 5.2 *Cinema 1 reverberation ISO 3382*

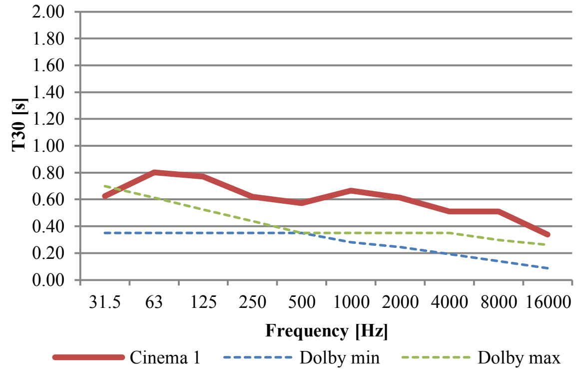

Figure 5.3 *Cinema 2 reverberation ISO 3382*

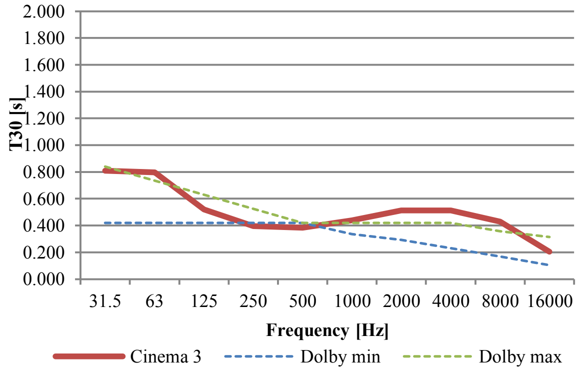

Figure 5.4 *Cinema 3 reverberation ISO 3382*

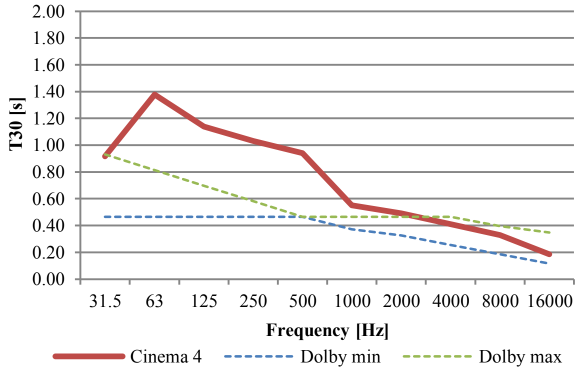

Figure 5.5 *Cinema 4 reverberation ISO 3382*

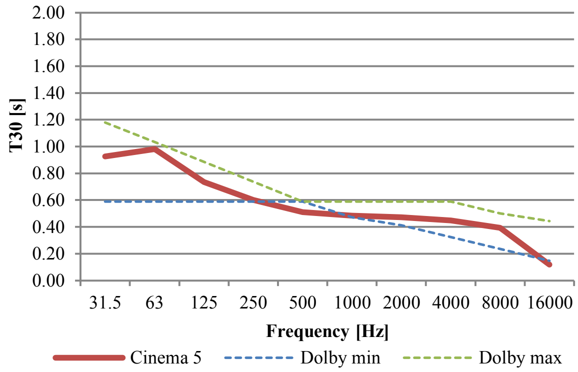

Figure 5.6 *Cinema 5 reverberation ISO 3382*

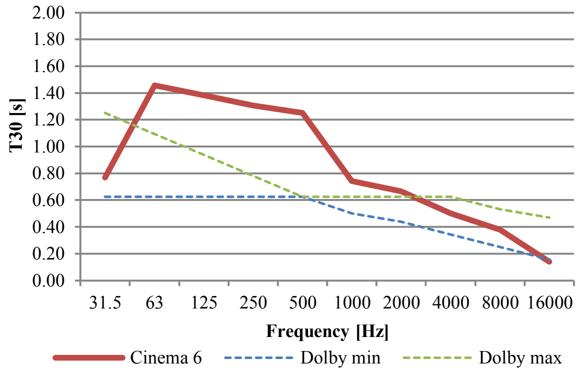

Figure 5.7 *Cinema 6 reverberation ISO 3382*

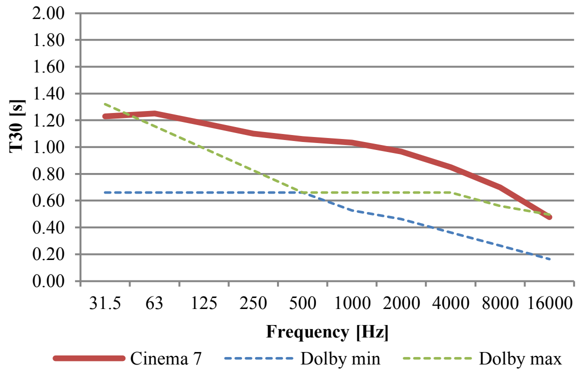

Figure 5.8 *Cinema 7 reverberation ISO 3382*

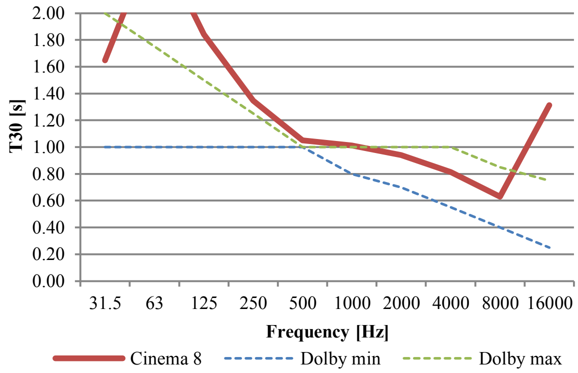

Figure 5.9 *Cinema 8 reverberation ISO 3382*

From these figures it is clearly visible that independent of volume, most of the cinemas do not met the Dolby criterion. Cinema 3 and 5 perform quite well, most of the frequency range lies within the lower and upper limit. All other cinemas follow about the same curve with here and there frequency ranges within the limits. Except for cinema 1, the reverberation characteristics of this cinema are really different from all the other cinemas. The reverberation time of this cinema exceeds the Dolby limits by a large factor.

Based on these results, it is clear that for probably every room size in the researched region it is possible to meet the Dolby guidelines. Presumably it is a matter of how much effort is spent on the acoustical design whether cinema acoustics conform the Dolby guidelines or not.

This overview of cinemas also shows that for large cinemas, the reverberation time is allowed to be relatively long. For cinema 8, with the volume of a small concert hall, the low frequent reverberation time exceeds 1 second by far. For a hall of this size this is not really surprising and it even isn't a large exceeding of the Dolby guidelines.

Chapter 6: Conclusion

The role of the acoustics in a cinema are changed due to the technical development of high quality surround sound systems. With this change standards are introduced to ensure the reproduction quality of cinemas. The most important standard for this is the Dolby guideline.

This report shows that for the seven researched cinemas in the Netherlands, most of them do not meet the Dolby criterion for reverberation. With this result in combination with the theorem that the reproduction quality of (some) acoustical properties depend on the reverberation time in mind, the expectation is that the reproduction quality of cinemas with a longer reverberation time will be significantly worse compared to cinemas with a short reverberation time. Related to Dolby's guideline, this means that cinemas with a small volume will show a better reproduction quality than the larger ones.

The graduation research project on "The Effect of the Acoustics of a Cinema on the Reproduction of a Movie Soundtrack" will investigate this relation between reverberation time and reproduction quality of these cinemas by using the newly introduced examination method of Hak and Wenmaekers [1].

Chapter 7: References

[1] C.C.J.M. Hak, R.H.C. Wenmaekers, "The effect of Room Acoustics on the Perceived Acoustics of Reproduced Sound", Internoise 2008, Shanghai, China (2008)

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[7] Digital Cinema Initiatives, "Digital Cinema System Specification" V1.2 (2008)

[8] Dolby Laboratories Inc., "Technical Guidelines for Dolby Stereo Theatres" Rev 1.33 (1994)

[9] Lucasfilm Ltd. THX Theatre Alignment Program "Recommended Guidelines For Presentation Quality and Theatre Performance For Indoor Theatres" (2000)

[10] Acoustics-Measurement of room acoustic parameters - Part 1: Performance rooms, International Standard ISO/DIS 3382-1 2009 (International Organization for Standardization, Geneva, Switzerland, 2009)

Appendix A.1: Cinema Audio History Timeline

1879	**Alexander Graham Bell**	*Two channel sound transmission*	
1895	**Development of the film projector**	*'Bioskop projector'*	Silent Era
1927	**Warner Brother's *The Jazz Singer***	*First commercial synchronized sound movie*	
1932	**Alexander Graham Bell**	*First known true stereo recording*	Monophonic Era
1933	**Alexander Graham Bell**	*Three channel recording (L-C-R)*	
1937	**Alexander Graham Bell**	*Three different approaches to three-channel synchronized movie recordings*	
1940	**Walt Disney's *Fantasia***	*First multichannel sound movie: 3 front channels and speakers. 1 surround channel, 96 speakers (premiere Los Angeles)*	Experimental Multichannel
1950's	**Magnetic stereophonic sound**	*3 or more front channels, 1 surround channel*	
1952	***This is Cinerama***	*First Cinerama film, three-projector image, 6 sound channels*	
…	**Lot of experiments**	*Due to unstable quality: drop in number of visitors*	
1975	**Dolby Stereo**	*Two channels with matrixed center. Optical track. Later with added matrixed surround.*	
1980's	**Dolby SR (Spectral Recording)**	*Enhanced noise reduction*	Digital Surround Sound Era
1987	**SMPTE Standard**	*5.1 digital channel configuration L-C-R-SL-SR-LFE*	
1992	**Dolby**	*SR-D / Dolby Digital 5.1 digital format*	
1993	**Digital Theater Systems**	*DTS 5.1 digital format*	
1993	**Sony**	*Sony Dynamic Digital Sound 7.1 digital format*	
…	**Technology**	*Ability to produce multichannel sound*	
Present	**Audience**	*Accustomed to explicit surround sound use*	

Main source for the events on the timeline:
M. Kerins "Beyond Dolby (stereo)", Indiana University Press (2011), ISBN 978-0-253-22252-7

Except the events:
1895: G. Nowell-Smith Et Al. "The Oxford History of World Cinema" Oxford University Press (1996), ISBN 0-19-811257-2 ISBN 0-19-874242-8, P. 240

1940: W. M. E. Garity, J. N. A. Hawkins "Fantasound" Journal of the Society of Motion Picture Engineers August (1941)

Appendix A.2: Measurement method ISO 3382-1

All reverberation measurements are performed according to the following measurement procedure. This procedure is based on ISO 3382-1 [1]. Two source positions are chosen as well as at least six receiver positions spread over the audience area.

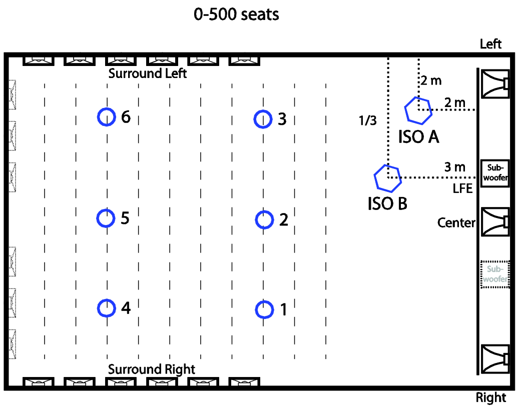


Figure B.1 *Source and receiver positions 0-500 seats*

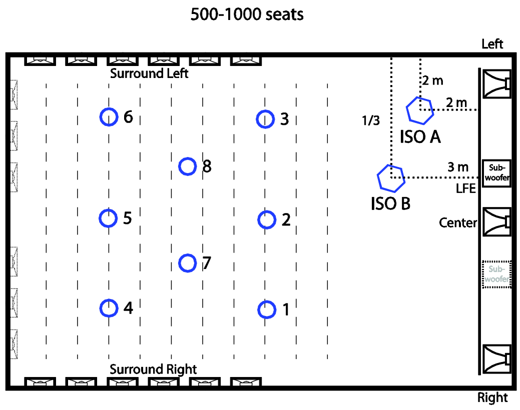


Figure B.2 *Source and receiver positions 500-1000 seats*

For cinemas with a seating capacity of up to 500 seats, the source and receiver points of figure B.1 are used, for the cinemas with a higher capacity two more points are added, as is visible in figure B.2. The sign with subscriptions ISO A and ISO B are the positions of the omnidirectional source. At position ISO A, the source is elevated to an height of 1.62 meter, at ISO B the source is elevated to an height of 1.81 meter. ISO B is placed at 1/3 of the width of the cinema.

The numbered circles are the receiver positions, the dashed lines represent seating rows. Positions 1-3 are placed in between the second and third row from the front and 4-6 are placed in between the third and fourth row from the back. The microphone is positioned upright at 1.10 m height. At both sides, the microphones should be placed at 2 meters distance from the wall. Positions 7 and 8 are positioned halfway the audience area and at a distance of 1/3 of the width of the cinema to the wall. Exception to this method is cinema 8, in this cinema only one source position is measured. Due to a short of time it wasn't possible to do the same measurements at position B.

Table B.1 shows the used measurement equipment for the4se measurements.

Table B.1 *Measurement equipment*

	Product name	**Serial number**
Netbook with Dirac 5 software	Dell Latitude 2110	
DAC/ADC	Acoustics Engineering Triton	03300354
Amplifier	Acoustics Engineering Amphion	0101
Omnidirectional source	Acoustics Engineering Pyrite	0203
Omnidirectional microphone	B&K Type 4230	2703329
Microphone power supply	Acoustics Engineering Delatron	

[1] Acoustics-Measurement of room acoustic parameters - Part 1: Performance rooms, International Standard ISO/DIS 3382-1 2009 (International Organization for Standardization, Geneva, Switzerland, 2009)

Appendix B: Cinema overview

Appendix B.1. Cinema 1

In this appendix cinema 1 is described in more detail. The floor plan is shown in Figure B.1.1 to indicate source and receiver positions of both the ISO measurements as well as the reproduction measurements with the HATS. The seats on the plan are an indication of the real seating plan. Speaker locations are shown, but not on scale. There might be speakers in the cinema which aren't shown on the drawings, those speakers were not used during testing. Figure B.1.2 shows the section of the cinema in which the height profile can be seen as well as the heights of the surround speakers. Figure B.1.3 and B.1.4 are pictures of the HATS in the cinema, Figure B.1.5. gives an overview of the cinema. Table B.1.1 shows the specifications of the cinema as measured during the visit, Table B.1.2 describes the materialization of the cinema. Reverberation time measurements were performed according to ISO 3382-1. Source and receiver positions are shown in the floor plan. T_{30} is presented in full octaves as minimum, maximum, and mean value (Graph B.1.1). In the same way the background noise on these positions is presented in Graph B.1.2 in relation to the Noise Criterion 25 curve. Table B.1.3 shows the temperature and humidity conditions during the measurements.
The phase and delay tests are described in Appendix C. The stationary microphone is placed within 1 meter of the center of the front left speaker, this distance incorporates an error of -0/+3 ms on the delay tests. Results of these tests are shown in Table B.1.4.

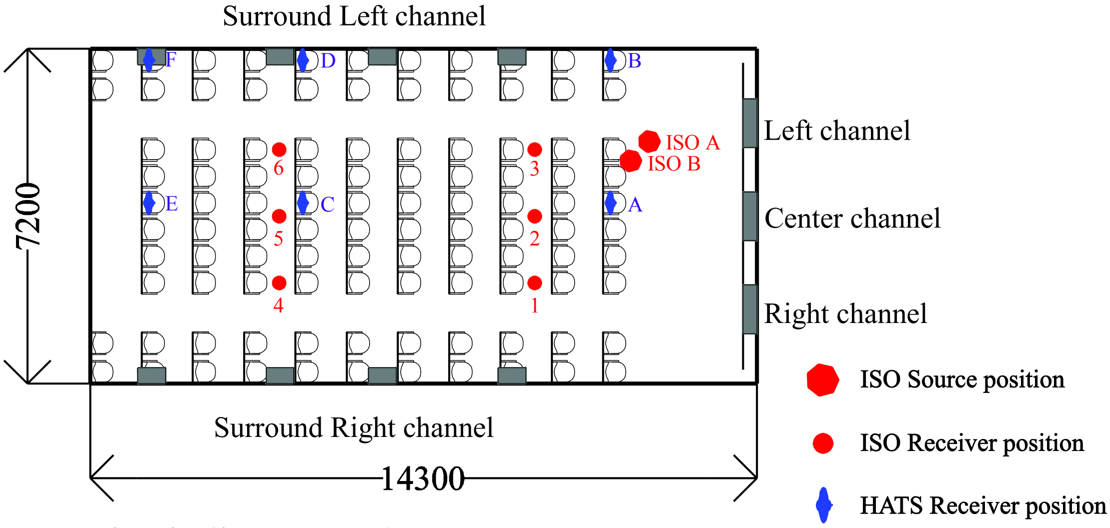


Figure B.1.1 *Floor plan (dimensions in mm)*

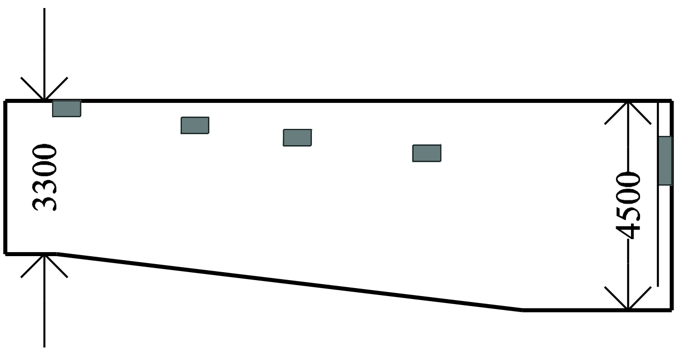


Figure B.1.2 *Section (dimensions in mm)*

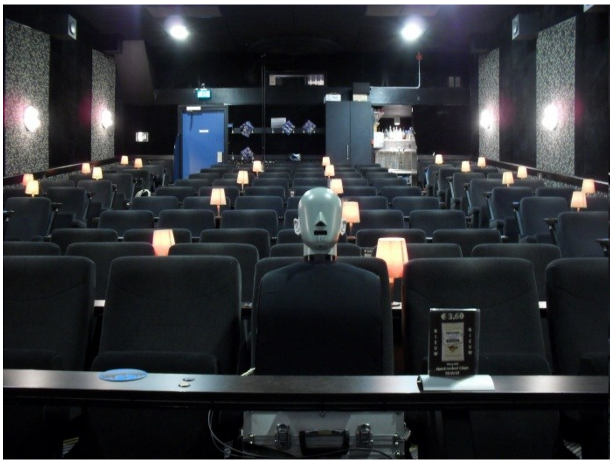


Figure B.1.3 *HATS at position A*

Figure B.1.4 *HATS at position B*

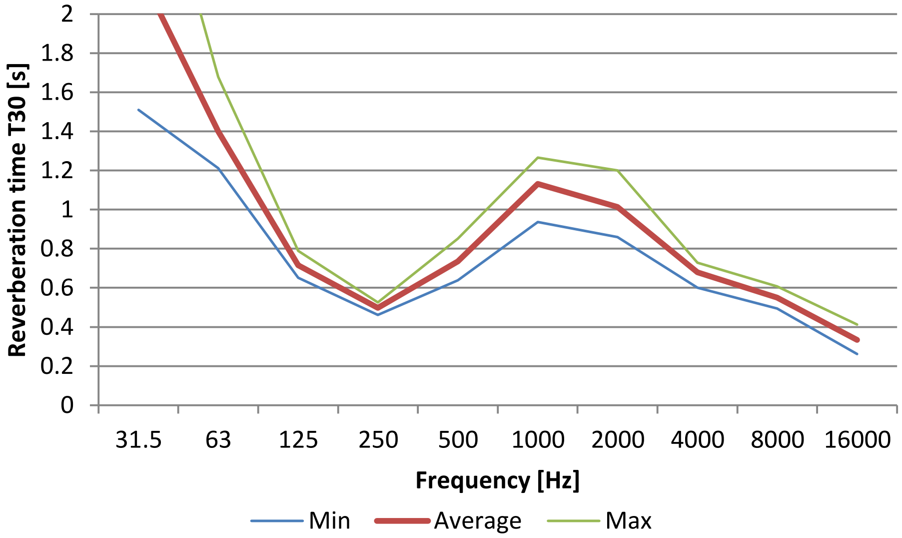
Figure B.1.5 *Overview of cinema 1*

Table B.1.1 *Cinema specifications*

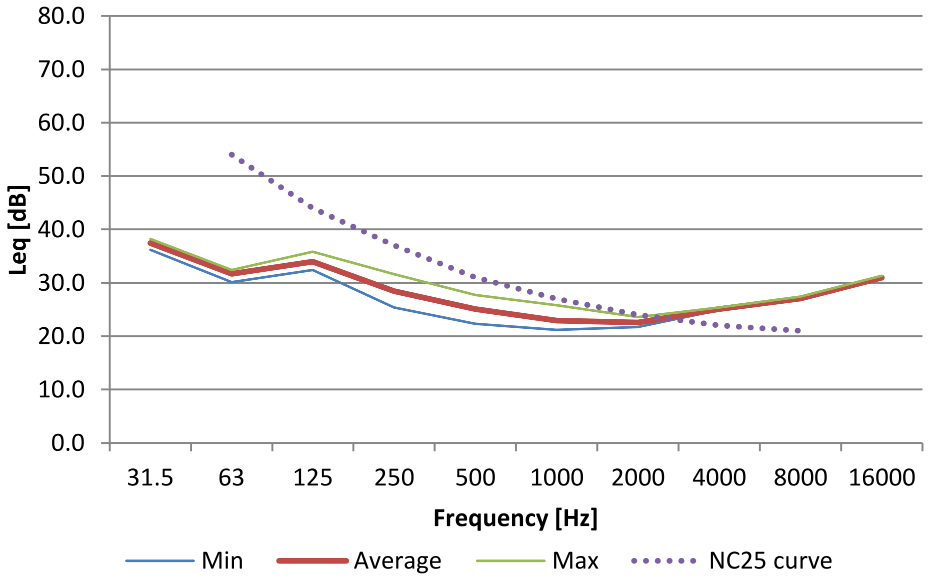
Seats	100
Floor area	103 m²
Volume	410 m³
Reverberation time (T_{30}, ISO 3382-1)	0.93 s
Background noise LAeq	32.5 dB(A)

Table B.1.2 *Materialization*

Floor	Hard floor, thin carpet
Walls	Hard wall, thin carpet
Ceiling	Absorbing modular ceiling
Seats	Folding seats, soft clothing all around
Specific acoustical aids	None
Projection screen	Acoustical transparent



Graph B.1.1 *Minimum, average and maximum T_{30} for 12 positions in full octaves*



Graph B.1.2 *Minimum, average and maximum background noise for 6 positions in full octaves*

Table B.1.3 *Temperature and relative humidity during measurements*

T_1	20.8 °C	RH_1	46.4 %
T_2	20.0 °C	RH_2	42.7 %
T_3	19.5 °C	RH_3	42.4 %

Table B.1.4 *Speaker configuration*

	Delay relative to left channel	In phase relative to left channel
C		Yes
R		Yes
SL1/SR1	21 ms	Yes
SL2/SR2	21 ms	Yes
SL3/SR3	21 ms	Yes
SL4/SR4	21 ms	Yes

SL1 = SurroundLeft, 1^{st} speaker on the left side, looking to the screen. Starting from the screen to the back.
SR1 = SurroundRight. 1^{st} speaker on the right side, looking to the screen. Starting from the screen to the back.

Appendix B.2. Cinema 2

In this appendix cinema 2 is described in more detail. The floor plan is shown in Figure B.2.1 to indicate source and receiver positions of both the ISO measurements as well as the reproduction measurements with the HATS. The seats on the plan are an indication of the real seating plan. Speaker locations are shown, but not on scale. There might be speakers in the cinema which aren't shown on the drawings, those speakers were not used during testing. Figure B.2.2 shows the section of the cinema in which the height profile can be seen as well as the heights of the surround speakers. Figure B.2.3 is a picture of the HATS in the cinema, Figures B.2.4 and B.2.5 give an overview of the cinema. Table B.2.1 shows the specifications of the cinema as measured during the visit, Table B.2.2 describes the materialization of the cinema. Reverberation time measurements were performed according to ISO 3382-1. Source and receiver positions are shown in the floor plan. T_{30} is presented in full octaves as minimum, maximum, and mean value (Graph B.2.1). In the same way the background noise on these positions is presented (Graph B.2.2). Table B.2.3 shows the temperature and humidity conditions during the measurements.

For this cinema, no results of the phase and delay test are available due to technical limitations.

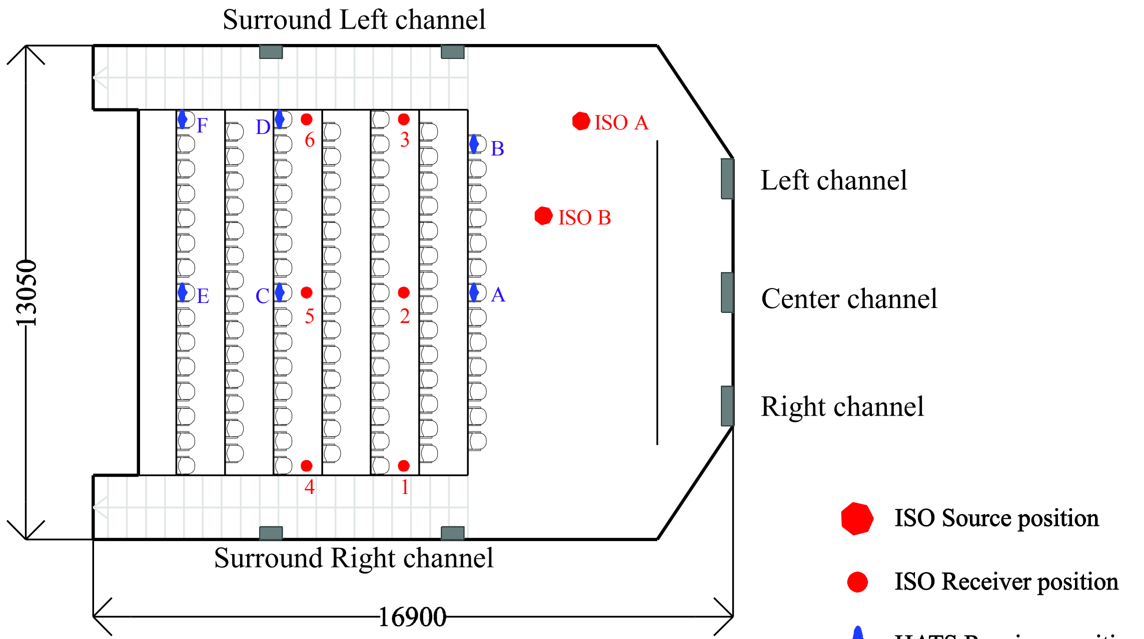


Figure B.2.1 *Floor plan (dimensions in mm)*

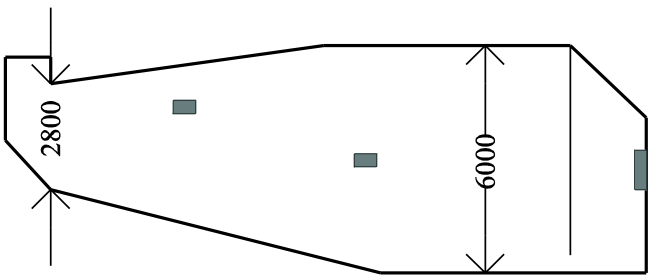


Figure B.2.2 *Section (dimensions in mm)*

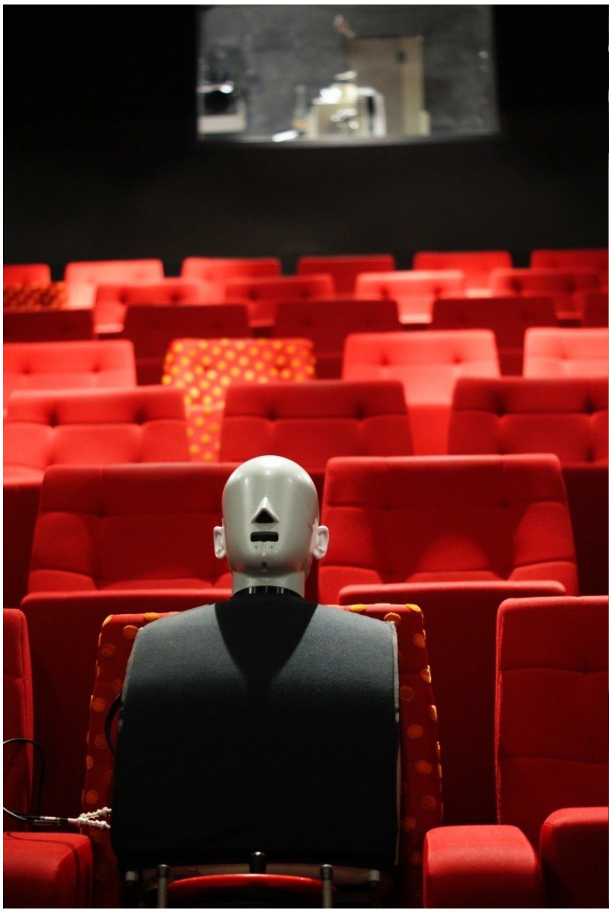


Figure B.2.3 *HATS at position A*

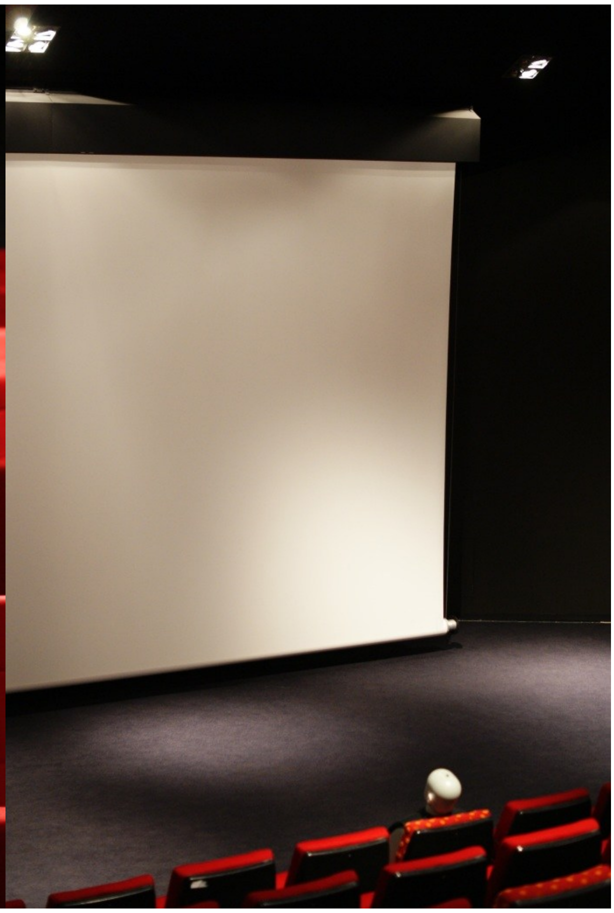


Figure B.2.4 *Overview of cinema 2*

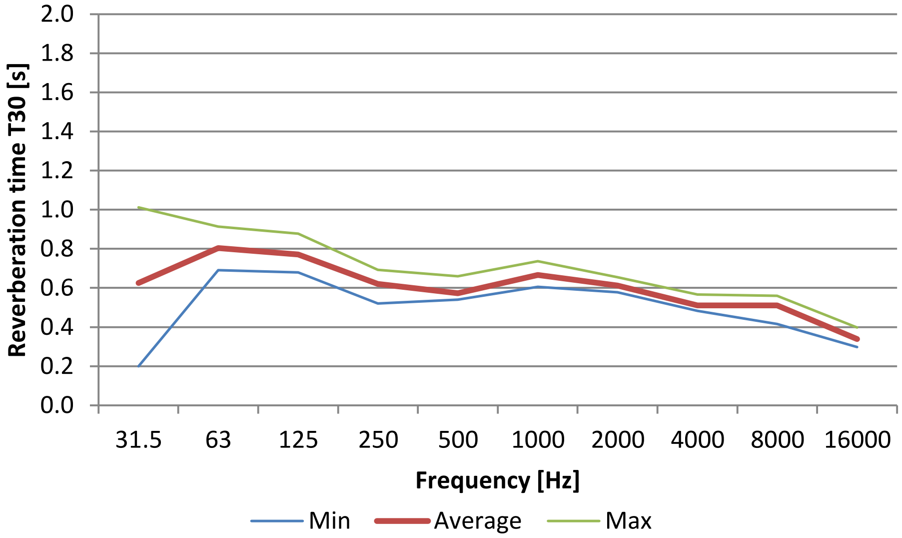
Figure B.2.5 *Overview of cinema 2*

Table B.2.1 *Cinema specifications*

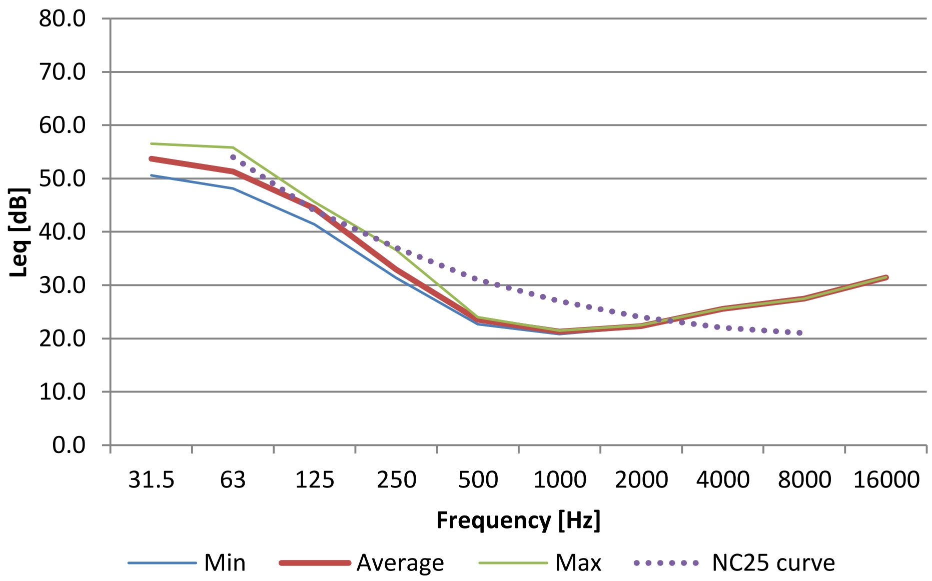
Seats	100
Floor area	200 m²
Volume	1023 m³
Reverberation time (T_{30}, ISO 3382-1)	0.62 s
Background noise LAeq	34.6 dB(A)

Table B.2.2 *Materialization*

Floor	Hard floor, thin carpet
Walls	Wood
Ceiling	Perforated gypsum board
Seats	Folding seats, soft clothing all around
Specific acoustical aids	Non flat ceiling
Projection screen	Acoustical transparent



Graph B.2.1 *Minimum, average and maximum T_{30} for 12 positions in full octaves*



Graph B.2.2 *Minimum, average and maximum background noise for 6 positions in full octaves*

Table B.2.3 *Temperature and relative humidity during measurements*

T_1	20.8 °C	RH_1	46.4 %
T_2	20.0 °C	RH_2	42.7 %
T_3	19.5 °C	RH_3	42.4 %

Appendix B.3. Cinema 3

In this appendix cinema 3 is described in more detail. The floor plan is shown in Figure B.3.1 to indicate source and receiver positions of both the ISO measurements as well as the reproduction measurements with the HATS. The seats on the plan are an indication of the real seating plan. Speaker locations are shown, but not on scale. There might be speakers in the cinema which aren't shown on the drawings, those speakers were not used during testing. Figure B.3.2 shows the section of the cinema in which the height profile can be seen as well as the heights of the surround speakers. Figure B.3.3 is a picture of the HATS in the cinema, Figures B.3.4 and B.3.5 give an overview of the cinema. Table B.3.1 shows the specifications of the cinema as measured during the visit, Table B.3.2 describes the materialization of the cinema. Reverberation time measurements were performed according to ISO 3382-1. Source and receiver positions are shown in the floor plan. T_{30} is presented in full octaves as minimum, maximum, and mean value (Graph B.3.1). In the same way the background noise on these positions is presented in Graph B.3.2 in relation to the Noise Criterion 25 curve. Table B.3.3 shows the temperature and humidity conditions during the measurements.
The phase and delay tests are described in Appendix C. The stationary microphone is placed within 1 meter of the center of the front left speaker, this distance incorporates an error of -0/+3 ms on the delay tests. Results of these tests are shown in Table B.3.4.

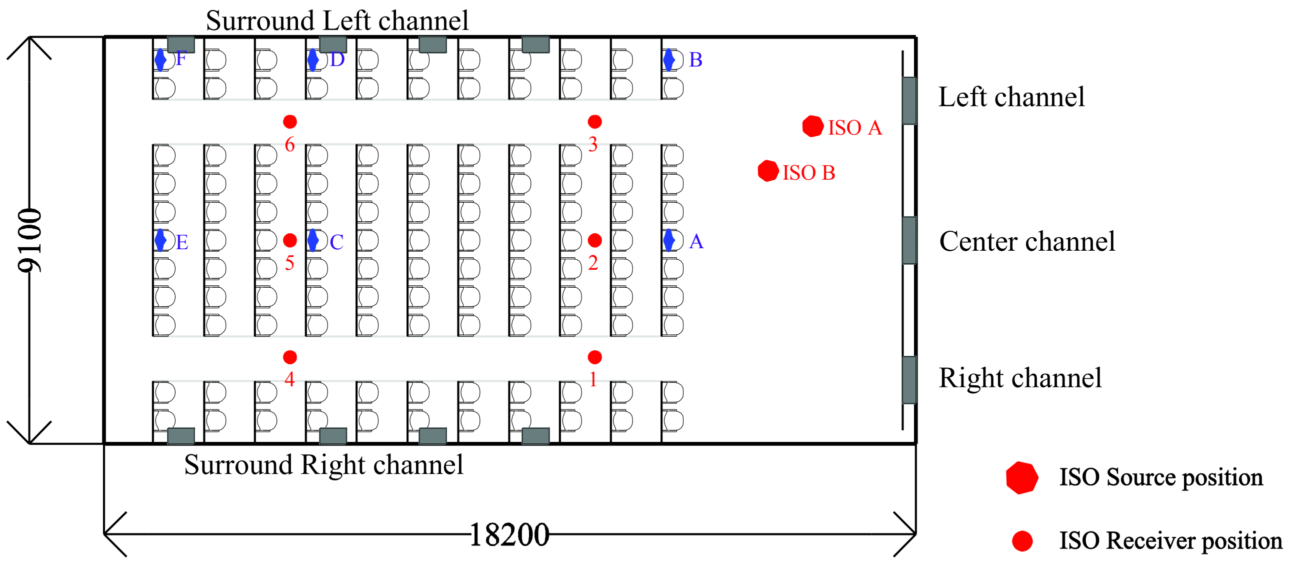


Figure B.3.1 *Floor plan (dimensions in mm)*

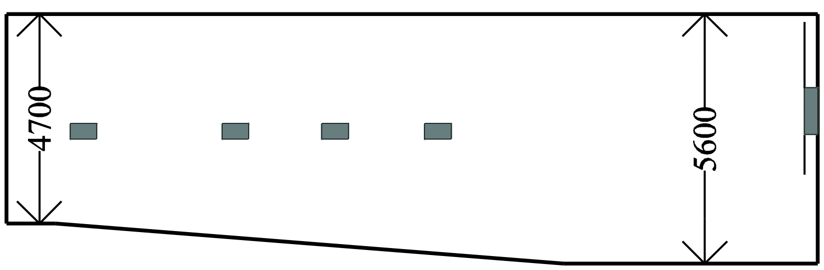


Figure B.3.2 *Section (dimensions in mm)*

Figure B.3.3 *HATS at position A*

Figure B.3.4 *Overview of cinema 3*

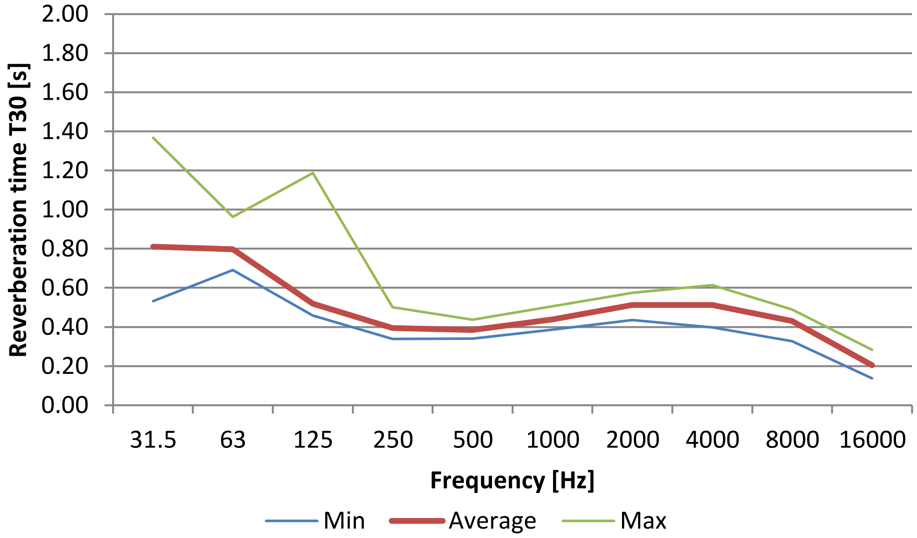
Figure B.3.5 *Overview of cinema 3*

Table B.3.1 *Cinema specifications*

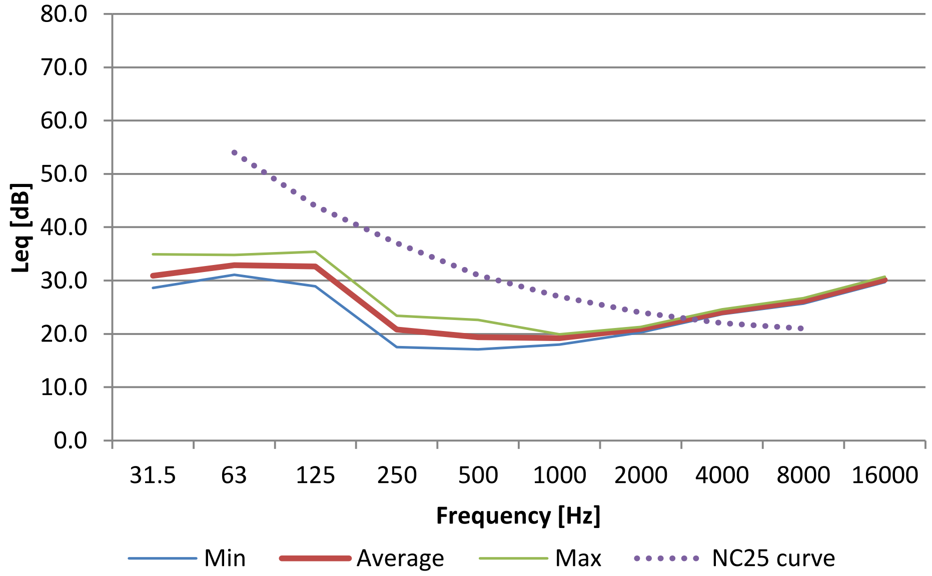
Seats	120
Floor area	166 m²
Volume	872 m³
Reverberation time (T_{30}, ISO 3382-1)	0.41 s
Background noise LAeq	30.7 dB(A)

Table B.3.2 *Materialization*

Floor	Hard floor, thick carpet
Walls	Side walls: 25% Thick carpet 25% Mass-spring-mass construction 50% Absorbing isles Back wall: Perforated absorbing wall Front wall: Sound absorbing baffle
Ceiling	Absorbing modular ceiling
Seats	Folding seats, soft clothing all around
Specific acoustical aids	None
Projection screen	Acoustical transparent



Graph B.3.1 *Minimum, average and maximum* T_{30} *for 12 positions in full octaves*



Graph B.3.2 *Minimum, average and maximum background noise for 6 positions in full octaves*

Table B.3.3 *Temperature and relative humidity during measurements*

T_1	19.3 °C	RH_1	43.4 %
T_2	20.2 °C	RH_2	41.9 %
T_3	20.3 °C	RH_3	41.9 %

Table B.3.4 *Speaker configuration*

	Delay relative to left channel	In phase relative to left channel
C		Yes
R		Yes
SL1/SR1	20 ms	Yes
SL2/SR2	20 ms	Yes
SL3/SR3	20 ms	Yes
SL4/SR4	20 ms	Yes

SL1 = SurroundLeft, 1st speaker on the left side, looking to the screen. Starting from the screen to the back.
SR1 = SurroundRight. 1st speaker on the right side, looking to the screen. Starting from the screen to the back.

Appendix B.4. Cinema 4

In this appendix cinema 4 is described in more detail. The floor plan is shown in Figure B.4.1 to indicate source and receiver positions of both the ISO measurements as well as the reproduction measurements with the HATS. The seats on the plan are an indication of the real seating plan. Speaker locations are shown, but not on scale. There might be speakers in the cinema which aren't shown on the drawings, those speakers were not used during testing. Figure B.4.2 shows the section of the cinema in which the height profile can be seen as well as the heights of the surround speakers. Figure B.4.3 is a picture of the HATS in the cinema, Figures B.4.4 and B.4.5 give an overview of the cinema. Table B.4.1 shows the specifications of the cinema as measured during the visit, Table B.4.2 describes the materialization of the cinema. Reverberation time measurements were performed according to ISO 3382-1. Source and receiver positions are shown in the floor plan. T_{30} is presented in full octaves as minimum, maximum, and mean value (Graph B.4.1). In the same way the background noise on these positions is presented in Graph B.4.2 in relation to the Noise Criterion 25 curve. Table B.4.3 shows the temperature and humidity conditions during the measurements.
The phase and delay tests are described in Appendix C. The stationary microphone is placed within 1 meter of the center of the front left speaker, this distance incorporates an error of -0/+3 ms on the delay tests. Results of these tests are shown in Table B.4.4.

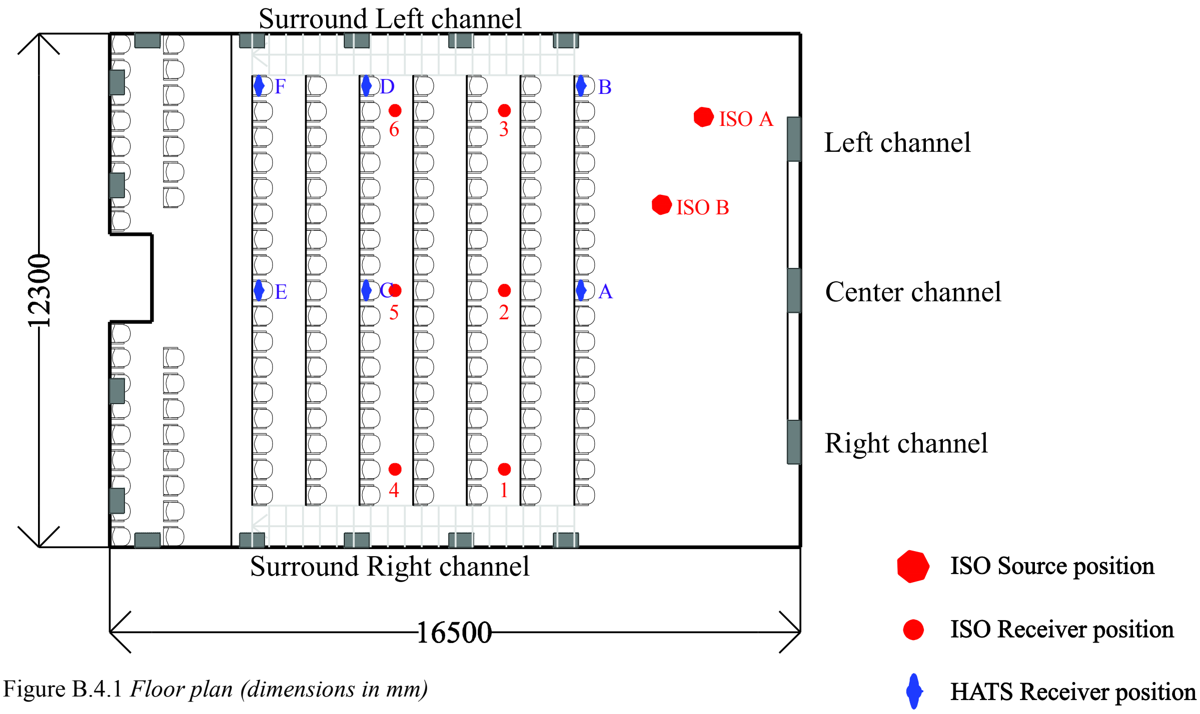


Figure B.4.1 *Floor plan (dimensions in mm)*

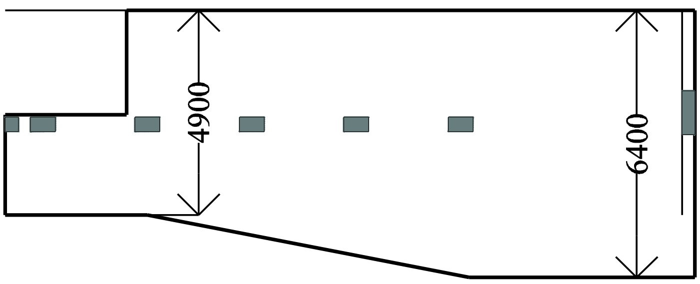


Figure B.4.2 *Section (dimensions in mm)*

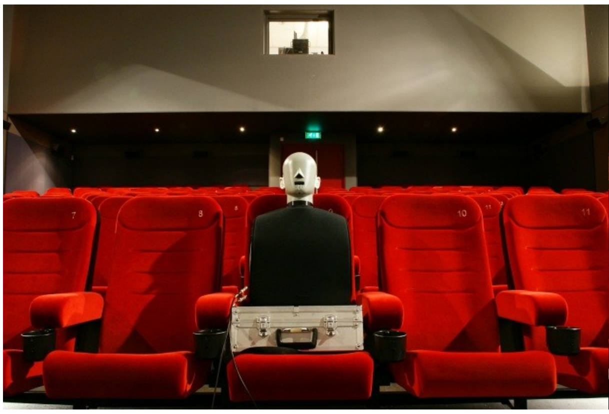


Figure B.4.3 *HATS at position A*

Figure B.4.4 *Overview of cinema 4*

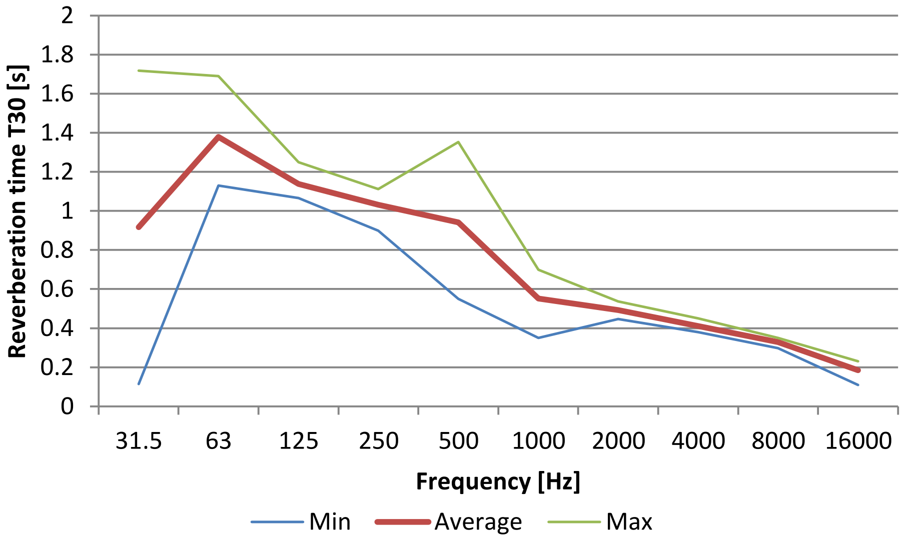
Figure B.4.5 *Overview of cinema 4*

Table B.4.1 *Cinema specifications*

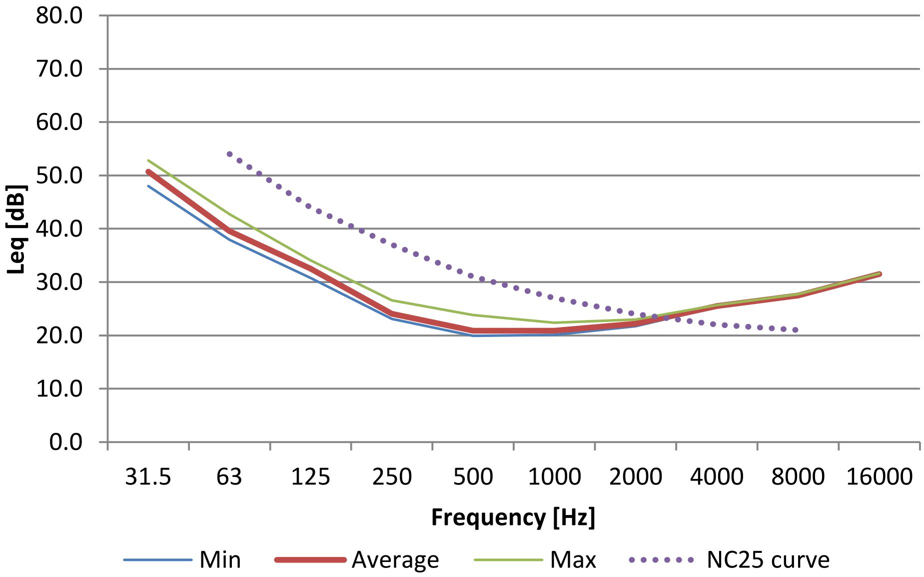
Seats	150
Floor area	200 m^2
Volume	1076 m^3
Reverberation time (T_{30}, ISO 3382-1)	0.75 s
Background noise LAeq	32.2 dB(A)

Table B.4.2 *Materialization*

Floor	Hard floor, thin carpet
Walls	Mass-spring-mass system
Ceiling	Unknown ceiling
Seats	Fixed seats, soft clothing all around
Specific acoustical aids	None
Projection screen	Acoustical transparent



Graph B.4.1 *Minimum, average and maximum T_{30} for 12 positions in full octaves*



Graph B.4.2 *Minimum, average and maximum background noise for 6 positions in full octaves*

Table B.4.3 *Temperature and relative humidity during measurements*

T_1	22.2 °C	RH_1	27.9 %
T_2	19.8 °C	RH_2	31.1 %
T_3	21.1 °C	RH_3	28.9 %

Table B.4.4 *Speaker configuration*

	Delay relative to left channel	In phase relative to left channel
C		Yes
R		Yes
SL1/SR1	18 ms	Yes
SL2/SR2	18 ms	Yes
SL3/SR3	18 ms	Yes
SL4/SR4	18 ms	Yes
SL5/SR5	18 ms	Yes
SL6/SR6	18 ms	Yes
SL7/SR7	18 ms	Yes

SL1 = SurroundLeft, 1st speaker on the left side, looking to the screen. Starting from the screen to the back.
SR1 = SurroundRight. 1st speaker on the right side, looking to the screen. Starting from the screen to the back.

Appendix B.5. Cinema 5

In this appendix cinema 5 is described in more detail. The floor plan is shown in Figure B.5.1 to indicate source and receiver positions of both the ISO measurements as well as the reproduction measurements with the HATS. The seats on the plan are an indication of the real seating plan. Speaker locations are shown, but not on scale. There might be speakers in the cinema which aren't shown on the drawings, those speakers were not used during testing. Figure B.5.2 shows the section of the cinema in which the height profile can be seen as well as the heights of the surround speakers. Figure B.5.3 is a picture of the HATS in the cinema, Figures B.5.4 and B.5.5 give an overview of the cinema. Table B.5.1 shows the specifications of the cinema as measured during the visit, Table B.5.2 describes the materialization of the cinema. Reverberation time measurements were performed according to ISO 3382-1. Source and receiver positions are shown in the floor plan. T_{30} is presented in full octaves as minimum, maximum, and mean value (Graph B.5.1). In the same way the background noise on these positions is presented in Graph B.5.2 in relation to the Noise Criterion 25 curve. Table B.5.3 shows the temperature and humidity conditions during the measurements.
The phase and delay tests are described in Appendix C. The stationary microphone is placed within 1 meter of the center of the front left speaker, this distance incorporates an error of -0/+3 ms on the delay tests. Results of these tests are shown in Table B.5.4.

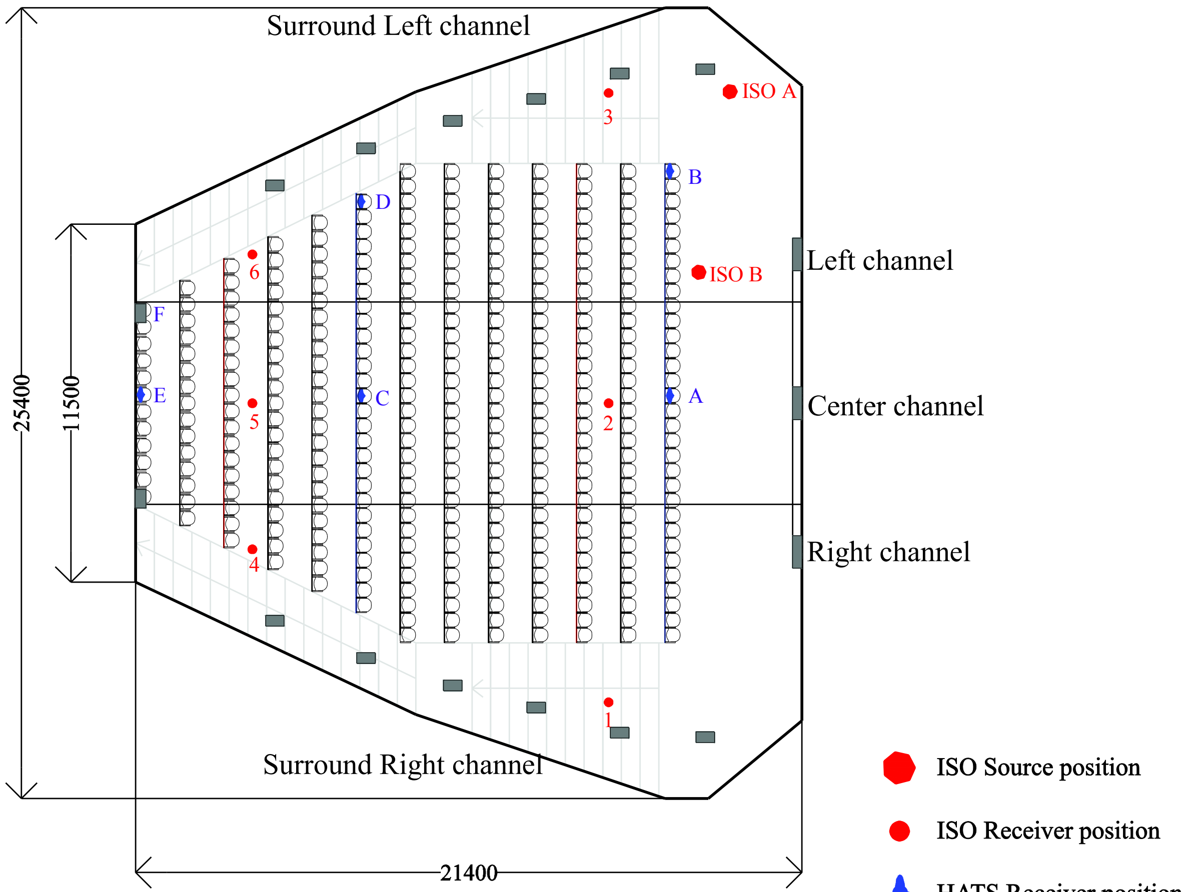


Figure B.5.1 *Floor plan (dimensions in mm)*

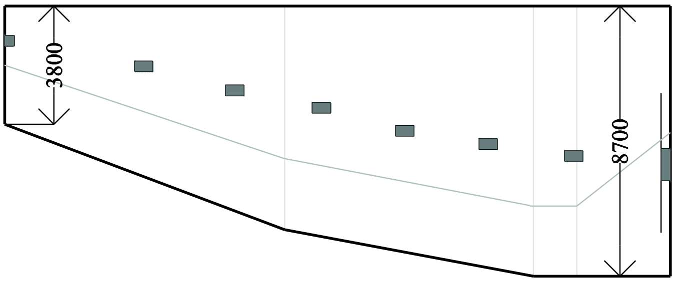


Figure B.5.2 *Section (dimensions in mm)*

Figure B.5.3 *HATS at position A*

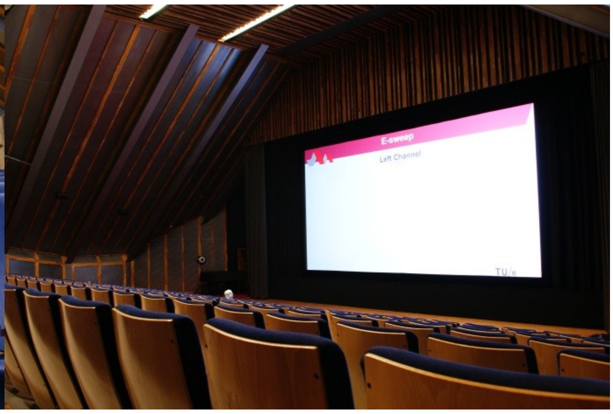


Figure B.5.4 *Overview of cinema 5*

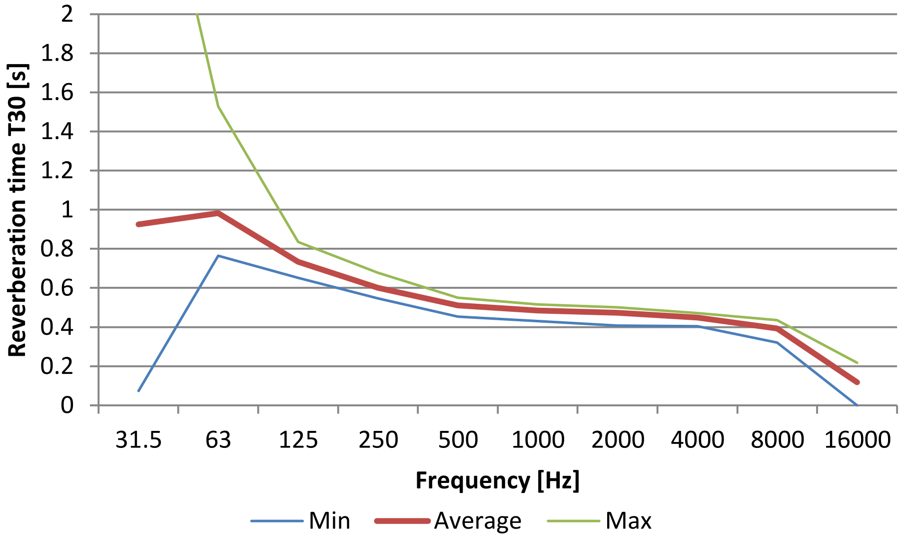
Figure B.5.5 *Overview of cinema 5*

Table B.5.1 *Cinema specifications*

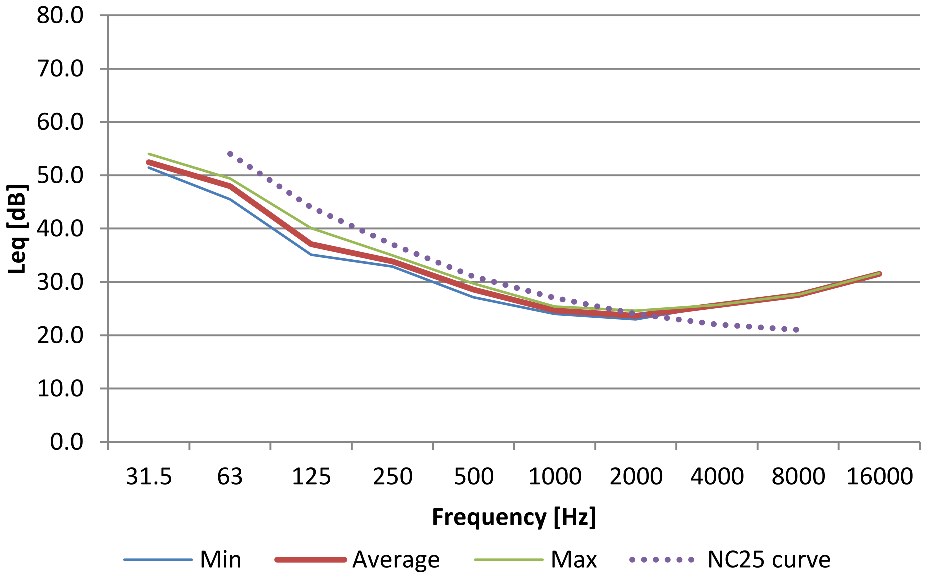
Seats	350
Floor area	428 m²
Volume	2568 m³
Reverberation time (T_{30}, ISO 3382-1)	0.50 s
Background noise LAeq	34.2 dB(A)

Table B.5.2 *Materialization*

Floor	Hard floor, thin carpet
Walls	Steel grid with absorption
Ceiling	Diffusive laths and absorption
Seats	Fixed seats, soft clothing all around
Specific acoustical aids	None
Projection screen	Acoustical transparent



Graph B.5.1 *Minimum, average and maximum T_{30} for 12 positions in full octaves*



Graph B.5.2 *Minimum, average and maximum background noise for 6 positions in full octaves*

Table B.5.3 *Temperature and relative humidity during measurements*

T_1	19.4 °C	RH_1	44.2 %
T_2	19.7 °C	RH_2	43.2 %
T_3	19.6 °C	RH_3	43.9 %

Table B.5.4 *Speaker configuration*

	Delay relative to left channel	In phase relative to left channel
C		Yes
R		Yes
SL1/SR1	14 ms	Yes
SL2/SR2	14 ms	Yes
SL3/SR3	14 ms	Yes
SL4/SR4	14 ms	Yes
SL5/SR5	14 ms	Yes
SL6/SR6	14 ms	Yes
SL7/SR7	14 ms	Yes

SL1 = SurroundLeft, 1st speaker on the left side, looking to the screen. Starting from the screen to the back.
SR1 = SurroundRight. 1st speaker on the right side, looking to the screen. Starting from the screen to the back.

Appendix B.6. Cinema 6

In this appendix cinema 6 is described in more detail. The floor plan is shown in Figure B.6.1 to indicate source and receiver positions of both the ISO measurements as well as the reproduction measurements with the HATS. The seats on the plan are an indication of the real seating plan. Speaker locations are shown, but not on scale. There might be speakers in the cinema which aren't shown on the drawings, those speakers were not used during testing. Figure B.6.2 shows the section of the cinema in which the height profile can be seen as well as the heights of the surround speakers. Figure B.6.3 is a picture of the HATS in the cinema, Figures B.6.4 and B.6.5 give an overview of the cinema. Table B.6.1 shows the specifications of the cinema as measured during the visit, Table B.6.2 describes the materialization of the cinema. Reverberation time measurements were performed according to ISO 3382-1. Source and receiver positions are shown in the floor plan. T_{30} is presented in full octaves as minimum, maximum, and mean value (Graph B.6.1). In the same way the background noise on these positions is presented in Graph B.6.2 in relation to the Noise Criterion 25 curve. Table B.6.3 shows the temperature and humidity conditions during the measurements.

The phase and delay tests are described in Appendix C. The stationary microphone is placed within 1 meter of the center of the front left speaker, this distance incorporates an error of -0/+3 ms on the delay tests. Results of these tests are shown in Table B.6.4.

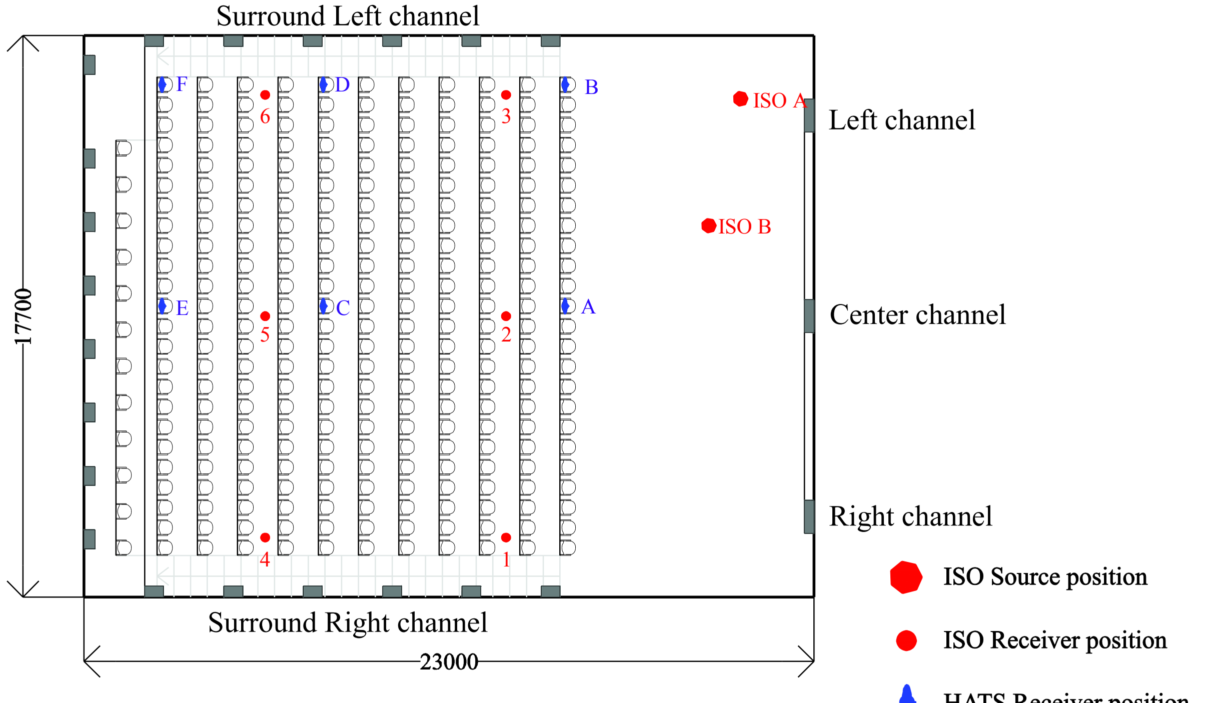


Figure B.6.1 *Floor plan (dimensions in mm)*

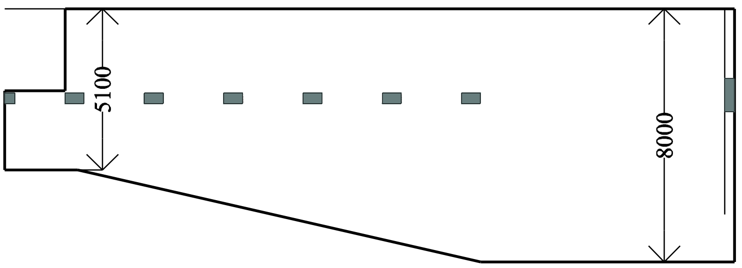


Figure B.6.2 *Section (dimensions in mm)*

Figure B.6.3 *HATS at position A*

Figure B.6.4 *Overview of cinema 6*

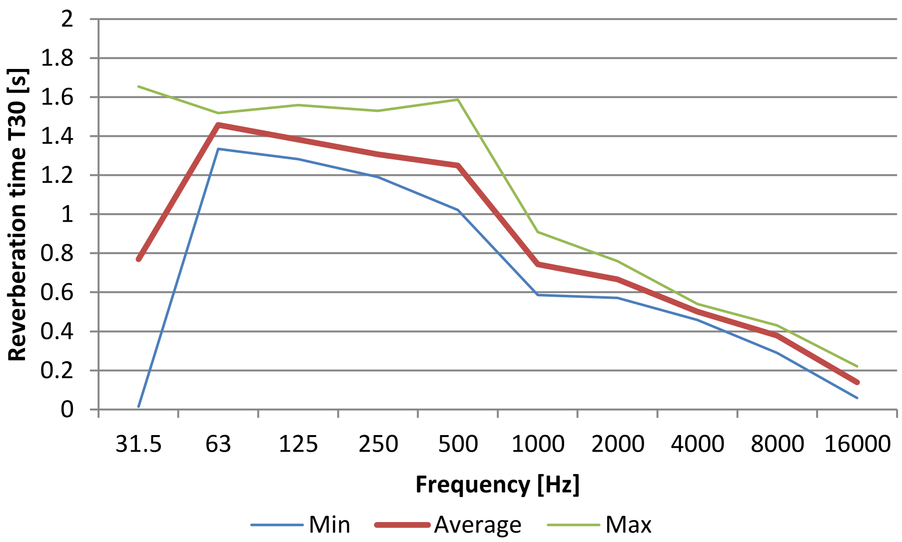
Figure B.6.5 *Overview of cinema 6*

Table B.6.1 *Cinema specifications*

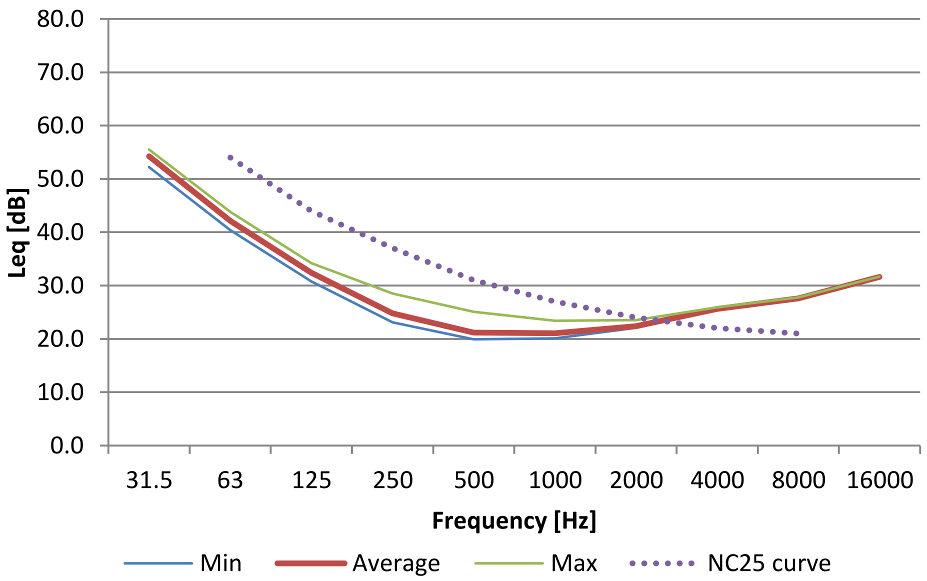
Seats	280
Floor area	280 m²
Volume	2724 m³
Reverberation time (T_{30}, ISO 3382-1)	1.00 s
Background noise LAeq	32.4 dB(A)

Table B.6.2 *Materialization*

Floor	Hard floor, thin carpet
Walls	Mass-spring-mass system
Ceiling	Unknown ceiling
Seats	Fixed seats, soft clothing all around
Specific acoustical aids	None
Projection screen	Acoustical transparent



Graph B.6.1 *Minimum, average and maximum* T_{30} *for 12 positions in full octaves*



Graph B.6.2 *Minimum, average and maximum background noise for 6 positions in full octaves*

Table B.6.3 *Temperature and relative humidity during measurements*

T_1	21.2 °C	RH_1	31.8 %
T_2	21.9 °C	RH_2	28.9 %

Table B.6.4 *Speaker configuration*

	Delay relative to left channel	In phase relative to left channel
C		Yes
R		Yes
SL1/SR1	18 ms	Yes
SL2/SR2	18 ms	Yes
SL3/SR3	18 ms	Yes
SL4/SR4	18 ms	Yes
SL5/SR5	18 ms	SL: No / SR: Yes
SL6/SR6	18 ms	Yes
SL7/SR7	18 ms	Yes
SL8/SR8	18 ms	Yes
SL9/SR9	18 ms	Yes
SL10/SR10	18 ms	Yes

SL1 = SurroundLeft, 1st speaker on the left side, looking to the screen. Starting from the screen to the back.
SR1 = SurroundRight. 1st speaker on the right side, looking to the screen. Starting from the screen to the back.

Appendix B.7. Cinema 7

In this appendix cinema 7 is described in more detail. The floor plan is shown in Figure B.7.1 to indicate source and receiver positions of both the ISO measurements as well as the reproduction measurements with the HATS. The seats on the plan are an indication of the real seating plan. Speaker locations are shown, but not on scale. There might be speakers in the cinema which aren't shown on the drawings, those speakers were not used during testing. Figure B.7.2 shows the section of the cinema in which the height profile can be seen as well as the heights of the surround speakers. Figure B.7.3 is a picture of the HATS in the cinema, Figures B.7.4 and B.7.5 give an overview of the cinema. Table B.7.1 shows the specifications of the cinema as measured during the visit, Table B.7.2 describes the materialization of the cinema. Reverberation time measurements were performed according to ISO 3382-1. Source and receiver positions are shown in the floor plan. T_{30} is presented in full octaves as minimum, maximum, and mean value (Graph B.7.1). In the same way the background noise on these positions is presented in Graph B.7.2 in relation to the Noise Criterion 25 curve. Table B.7.3 shows the temperature and humidity conditions during the measurements.
The phase and delay tests are described in Appendix C. The stationary microphone is placed within 1 meter of the center of the front left speaker, this distance incorporates an error of -0/+3 ms on the delay tests. Results of these tests are shown in Table B.7.4.

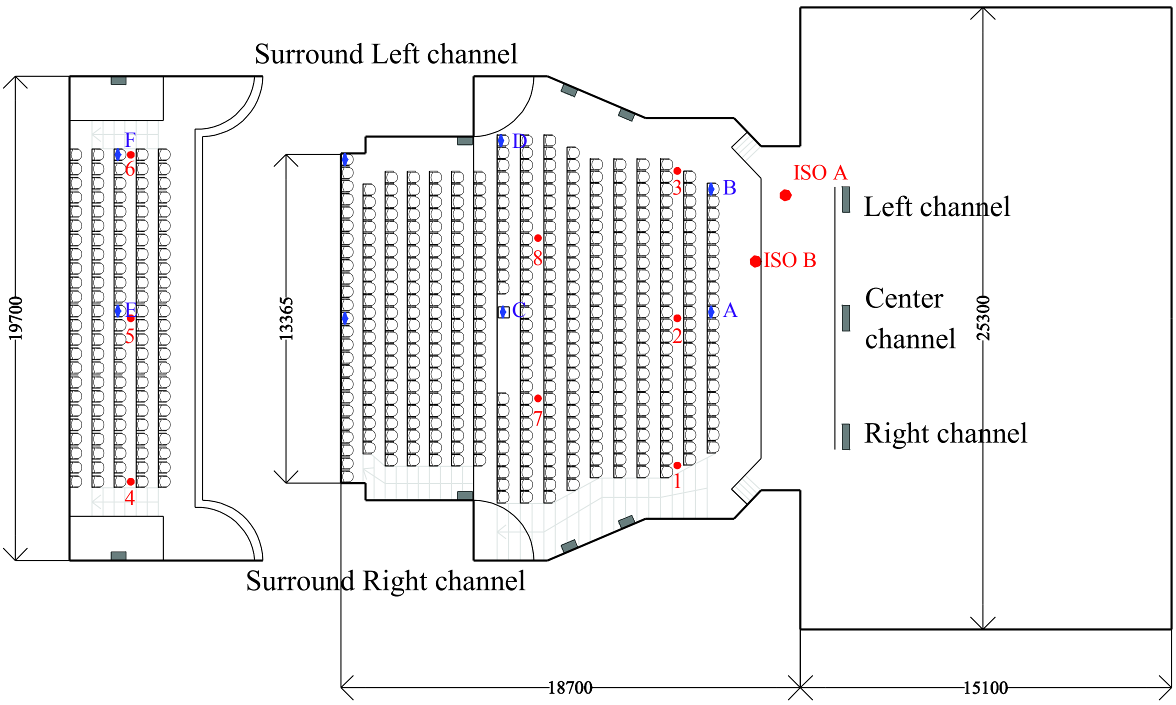
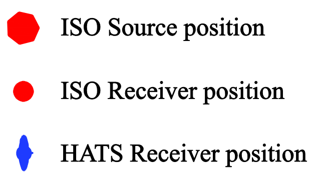


Figure B.7.1 *Floor plan (dimensions in mm)*



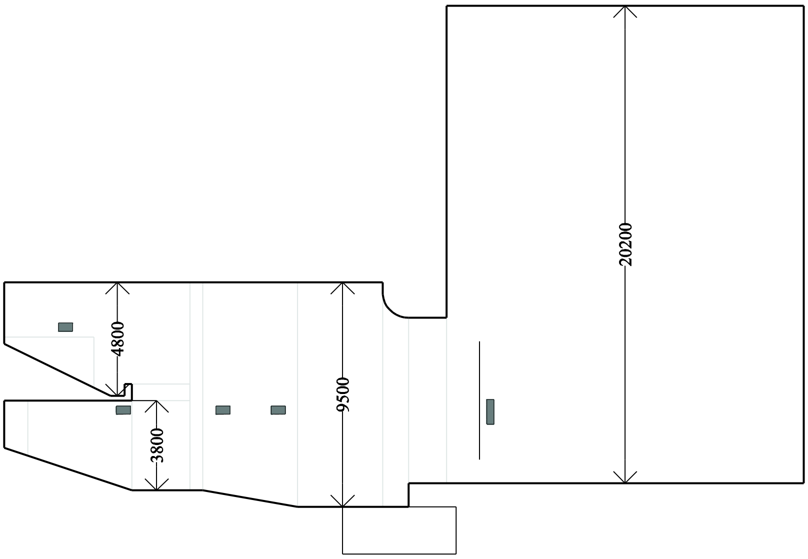


Figure B.7.2 *Section (dimensions in mm)*

Figure B.7.3 *HATS at position A*

Figure B.7.4 *Overview of cinema 7*

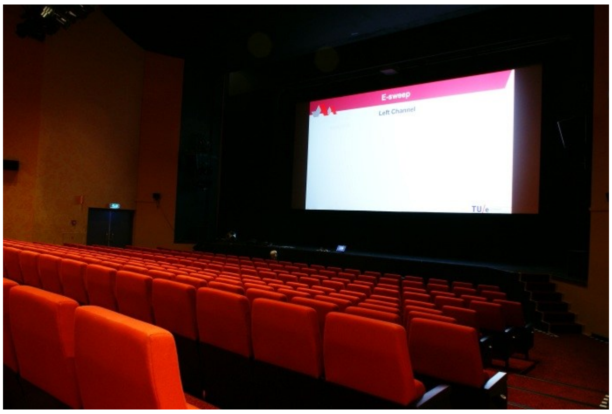


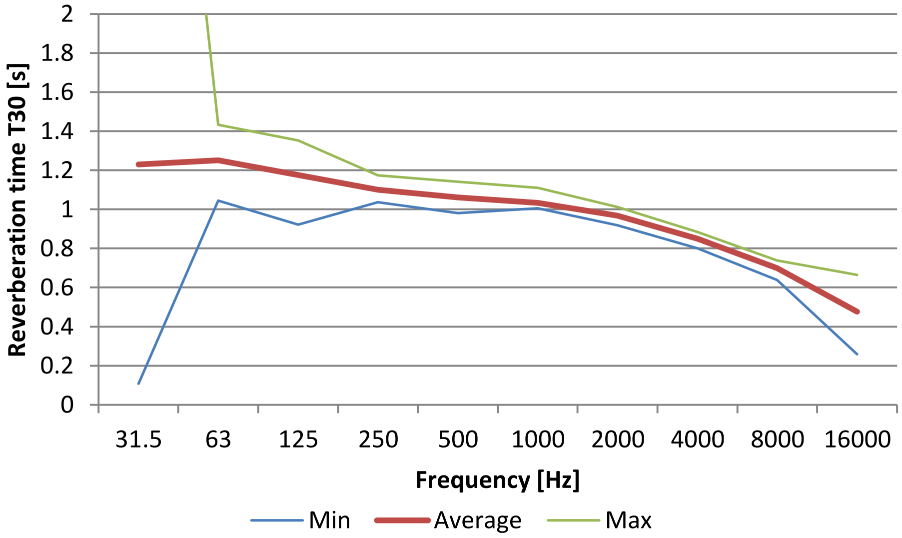
Figure B.7.5 *Overview of cinema 7*

Table B.7.1 *Cinema specifications*

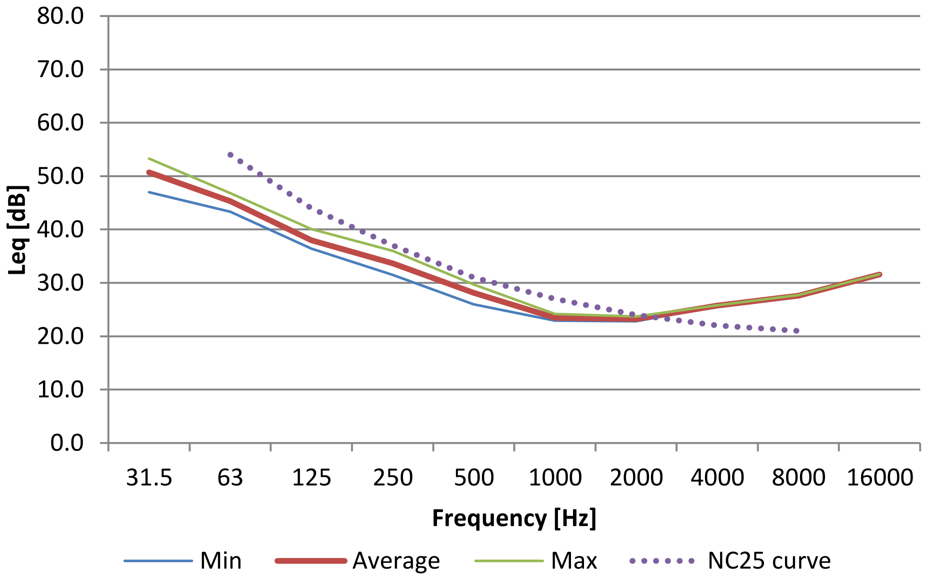
Seats	530
Floor area	435 m²
Volume	3828 m³ (11140 m³ incl. flytower)
Reverberation time (T_{30}, ISO 3382-1)	1.05 s
Background noise LAeq	34.0 dB(A)

Table B.7.2 *Materialization*

Floor	Hard floor, thin carpet
Walls	Baffled wall
Ceiling	Unknown
Seats	Folding seats, soft clothing all around
Specific acoustical aids	None
Projection screen	Acoustical transparent



Graph B.7.1 *Minimum, average and maximum T_{30} for 16 positions in full octaves*



Graph B.7.2 *Minimum, average and maximum background noise for 8 positions in full octaves*

Table B.7.3 *Temperature and relative humidity during measurements*

T_1	21.4 °C	RH_1	32.9 %
T_2	22.0 °C	RH_2	31.0 %

Table B.7.4 *Speaker configuration*

	Delay relative to **right** channel	In phase relative to **right** channel
L		No
C		Yes
SL1/SR1	14 ms	Yes
SL2/SR2	14 ms	Yes
SL3/SR3	14 ms	Yes
SL4/SR4	14 ms	Yes

SL1 = SurroundLeft, 1st speaker on the left side, looking to the screen. Starting from the screen to the back.
SR1 = SurroundRight. 1st speaker on the right side, looking to the screen. Starting from the screen to the back.

Appendix B.8. Cinema 8

In this appendix cinema 8 is described in more detail. The floor plan is shown in Figure B.8.1 to indicate source and receiver positions of both the ISO measurements as well as the reproduction measurements with the HATS. The seats on the plan are an indication of the real seating plan. Speaker locations are shown, but not on scale. There might be speakers in the cinema which aren't shown on the drawings, those speakers were not used during testing. Figure B.8.2 shows the section of the cinema in which the height profile can be seen as well as the heights of the surround speakers. Figure B.8.3 is a picture of the HATS in the cinema, Figures B.8.4 and B.8.5 give an overview of the cinema. Table B.8.1 shows the specifications of the cinema as measured during the visit, Table B.8.2 describes the materialization of the cinema. Reverberation time measurements were performed according to ISO 3382-1. Source and receiver positions are shown in the floor plan. T_{30} is presented in full octaves as minimum, maximum, and mean value (Graph B.8.1In the same way the background noise on these positions is presented in Graph B.8.2 in relation to the Noise Criterion 25 curve. Table B.8.3 shows the temperature and humidity conditions during the measurements.
For cinema 8 it was not possible to perform phase and delay tests. Table B.8.4. shows the delay *settings* of the cinema audio processor.

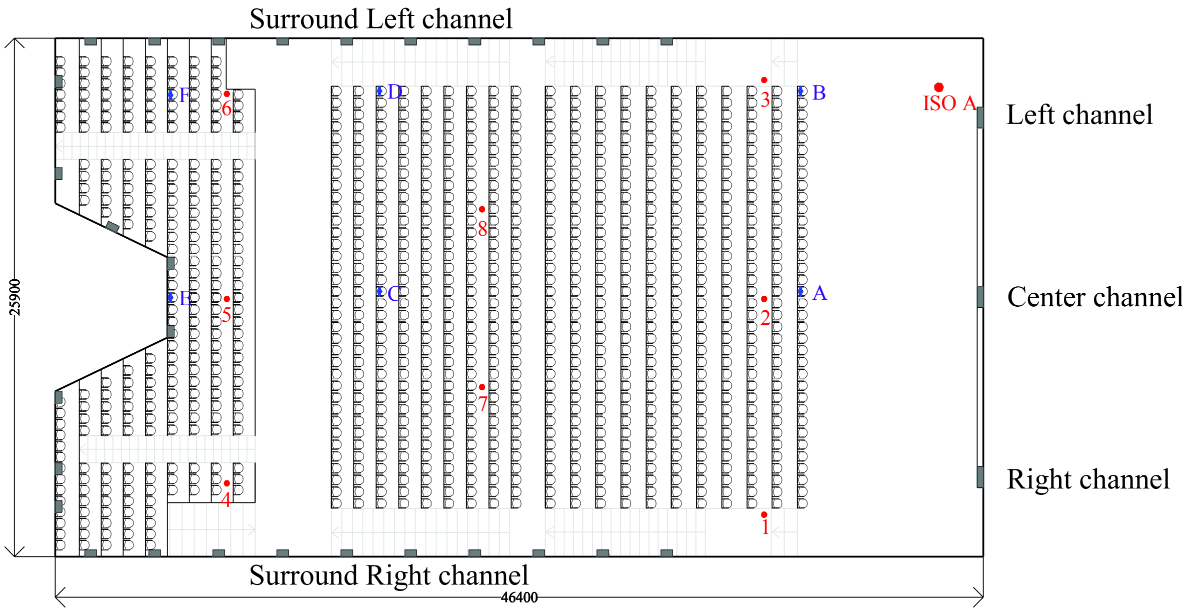


Figure B.8.1 *Floor plan (dimensions in mm)*

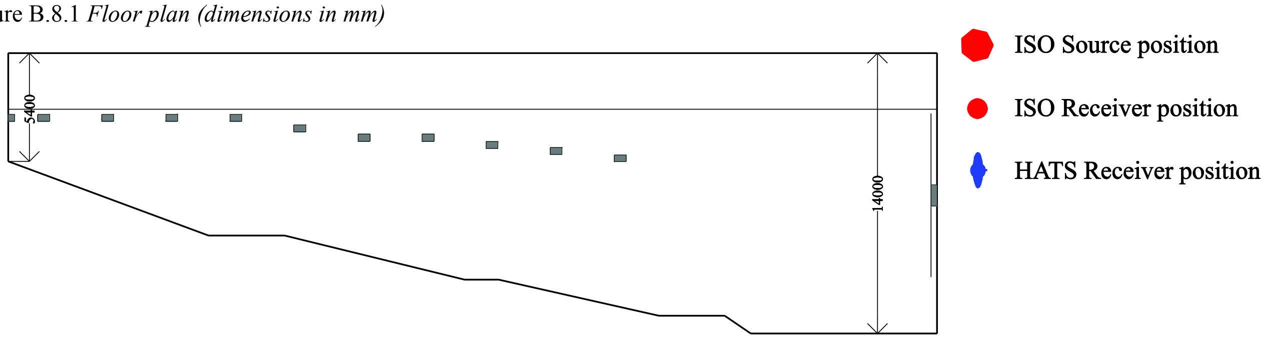


Figure B.8.2 *Section (dimensions in mm)*

Figure B.8.3 *HATS at position A*

Figure B.8.4 *Overview of cinema 8*

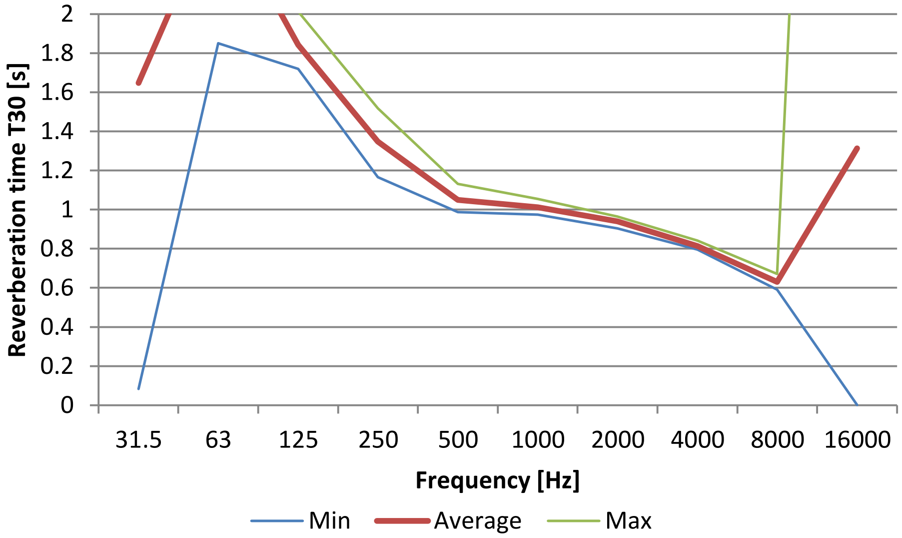
Figure B.8.5 *Overview of cinema 8*

Table B.8.1 *Cinema specifications*

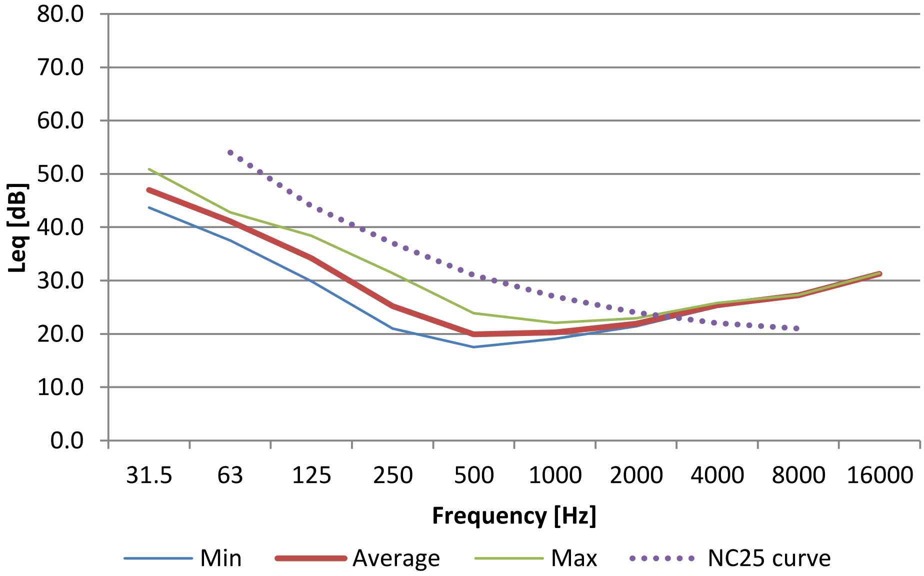
Seats	1000
Floor area	1165 m^2
Volume	12896 m^3
Reverberation time (T_{30}, ISO 3382-1)	1.03 s
Background noise LAeq	32.0 dB(A)

Table B.8.2 *Materialization*

Floor	Hard floor, carpet
Walls	Soft cloth on panel
Ceiling	Visual ceiling: open grid. Real ceiling: Unknown
Seats	Fixed seats, soft clothing, except for the backside
Specific acoustical aids	None
Projection screen	Acoustical transparent



Graph B.8.1 *Minimum, average and maximum T_{30} for 8 positions in full octaves*



Graph B.8.2 *Minimum, average and maximum background noise for 8 positions in full octaves*

Table B.8.3 *Temperature and relative humidity during measurements*

T_1	18.2 °C	RH_1	38.0 %
T_2	18.5 °C	RH_2	37.5 %

Table B.8.4 *Speaker configuration*

	Delay relative to left channel	In phase relative to left channel
C		
R		
SL1,2,3/SR1,2,3	13 ms	
SL4,5,6/SR4,5,6	32 ms	
SL7,8,9,10/SR7,8,9,10	51 ms	

SL1 = SurroundLeft, 1st speaker on the left side, looking to the screen. Starting from the screen to the back.
SR1 = SurroundRight. 1st speaker on the right side, looking to the screen. Starting from the screen to the back.

Appendix B.9. Studio 1

In this appendix studio 1 is described in more detail. The floor plan is shown in Figure B.9.1 to indicate receiver positions of the reproduction measurements with the HATS. The seats on the plan are an indication of the real seating plan. Speaker locations are shown, but not on scale. There might be speakers in the cinema which aren't shown on the drawings, those speakers were not used during testing. Figure B.9.2 shows the section of the studio in which the height profile can be seen as well as the heights of the surround speakers. Figure B.9.3 and B.9.4 are pictures of the HATS at the mixing desk. Figure B.9.5. gives an overview of the studio. Table B.9.1 shows the specifications of the studio as measured during the visit, Table B.9.2 describes the materialization of the cinema. Reverberation time measurements were performed according to ISO 3382-1. T_{30} is presented in full octaves in Graph B.9.1.

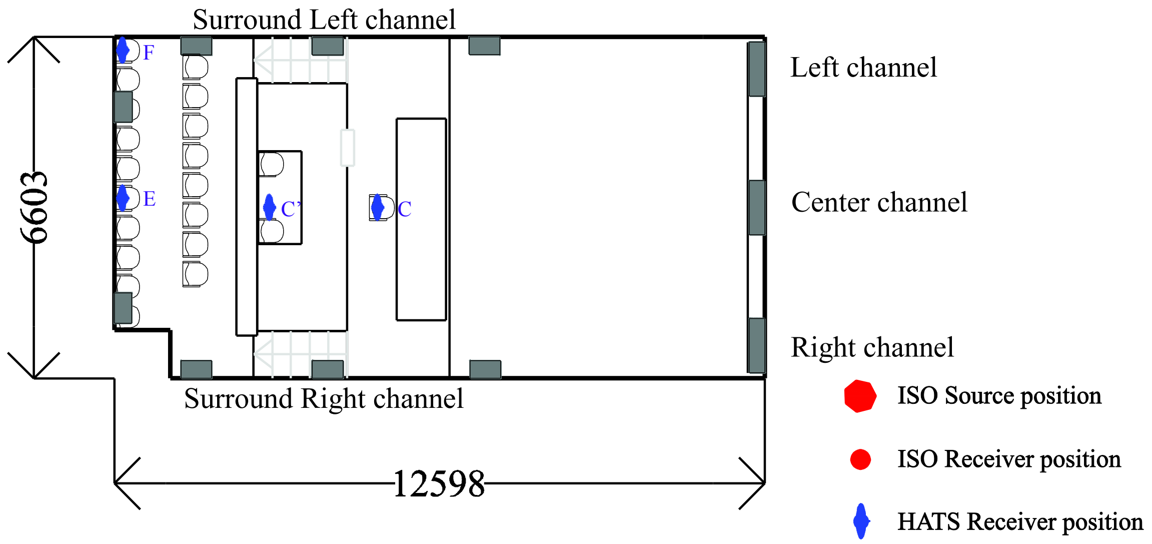


Figure B.9.1 *Floor plan (dimensions in mm)*

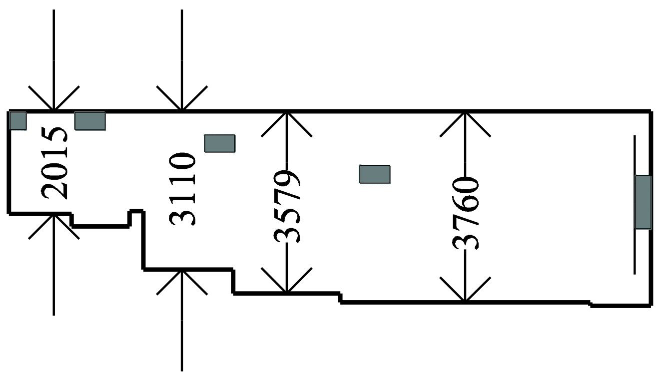


Figure B.9.2 Section *(dimensions in mm)*

Figure B.9.3 *HATS at position C*

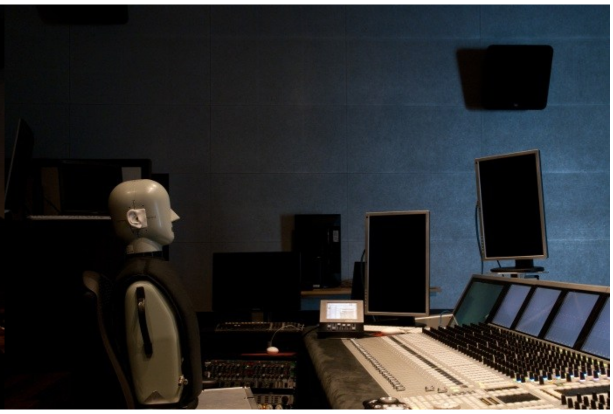


Figure B.9.4 *HATS at position C*

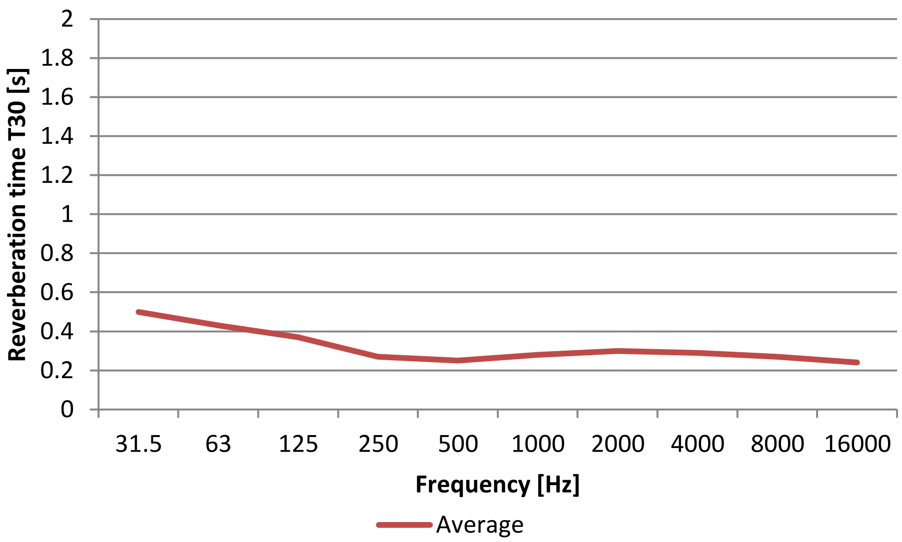
Figure B.9.5 *Overview of cinema 9*

Table B.9.1 *Studio specifications*

Seats	20
Floor area	82 m²
Volume	275 m³
Reverberation time (T_{30}, ISO 3382-1)	0.27 s
Background noise LAeq	- dB(A)

Table B.9.2 *Materialization*

Floor	Hard floor, thin carpet. Luxury wood finishings
Walls	Steel grid, absorption. Baffled wall behind screen
Ceiling	Absorbing modular ceiling with gaps
Seats	Folding seats, soft clothing all around. Sofa. Desk chairs.
Specific acoustical aids	None
Projection screen	Acoustical transparent



Graph B.9.1 *Reverberation time T_{30} according to literature*

Appendix C: Measurement plan

1. ISO 3382-1 reverberation and background noise

All standardized reverberation measurements are performed according to the following measurement procedure. This procedure is based on ISO 3382-1. Two source positions are chosen as well as at least six receiver positions spread over the audience area.

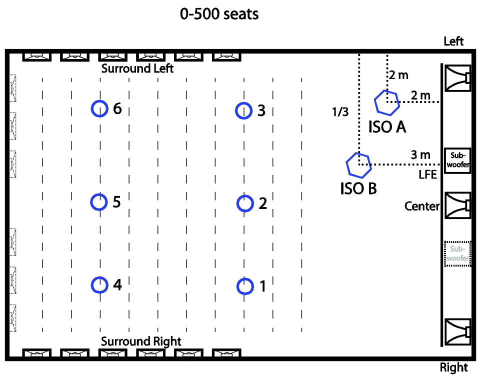


Figure C.1.1 Source and receiver positions 0-500 seats

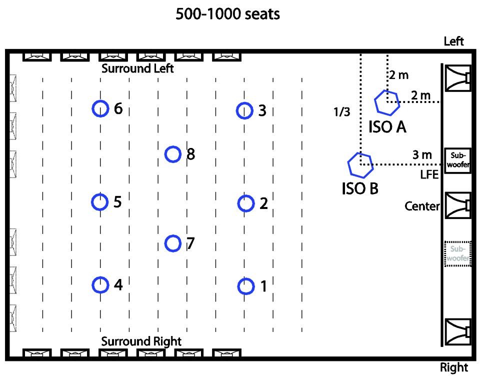


Figure C.1.2 Source and receiver positions 500-1000 seats

For cinemas with a seating capacity of up to 500 seats, the source and receiver points of figure C.1.1 are used, for the cinemas with a higher capacity two more points are added, as is visible in figure C.1.2. The sign with subscriptions ISO A and ISO B are the positions of the omnidirectional source. At position ISO A, the source is elevated to an height of 1.62 meter, at ISO B the source is elevated to an height of 1.81 meter. ISO B is placed at 1/3 of the width of the cinema.
The numbered circles are the receiver positions, the dashed lines represent seating rows. Positions 1-3 are placed in between the second and third row from the front and 4-6 are placed in between the third and fourth row from the back. The microphone is positioned upright at 1.10 m height. At both sides, the microphones should be placed at 2 meters distance from the wall. Positions 7 and 8 are positioned halfway the audience area and at a distance of 1/3 of the width of the cinema to the wall. For these measurements an e-sweep of 10.92s is used.
Exception to this method is cinema 8, in this cinema only one source position is measured. Due to a short of time it wasn't possible to do the same measurements at position C.

For all six or eight receiver positions also the background noise is recorded, using the same microphone. This microphone is calibrated at 1 kHz. For each position a recording of 10.92s is made.

Table C.1.1 shows the used measurement equipment for these measurements.

Table C.1.1 Equipment for ISO 3382-1 and background noise measurements

	Product name	**Serial number**
Netbook with Dirac 5 software	Dell Latitude 2110	
DAC/ADC	Acoustics Engineering Triton	03300354
Amplifier	Acoustics Engineering Amphion	0101
Omnidirectional source	Acoustics Engineering Pyrite	0203
Omnidirectional microphone	B&K Type 4230	2703329
Microphone power supply	Acoustics Engineering Delatron	
Microphone calibrator	B&K Type 4230	1441834

2. Reproduction measurements

2.1 Channel check

All measurements start with a channel check. A DCP file is played with on each channel subsequently 10s MLS sound (maximum length sequence) followed by 5s silence. The order in the DCP file is: L-C-R-SL-SR according to the SMPTE channel numbering. In the cinema, the same sequence should be audible to confirm the correct channel assignment.

2.2 Sound pressure level check

In each cinema, the equipment has to be set to a sound level which is high enough to obtain good INR values for the impulse responses of the measurements (45+ dB). For the synchronous tested cinemas, this can be directly analyzed with the measurement software. For the asynchronous tested cinemas, the steps of "Data processing" of section 2.3 has to be followed to obtain the impulse response.
The front left loudspeaker is used to set and check the sound pressure level of the cinema. The same procedures as described in 2.3 and 2.4 has to be followed.

2.3 Asynchronous Measurements

Source positions and combinations

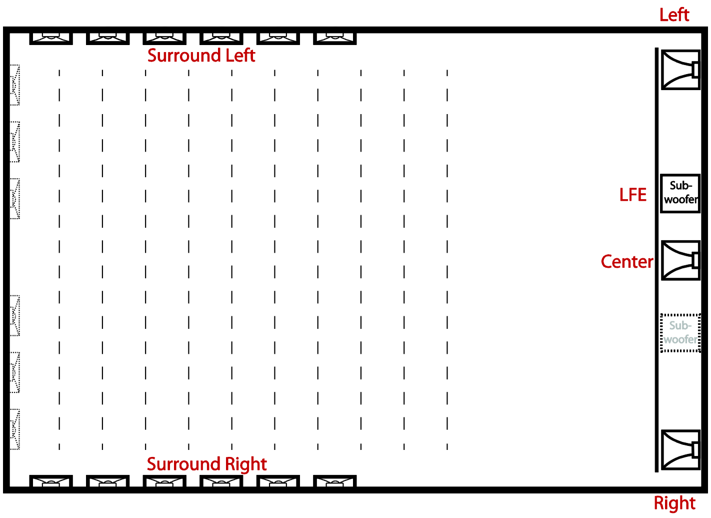


Figure C.2.1 *Cinema loudspeaker positions*

In Figure C.2.1, the different sound channels of a regular 5.1 equipped cinema are shown. Table D.2.1 shows the loudspeaker combinations used for the reproduction measurements.

Table C.2.1 *loudspeaker combinations*

Combination	Left	Right	Surround Left	Surround Right
Front	✓	✓		
Surround			✓	✓
Both	✓	✓	✓	✓

Table C.2.2 shows the content of the DCP file that is installed on the cinema server. Measurements are performed to indicate the crosstalk in the cinema and measurements are performed to determine the reproduction quality. The following content is assigned to the tracks that show 'Sweep': 265856 samples silence + 524288 samples e-sweep + 265856 samples silence. With a sample rate of 48000Hz,

the total duration per track is exactly 22.00 s. The e-sweep is generated from 0.01 Hz to 24000 Hz with 2^{19} samples ≈ 10.92s.
Every channel has to be defined in the DCP file, so the grey cells of the table represent completely silent audio files of exactly the same length as the sweep sound file. Two signals of respectively 800 Hz and 200 Hz are present to indicate the progress of the playback.
All these combinations are played in one sequence.

Table C.2.2 *DCP file content, performed measurements*

A-F	Measurement	Left	Center	Right	Surround Left	Surround Righ	LFE
	Signal, 800 Hz 2s						
A01	Crosstalk Left	Sweep					
A03	Crosstalk Right			Sweep			
A04	Crosstalk Left Surround				Sweep		
A05	Crosstalk Right Surround					Sweep	
	Signal, 200 Hz 2s						
A06	Reproduction Front	Sweep		Sweep			
A08	Reproduction Surround				Sweep	Sweep	
A09	Reproduction Both	Sweep		Sweep	Sweep	Sweep	
A10	Crosstalk L+SL	Sweep			Sweep		
A11	Crosstalk R+SR			Sweep		Sweep	

Receiver positions

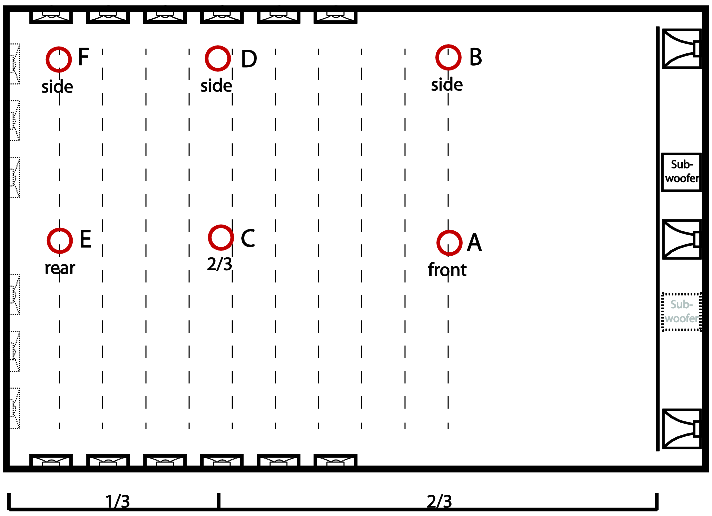


Figure C.2.2 *HATS positions*

Figure C.2.2 shows the measurement points for the Head And Torso Simulator. The six points are chosen because of their specific locations. Points A, C and E are chosen in the *center line* of the cinema, the distance between the left and the right loudspeaker channels is about equal. Points B, D and F are on the far *side* of the row, on these locations, the imbalance between the left and right loudspeaker channels is the largest.
Points A and B are situated in the front row of the cinema, the relative displacement of the front loudspeakers is the largest and the distance to the loudspeakers is the smallest. Points C and D are positioned at $2/3^{rd}$ of the cinema length from the screen. On this distance, the sweetspot of the cinema

is located, because of cinema alignment instructions. Also in the sound studio, the sound engineer is located at 2/3rd of its studio, so basically movies are mixed for this listener's position.
The back row of the cinema shows the opposite of the front row, relative displacement of the front loudspeakers is the smallest here. Also this row is as far away from the front loudspeakers as possible, making the impact of the hall on the impulse response measurement probably the largest.
At measurement points B, D and F, the side points of the rows, the head of the HATS is rotated so that the nose is pointing towards the center of the screen where for the position on the center line the HATS is looking forward. The body of the HATS isn't rotated.

The HATS is connected to the DAC/ADC, in every cinema it is checked that the left ear is connected to the left channel, and the right ear to the right channel.

The HATS is elevated, so that the ears are at average human ears height. In every cinema, the same flightcase is used for this.

In all cinemas the temperature and humidity is registered during the measurements.

Table C.2.3 *Equipment for reproduction measurements*

	Product name	**Serial number**
Netbook with Dirac 5 software and Audacity 1.3	Dell Latitude 2110	
DAC/ADC	Acoustics Engineering Triton	03300354
Microphone power supply	Acoustics Engineering Delatron	
Head and Torso Simulator	B&K - Type 4128C	
Thermo-/hygrometer	Lambrecht HygroLog D	19813008

Data processing
The signal that is recorded is a sequence of e-sweeps and their resulting room responses. This sequence is cut into parts of exactly 1,100,000 samples where each part one sweep and room response covers.
Every part is deconvolved with another file of exactly 1,100,000 samples, including the original 524288 samples e-sweep and the remaining samples silence, resulting in the impulse response for the particular cinema/loudspeaker/location combination.

To get the room-in-room impulse responses of the reproduction combinations, the impulse responses are convolved with the impulse response of the recording room. This resulting R-I-R impulse response is treated as described in Appendix D.

2.4 Synchronous Measurements

For the synchronous measurements, the same method is used, but with the laptop connected to equipment that is able to configure the demanded channels according to Table C.2.2, the e-sweep is generated internally and the recorded signal is instantaneously deconvolved by the measurement software.

3. Phase and delay measurement

To determine the delay of the loudspeakers relative to the frontloudspeakers and whether all loudspeakers are connected in the same phase or not, another DCP file is installed on the cinema server. This file contains one track. This track contains for all the full range channels (L-C-R-SL-SR) the same audio file. The LFE channel is still only silence. The audio on the track consists of 10 minutes long 2s silence and 2s a pure tone of 150Hz. The onset is important for both the delay and phase examination. By recording the output of two loudspeakers at very close distance (within centimeters) at the same time, the sound delay and phase difference can be examined. One of those loudspeakers is the reference loudspeaker. Figure C.2.3 shows an example. In the left pictures the original pure tone is visible for two channels (upper and lower sinusoid), on the right side the recorded output is shown. The onsets in the same direction (white circle) show that these loudspeaker are connected in the same phase. The displacement of the lower sinusoid indicates a delay in the sound. These delays, in the range of 0 to 50 ms, are measured with in accuracy of about up to 3 ms, due to placement difficulties of the reference loudspeaker microphone.

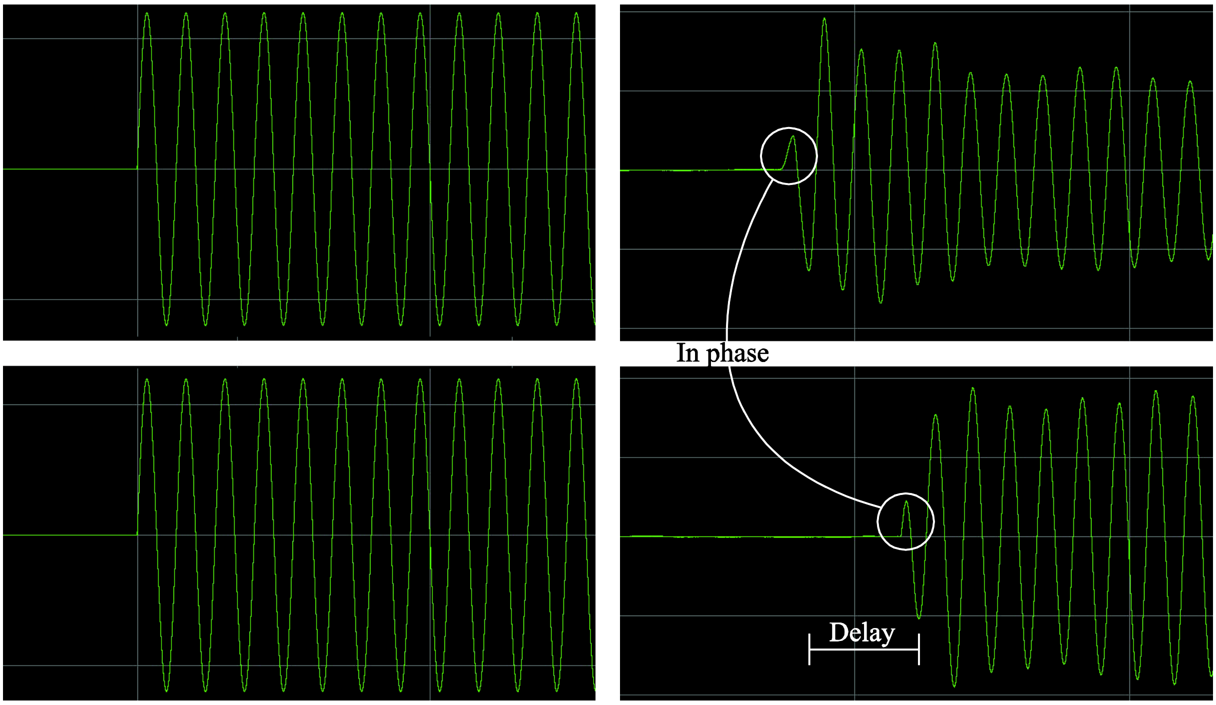


Figure C.2.3 *Phase and delay example*

For these measurements, the equipment shown in Table C.2.4 is used.

Table C.2.4 *Equipment for phase and delay measurements*

	Product name	**Serial number**
Netbook with Dirac 5 software and Audacity 1.3	Dell Latitude 2110	
DAC/ADC	Acoustics Engineering Triton	03300354
Microphone power supply	Acoustics Engineering Delatron	
Omnidirectional microphone	B&K Type 4230 B&K Type 4230	2703329 2471031

Appendix D: Measurement quality

For the analysis of acoustical parameters, the quality of the measurements is important. According to [1] the Impulse response to Noise Ratio (INR) is an indicator of measurement quality. The normative value in this examination is the required INR for the reverberation parameters. For T_{20} evaluation, an INR of at least 35 dB (-5 to -25 dB and 10 dB headroom) is required. For T_{30} this is 45 dB in each examined octave[1].
Because of the convolution process, both the recording room and the playback room have influence on the quality of the room-in-room impulse response.

1. Recording room

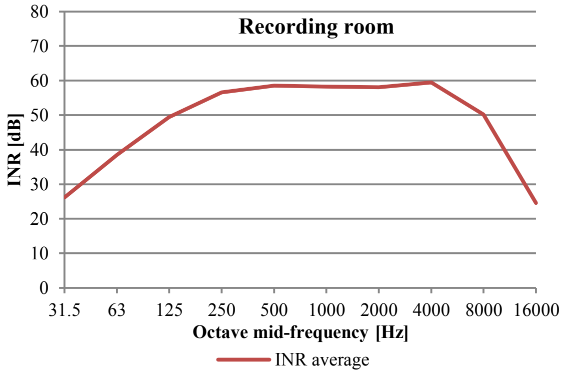


Figure D.1 *Recording room INR, two channel averaged, Muziekgebouw Eindhoven*

Figure D.1 shows the INR curve of the measurement performed in the Muziekgebouw Eindhoven with an HATS and an omnidirectional source. Table D.1 shows the relevant data for the 500 Hz and 1000 Hz octaves.

Table D.1 *INR data 500Hz and 1000Hz octaves*

	Minimum INR [dB]	Average INR [dB]	Maximum INR [dB]
Muziekgebouw Eindhoven	57.2	57.8	58.5

2. Playback room

Figures D.2 through D.10 show the average, minimum and maximum INR value curves for all performed measurements in the cinemas using the cinema loudspeakers and the HATS. Table D.2 shows the relevant data for the 500 Hz and 1000 Hz octaves.

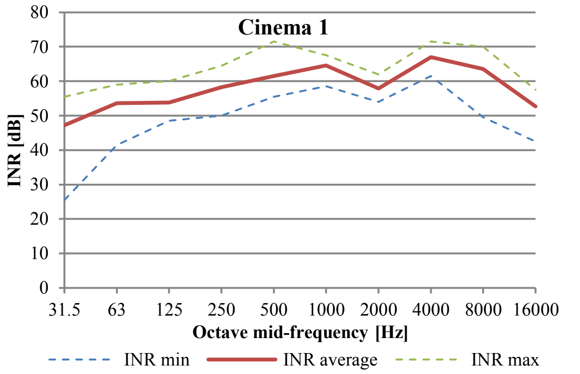


Figure D.2 *Cinema 1 INR, ear averaged, three loudspeaker combinations, six positions*

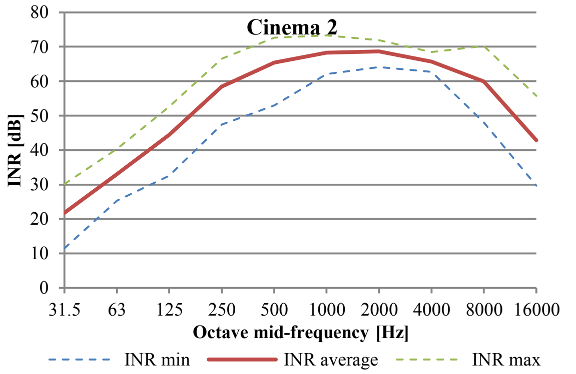


Figure D.3 *Cinema 2 INR, ear averaged, three loudspeaker combinations, six positions*

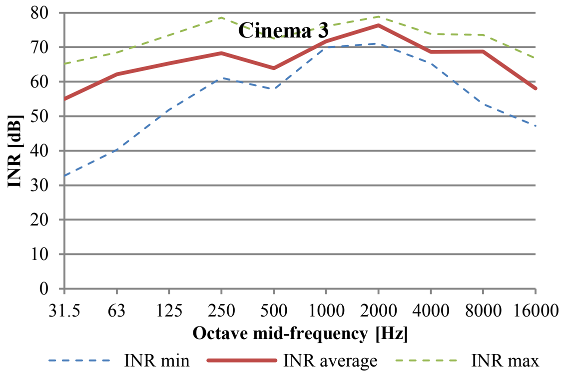


Figure D.4 *Cinema 3 INR, ear averaged, three loudspeaker combinations, six positions*

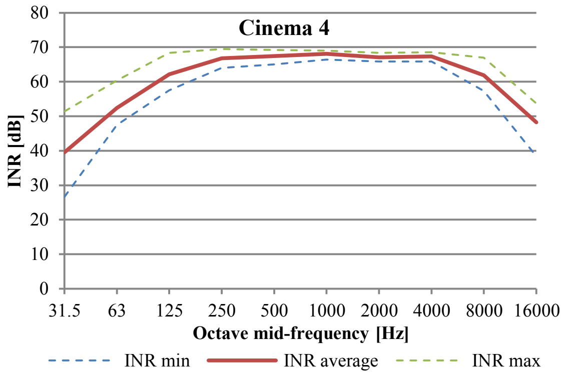


Figure D.5 *Cinema 4 INR, ear averaged, three loudspeaker combinations, six positions*

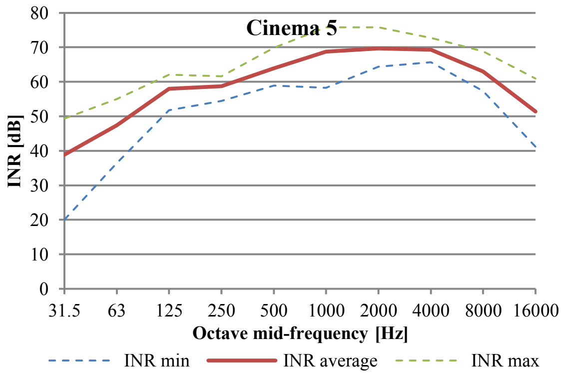


Figure D.6 *Cinema 5 INR, ear averaged, three loudspeaker combinations, six positions*

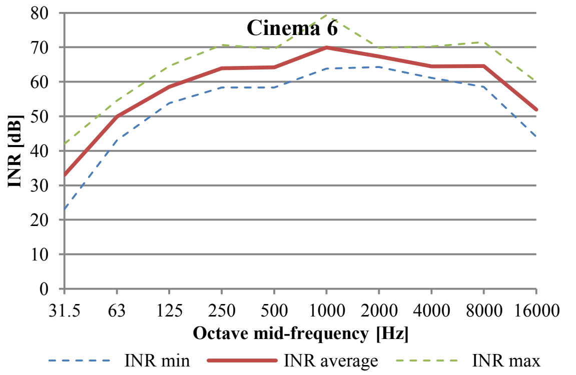


Figure D.7 *Cinema 6 INR, ear averaged, three loudspeaker combinations, six positions*

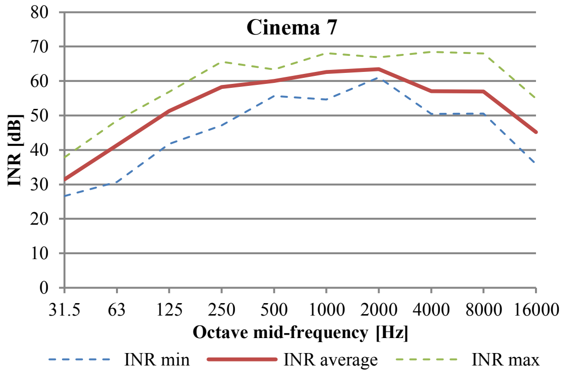


Figure D.8 *Cinema 7 INR, ear averaged, three loudspeaker combinations, six positions*

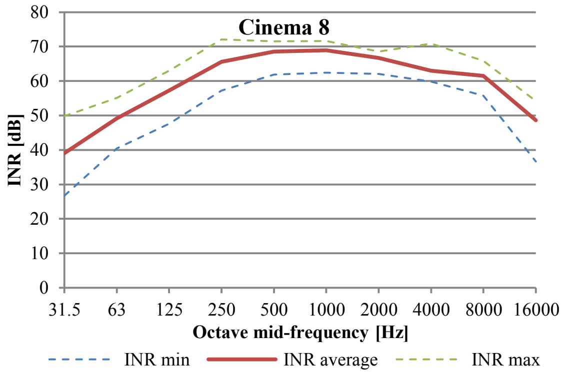


Figure D.9 *Cinema 8 INR, ear averaged, three loudspeaker combinations, six positions*

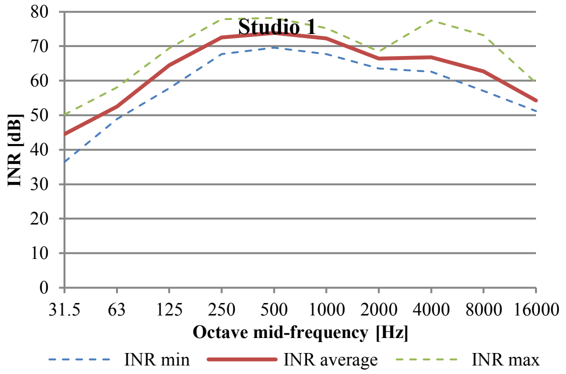


Figure D.10 *Studio 1 INR, ear averaged, three loudspeaker combinations, six positions*

Table D.2 *INR data 500Hz and 1000Hz octaves*

	Minimum INR [dB]	Average INR [dB]	Maximum INR [dB]
Studio 1	67.7	73.1	78.2
Cinema 1	55.5	63.0	71.5
Cinema 2	53.0	66.8	73.3
Cinema 3	57.8	67.8	76.1
Cinema 4	65.1	67.8	69.2
Cinema 5	58.3	66.3	75.8
Cinema 6	58.4	67.1	79.3
Cinema 7	54.6	61.3	68.1
Cinema 8	61.9	68.8	71.6

3. Room-in-room

The convolved impulse responses (room-in-room responses) need some preparation before the INR of the impulse response can be calculated. Figure D.11 shows that because of the different noise floors of the playback- and recording room impulse responses, the resulting convolved room-in-room responses need to be edited to calculate the Impulse response to Noise Ratio. The files of the room-in-room responses are cut at the red line to preserve the impulse response and the realistic noise floor.

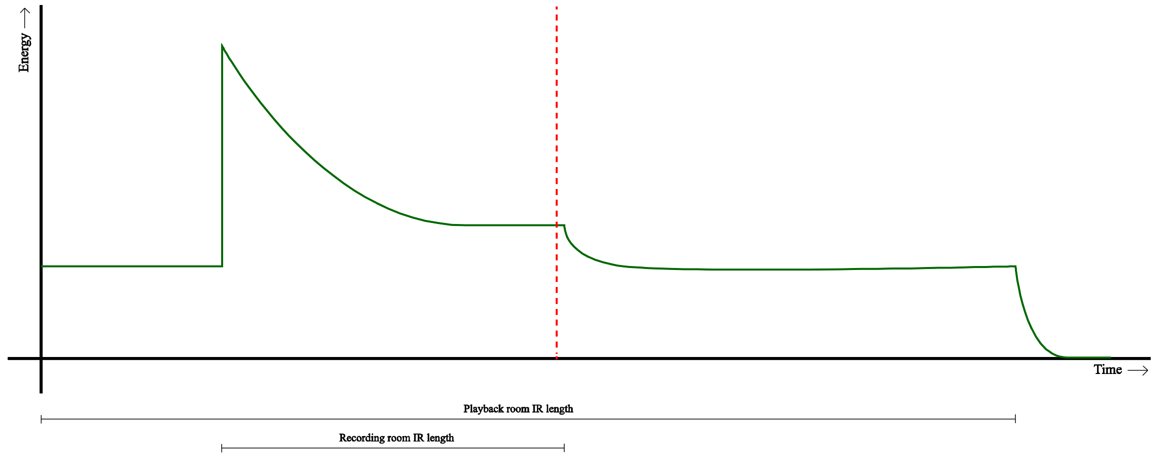


Figure D.11 *Schematic overview of the Energy Time Curve of a cinema impulse response convolved with the Concert Hall impulse response*

Figures D.12 through D.20 show the minimum, maximum and average INR curves of the room-in-room responses after modification of the convolved files.

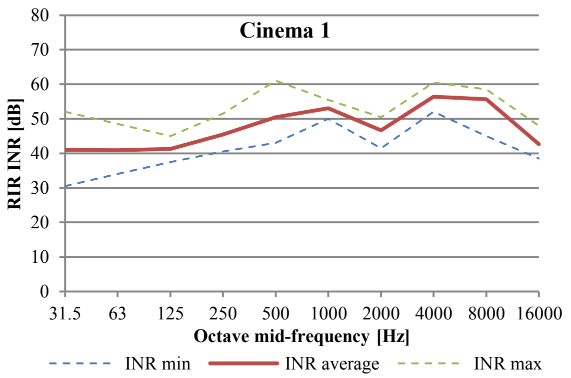


Figure D.12 *Convolved Cinema 1 INR, ear averaged, three loudspeaker combinations, six positions*

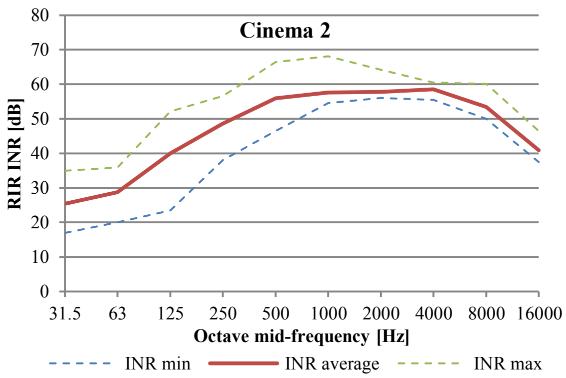


Figure D.13 *Convolved Cinema 2 INR, ear averaged, three loudspeaker combinations, six positions*

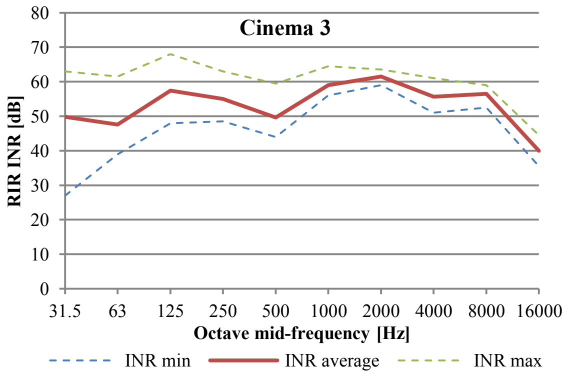


Figure D.14 *Convolved Cinema 3 INR, ear averaged, three loudspeaker combinations, six positions*

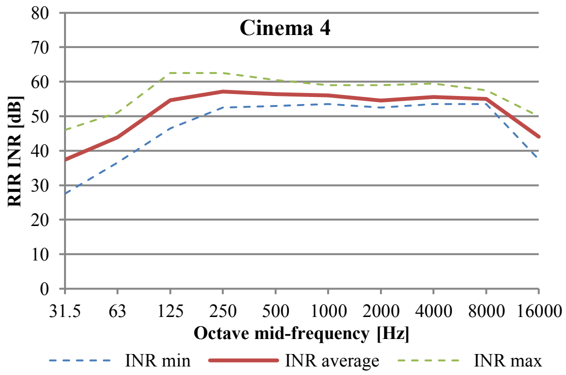


Figure D.15 *Convolved Cinema 4 INR, ear averaged, three loudspeaker combinations, six positions*

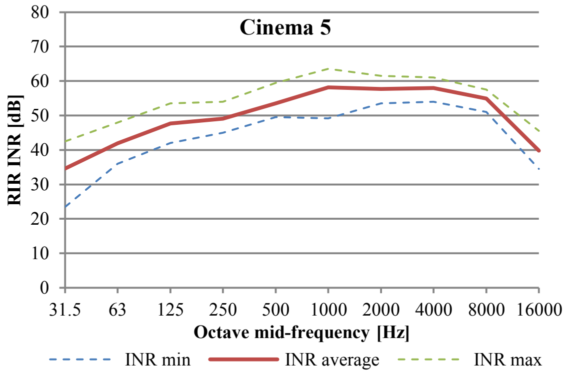


Figure D.16 *Convolved Cinema 5 INR, ear averaged, three loudspeaker combinations, six positions*

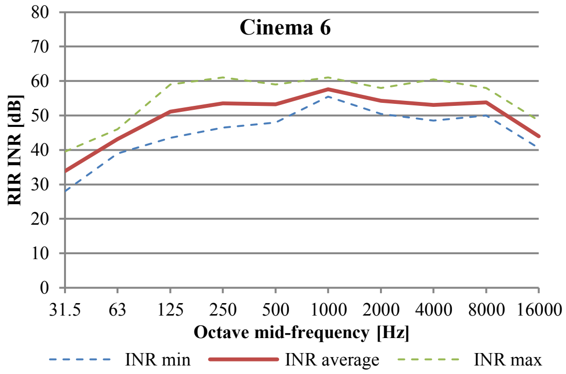


Figure D.17 *Convolved Cinema 6 INR, ear averaged, three loudspeaker combinations, six positions*

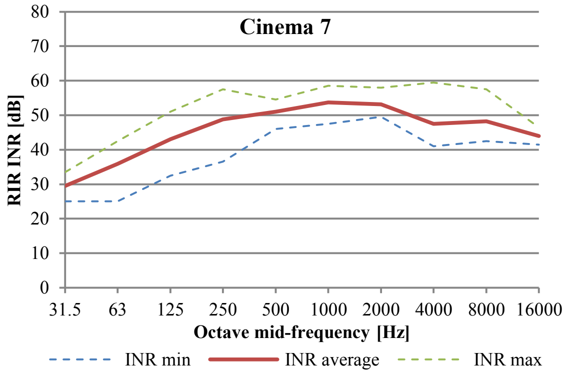


Figure D.18 *Convolved Cinema 7 INR, ear averaged, three loudspeaker combinations, six positions*

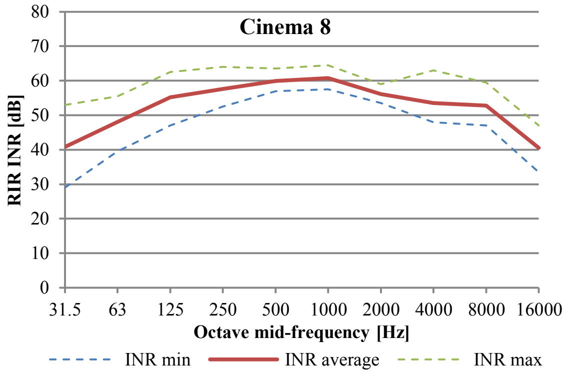


Figure D.19 *Convolved Cinema 8 INR, ear averaged, three loudspeaker combinations, six positions*

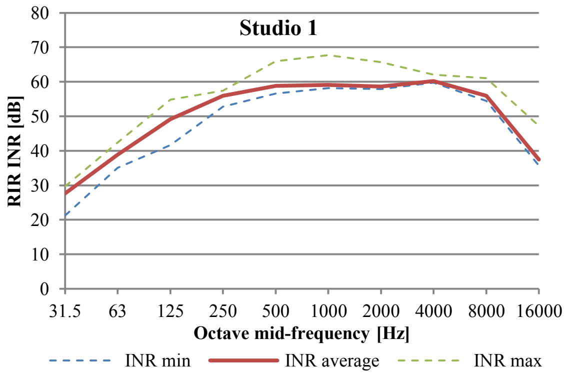


Figure D.20 *Convolved Studio 1 INR, ear averaged, three loudspeaker combinations, six positions*

In Table D.3, the relevant INR values for the different room in room responses are shown. In Table D.4 the average results of the recording room, the playback and the convolution of both is shown as overview of all measurements.

Table D.3 *INR data 500Hz and 1000Hz octaves*

	Minimum INR [dB]	Average INR [dB]	Maximum INR [dB]
Studio 1	56.6	59.0	67.7
Cinema 1	43.0	51.7	61.0
Cinema 2	46.5	56.8	68.1
Cinema 3	44.0	54.3	64.5
Cinema 4	53.0	56.2	60.5
Cinema 5	49.2	55.9	63.5
Cinema 6	48.0	55.4	61.0
Cinema 7	46.0	52.4	58.5
Cinema 8	57.0	60.3	64.5

Table D.4 Average INR values 500-1000Hz

	Average INR recording room [dB]	Average INR playback room [dB]	Average INR room-in-room [dB]
Studio 1	57.8	73.1	59.0
Cinema 1	57.8	63.0	51.7
Cinema 2	57.8	66.8	56.8
Cinema 3	57.8	67.8	54.3
Cinema 4	57.8	67.8	56.2
Cinema 5	57.8	66.3	55.9
Cinema 6	57.8	67.1	55.4
Cinema 7	57.8	61.3	52.4
Cinema 8	57.8	68.8	60.3

4. Conclusion

Based on these results can be concluded that the impulse responses are of good quality. With average INR values beyond 50 dB and minimum INR values of just below 45 dB, the T_{30} can be used to examine the reverberation error.

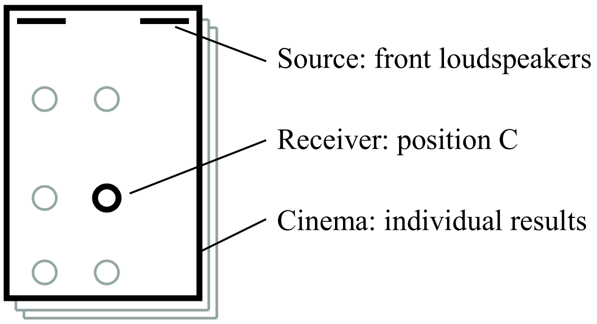
5. References:

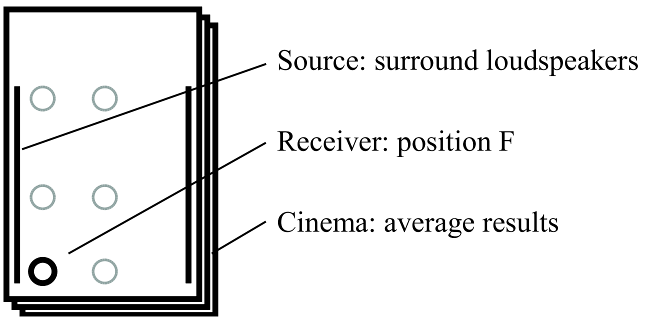
[1] C.C.J.M. Hak, J.P.M. Hak, R.H.C. Wenmaekers, "INR as an Estimator for the Decay Range of Room Acoustic Impulse Responses", AES Convention Amsterdam (2008)

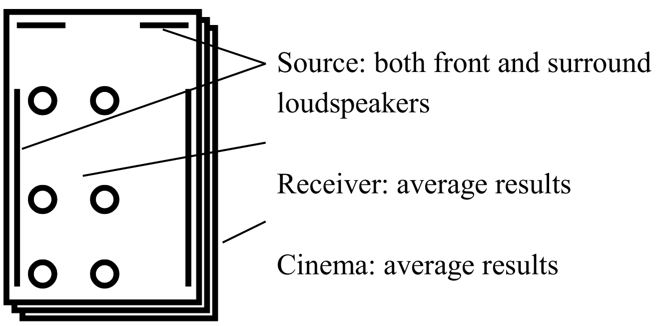
Appendix E: Graphs

On the following pages different results of the research are presented in graphs. First the cinemas are compared to each other for the most fundamental situation: Source - front loudspeakers, receiver – mix engineers position (center line, 2/3rd distance from the screen).
Then the average effect of different loudspeaker combinations is compared. Hereafter the different positions in the cinema related to the different loudspeaker combinations are compared. On each page one parameter is shown with on the left row the side positions and on the right row the center line positions, on the top the front loudspeaker combination, in the middle the surround loudspeaker combination and on the bottom both loudspeaker combinations.
At last, the average crosstalk for the different positions is shown, again with on the left row the side positions and on the right row the center line positions, on the top the front loudspeaker combination, in the middle the surround loudspeaker combination and on the bottom both loudspeaker combinations.

Every graph is accompanied by a visual representation of the involved variables, as explained in the following examples:







The black lines represent the loudspeaker combination that is used in the measurement: front loudspeakers left and right, surround loudspeakers left and right and both front and surround loudspeakers combined left and right.

The bold circles represents the involved measurement receiver position(s). For example, only one bold black circle and five grey circles means that the exact value of the bold position is shown in the graph. When multiple positions are indicated by a bold circle, the shown values in the graph are averaged over these bold positions.

Whether the values shown in the graph are individual or averaged cinema values is indicated by the type of enclosure of the legend. If the legend shows one black outline and two smaller grey outlines, the shown values are individual cinema results. When the legend shows multiple thick black outlines, the results are averaged over all measured cinemas for the marked source-receiver combination.

For the graphs in which the cinema results are averaged, the standard error (SE) of the mean is shown by the whiskers on the graph. Also in all graphs the relevant jnd value is shown.

Cinema comparison

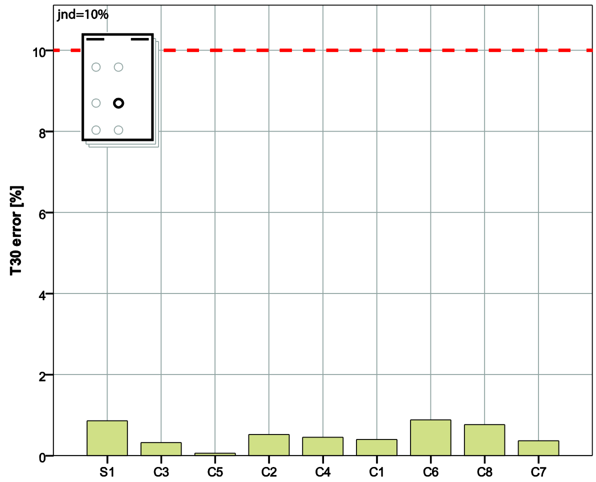


Figure E.1 *T_{30} error with cinema; front loudspeakers; position C; 500; 1000 Hz averaged; ears averaged*

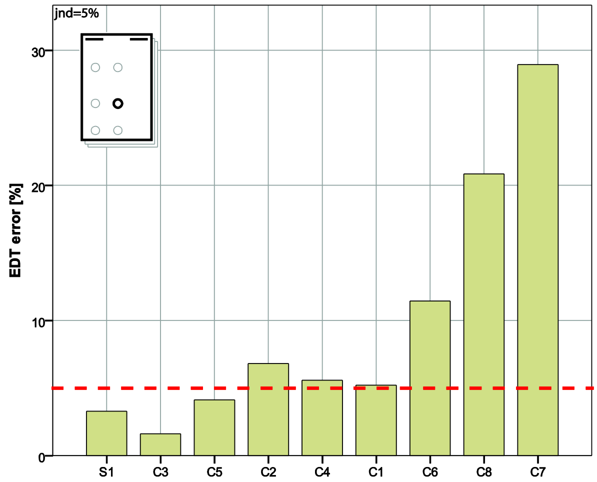


Figure E.2 *EDT error per cinema; front loudspeakers; position C; 500, 1000 Hz averaged; ears averaged*

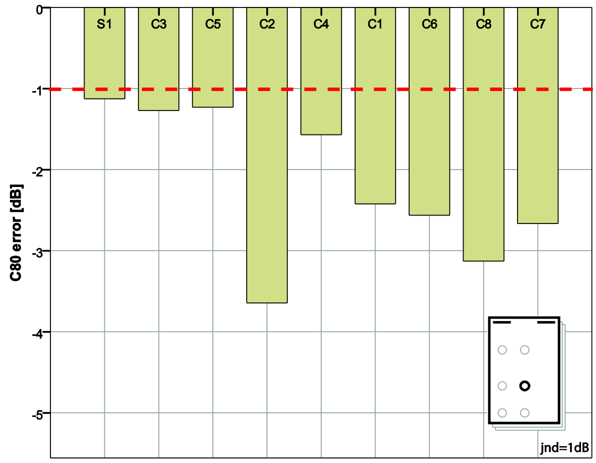


Figure E.3 *C_{80} error per cinema; front loudspeakers; position C; 500, 1000 Hz averaged; ears averaged*

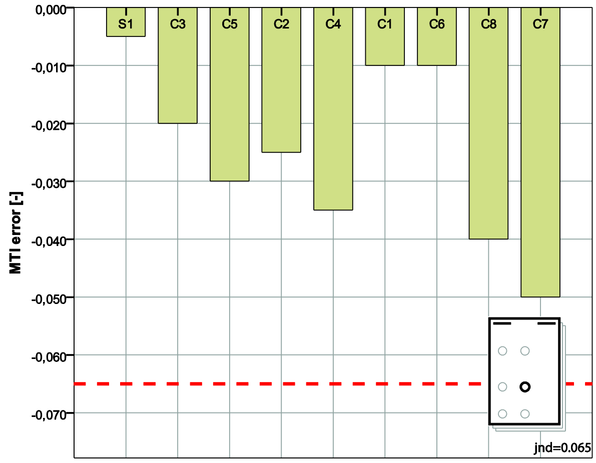


Figure E.4 *MTI error per cinema; front loudspeakers; position C; 500, 2000 Hz averaged; best ear averaged*

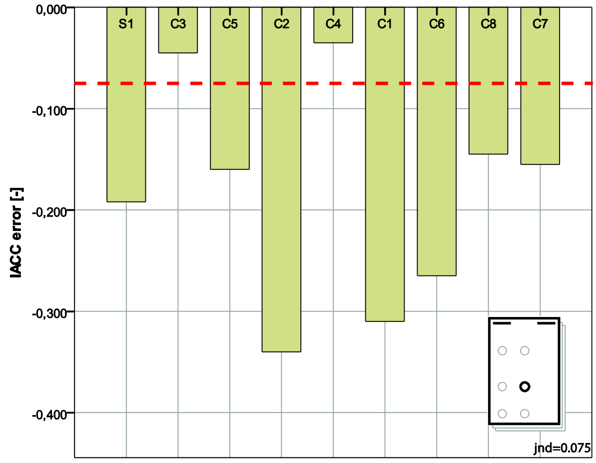


Figure E.5 *IACC error per cinema; front loudspeakers; position C; 500, 1000 Hz averaged*

Loudspeaker combination average

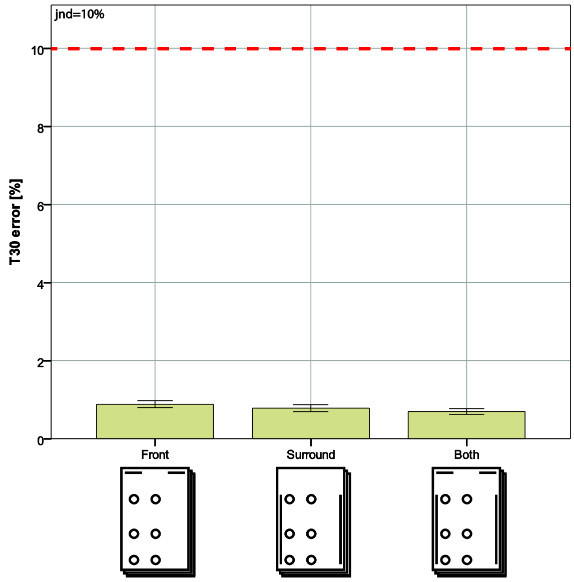


Figure E.6 *T_{30} error with SE per loudspeaker combination; all cinemas and positions averaged; 500, 1000 Hz averaged; ears averaged*

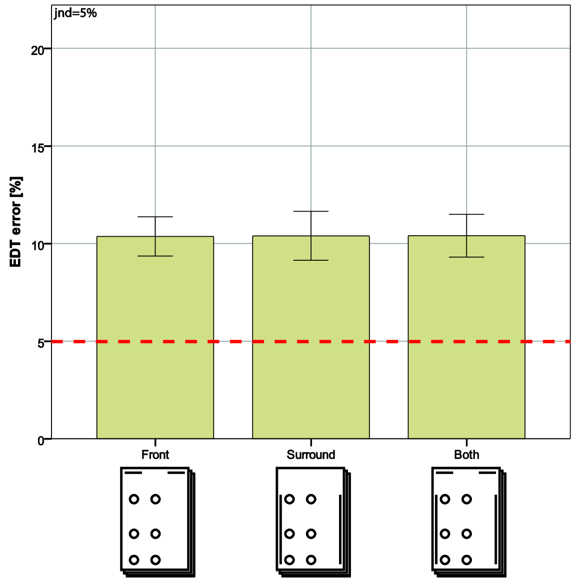


Figure E.7 *EDT error with SE per loudspeaker combination; all cinemas and positions averaged; 500, 1000 Hz averaged; ears averaged*

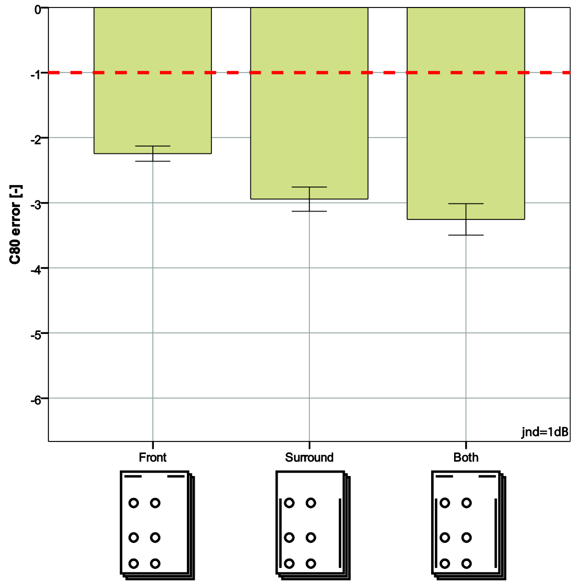


Figure E.8 *C_{80} error with SE per loudspeaker combination; all cinemas and positions averaged; 500, 1000 Hz averaged; ears averaged*

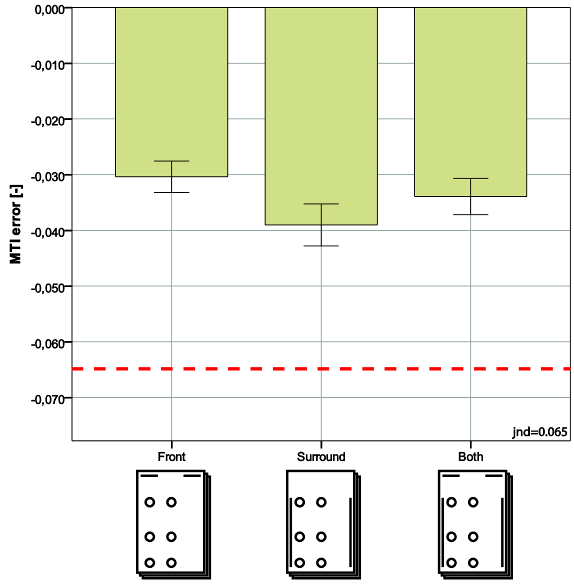


Figure E.9 *MTI error with SE per loudspeaker combination; all cinemas and positions averaged; 500, 2000 Hz averaged; best ear averaged*

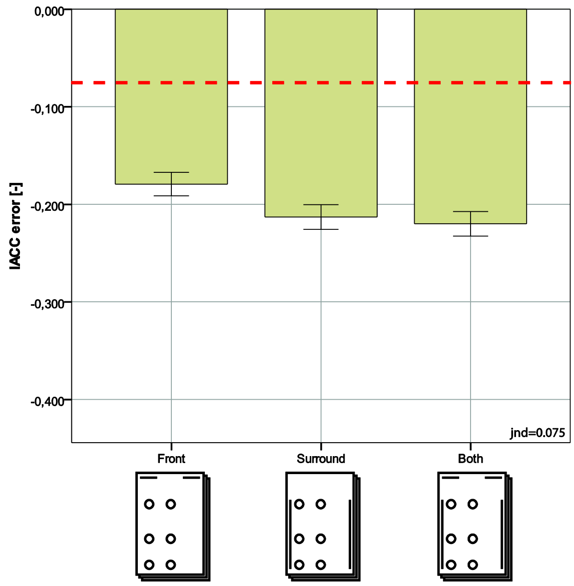


Figure E.10 *IACC error with SE per loudspeaker combination; all cinemas and positions averaged; 500, 1000 Hz averaged*

Position differences T_{30} error

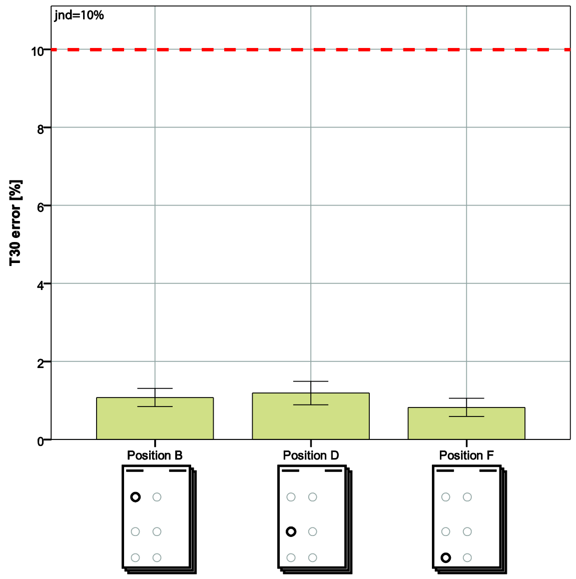


Figure E.11 *T_{30} error with SE per side position; all cinemas averaged; front loudspeakers; 500, 1000 Hz averaged; ears averaged*

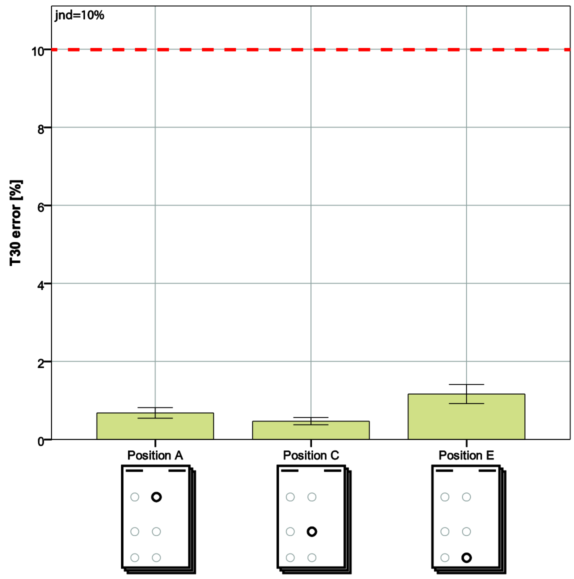


Figure E.12 *T_{30} error with SE per center line position; all cinemas averaged; front loudspeakers; 500, 1000 Hz averaged; ears averaged*

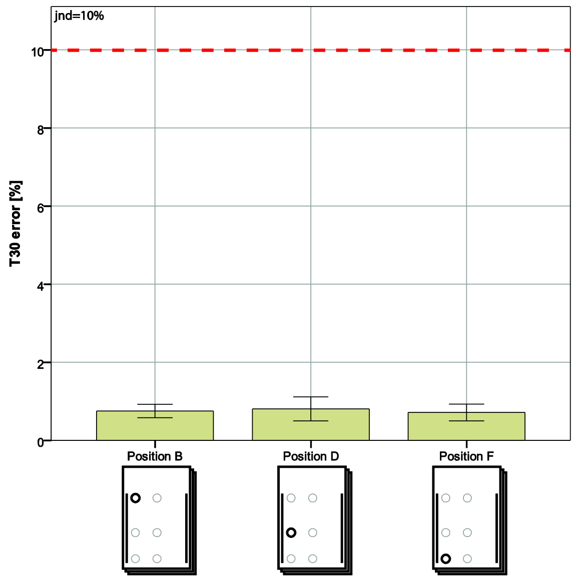


Figure E.13 *T_{30} error with SE per side position; all cinemas averaged; surround loudspeakers; 500, 1000 Hz averaged; ears averaged*

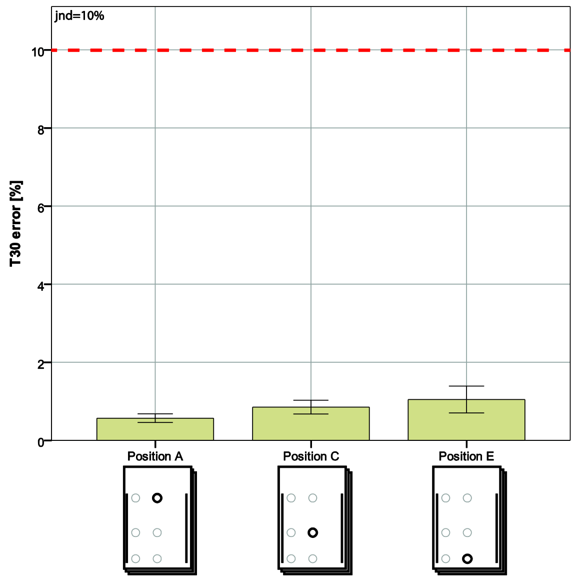


Figure E.14 *T_{30} error with SE per center line position; all cinemas averaged; surround loudspeakers; 500, 1000 Hz averaged; ears averaged*

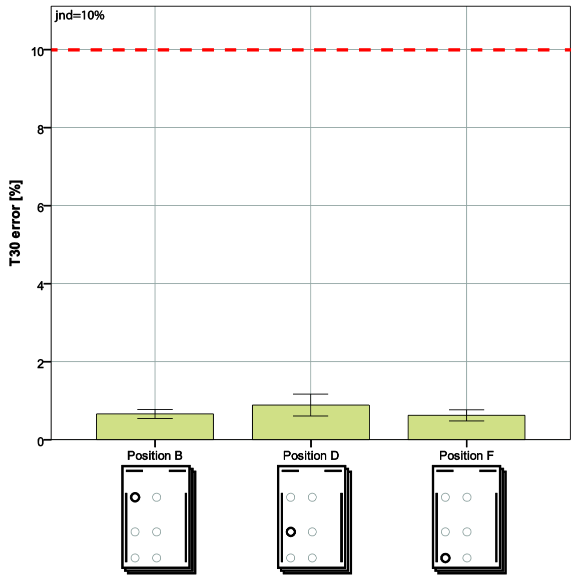


Figure E.15 *T_{30} error with SE per side position; all cinemas averaged; both front and surround loudspeakers; 500, 1000 Hz averaged; ears averaged*

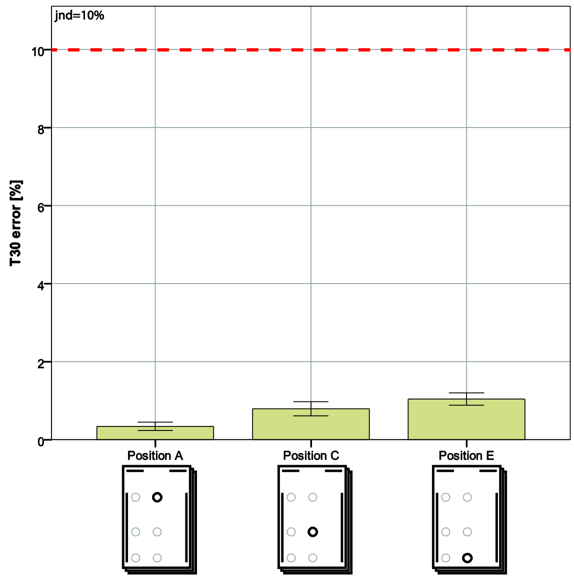


Figure E.16 *T_{30} error with SE per center line position; all cinemas averaged; both front and surround loudspeakers; 500, 1000 Hz averaged; ears averaged*

Position differences EDT error

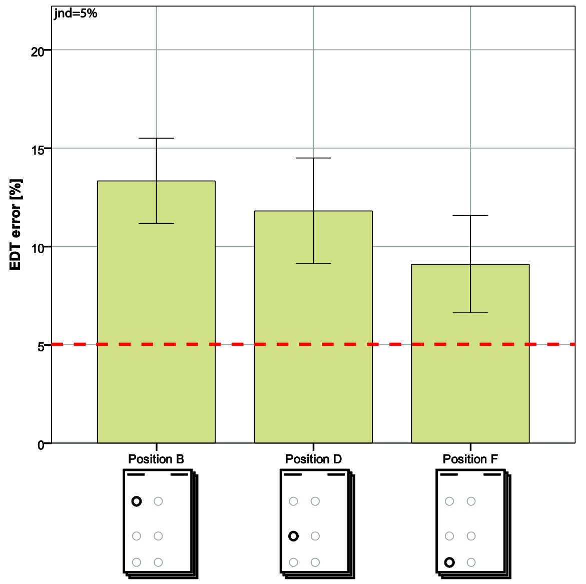


Figure E.17 *EDT error with SE per side position; all cinemas averaged; front loudspeakers; 500, 1000 Hz averaged; ears averaged*

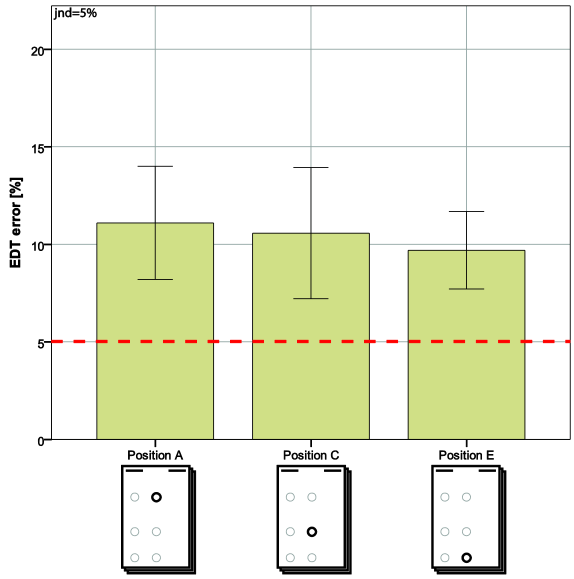


Figure E.18 *EDT error with SE per center line position; all cinemas averaged; front loudspeakers; 500, 1000 Hz averaged; ears averaged*

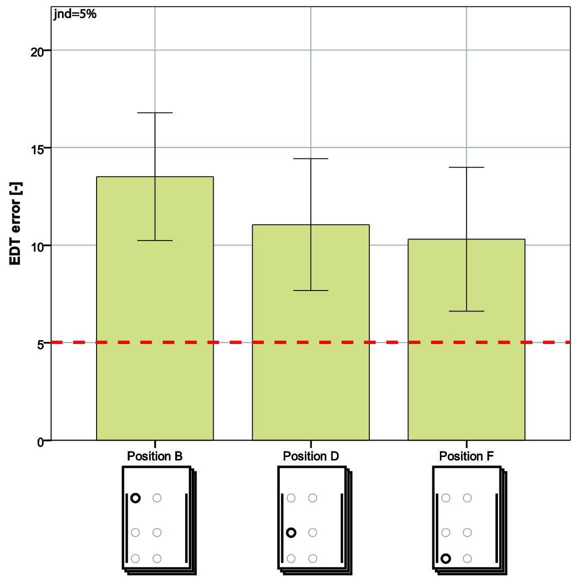


Figure E.19 *EDT error with SE per side position; all cinemas averaged; surround loudspeakers; 500, 1000 Hz averaged; ears averaged*

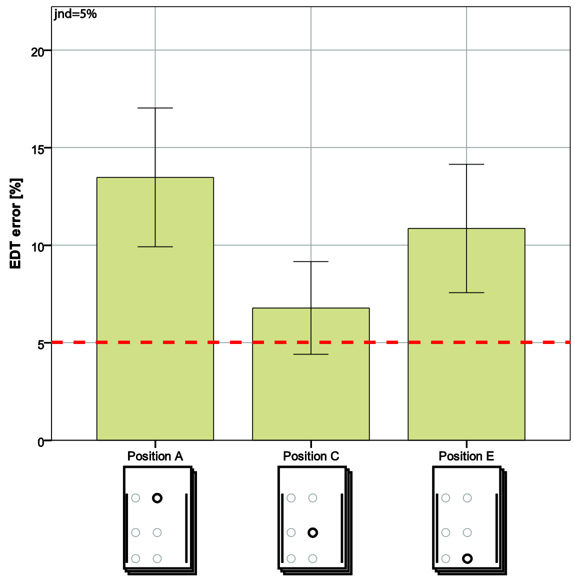


Figure E.20 *EDT error with SE per center line position; all cinemas averaged; surround loudspeakers; 500, 1000 Hz averaged; ears averaged*

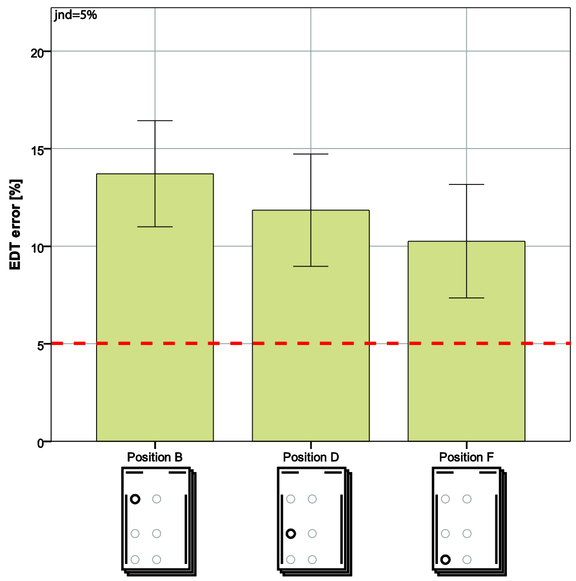


Figure E.21 *EDT error with SE per side position; all cinemas averaged; both front and surround loudspeakers; 500, 1000 Hz averaged; ears averaged*

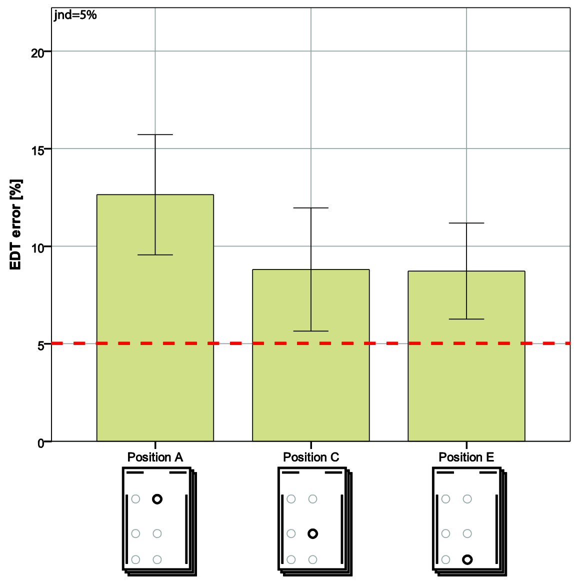


Figure E.22 *EDT error with SE per center line position; all cinemas averaged; both front and surround loudspeakers; 500, 1000 Hz averaged; ears averaged*

Position differences C_{80} error

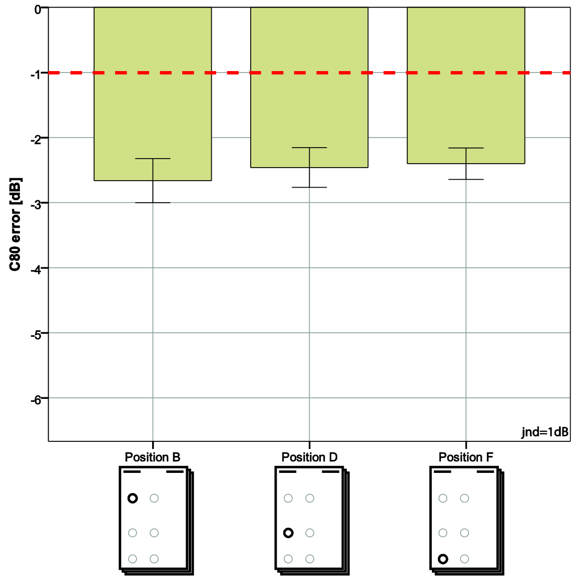


Figure E.23 *C_{80} error with SE per side position; all cinemas averaged; front loudspeakers; 500, 1000 Hz averaged; ears averaged*

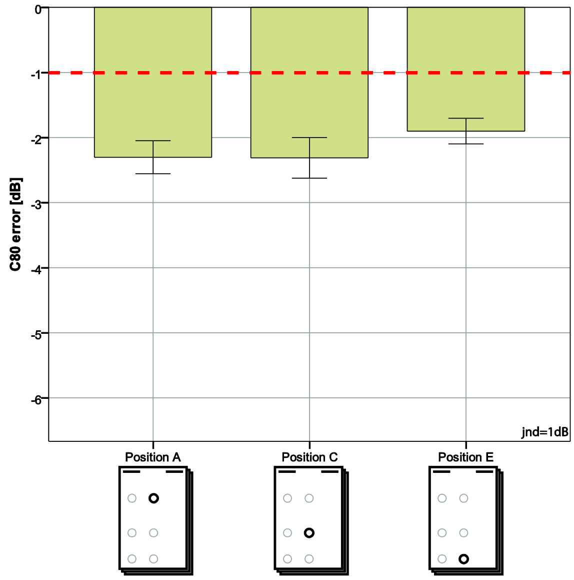


Figure E.24 *C_{80} error with SE per center line position; all cinemas averaged; front loudspeakers; 500, 1000 Hz averaged; ears averaged*

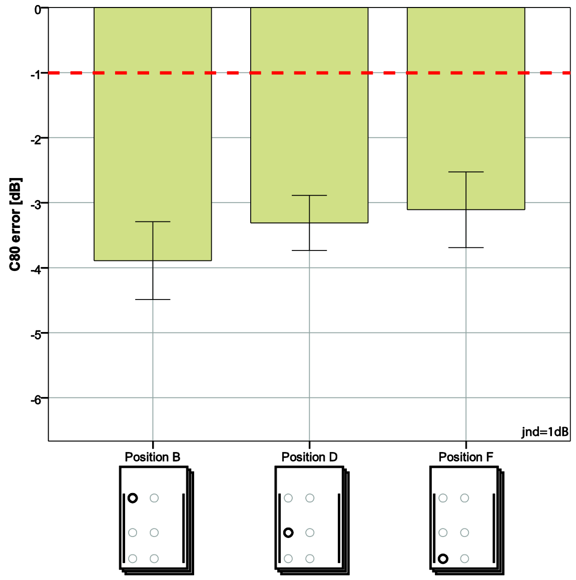


Figure E.25 *C_{80} error with SE per side position; all cinemas averaged; surround loudspeakers; 500, 1000 Hz averaged; ears averaged*

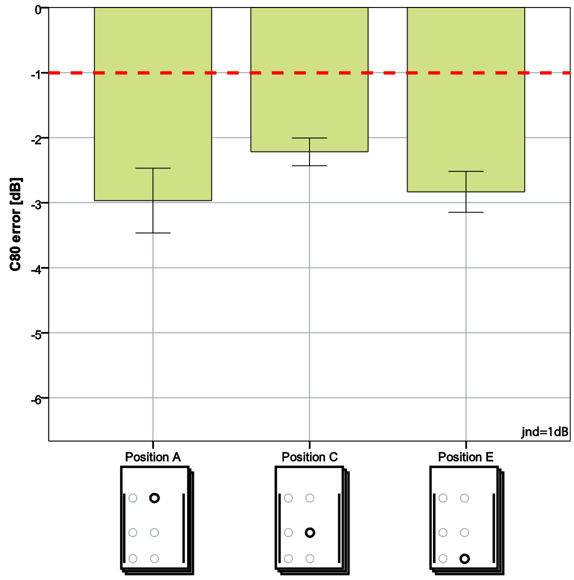


Figure E.26 *C_{80} error with SE per center line position; all cinemas averaged; surround loudspeakers; 500, 1000 Hz averaged; ears averaged*

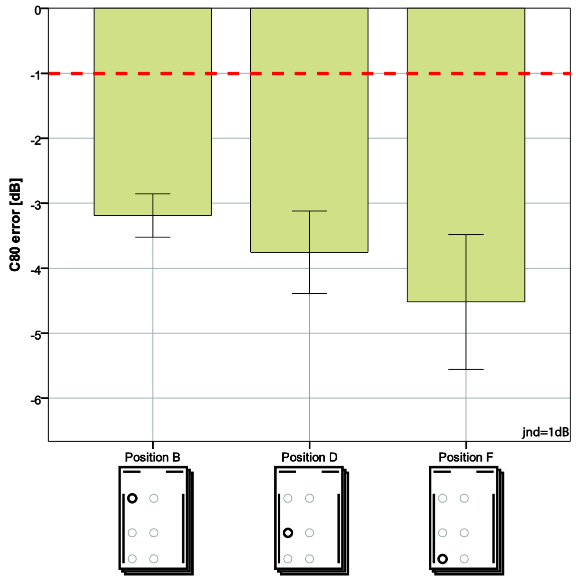


Figure E.27 *C_{80} error with SE per side position; all cinemas averaged; both front and surround loudspeakers; 500, 1000 Hz averaged; ears averaged*

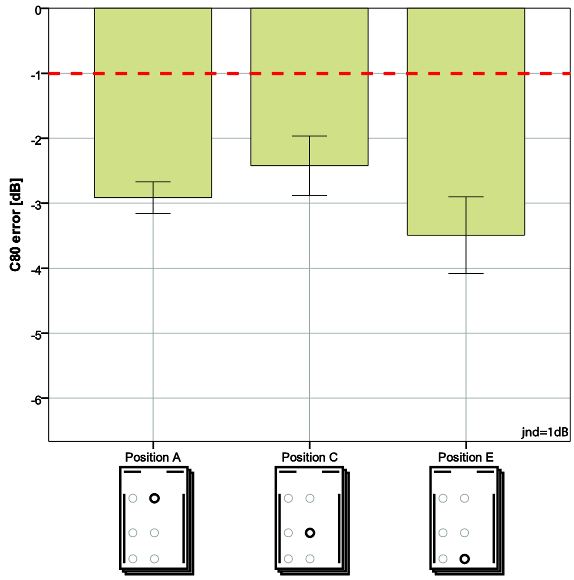


Figure E.28 *C_{80} error with SE per center line position; all cinemas averaged; both front and surround loudspeakers; 500, 1000 Hz averaged; ears averaged*

Position differences MTI error

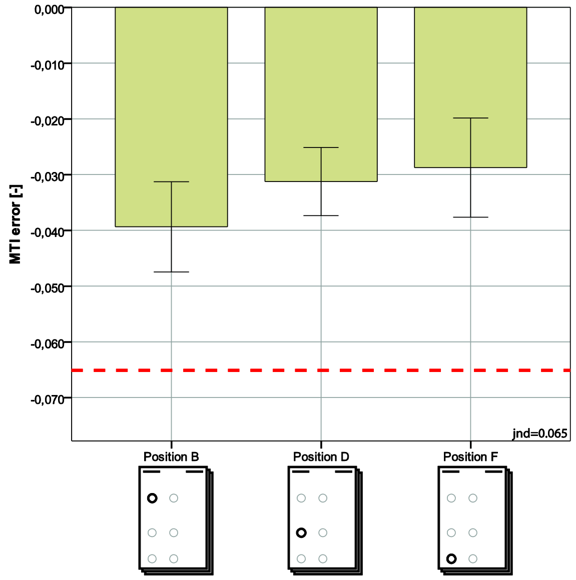


Figure E.29 *MTI error with SE per side position; all cinemas averaged; front loudspeakers; 500, 2000 Hz averaged; best ear averaged*

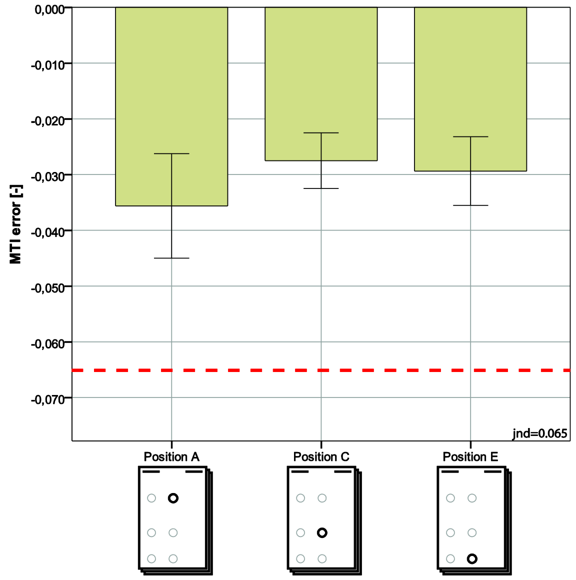


Figure E.30 *MTI error with SE per center line position; all cinemas averaged; front loudspeakers; 500, 2000 Hz averaged; best ear averaged*

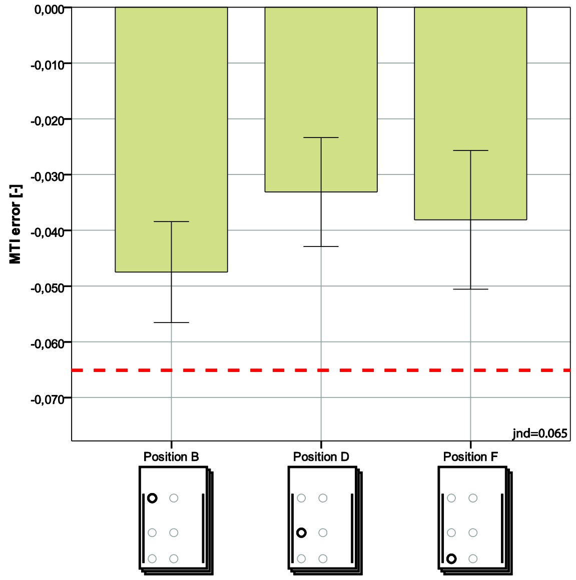


Figure E.31 *MTI error with SE per side position; all cinemas averaged; surround loudspeakers; 500, 2000 Hz averaged; best ear averaged*

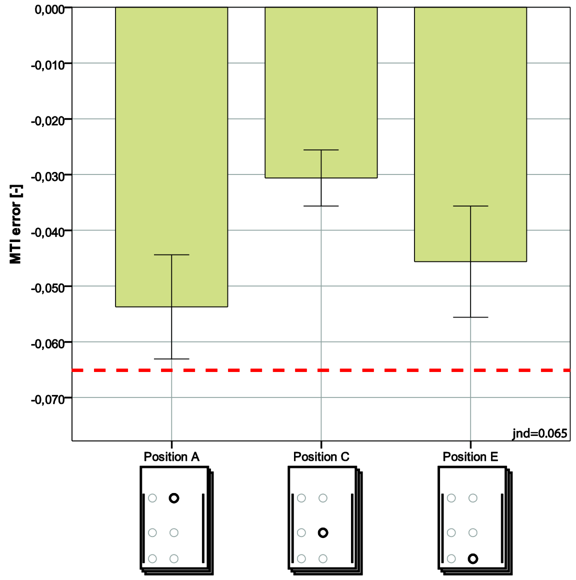


Figure E.32 *MTI error with SE per center line position; all cinemas averaged; surround loudspeakers; 500, 2000 Hz averaged; best ear averaged*

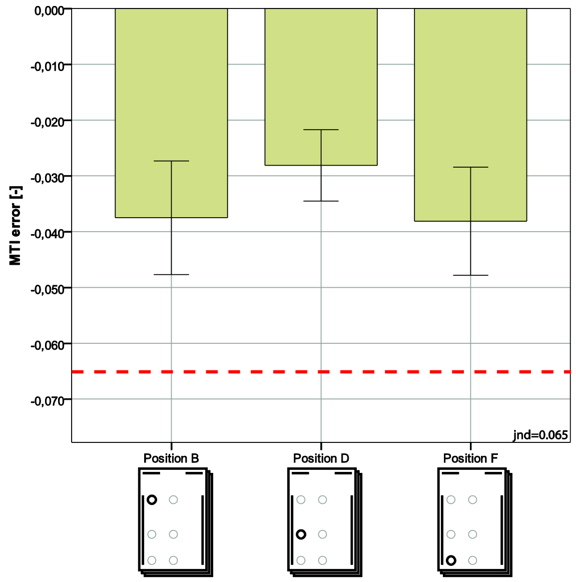


Figure E.33 *MTI error with SE per side position; all cinemas averaged; both front and surround loudspeakers; 500, 2000 Hz averaged; best ear averaged*

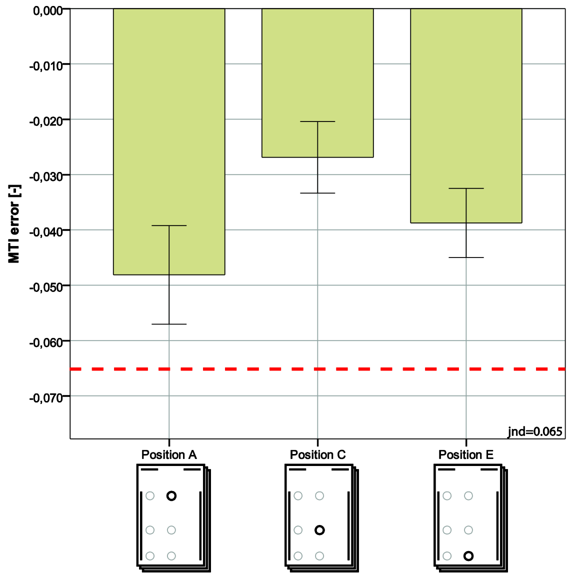


Figure E.34 *MTI error with SE per center line position; all cinemas averaged; both front and surround loudspeakers; 500, 2000 Hz averaged; best ear averaged*

Position differences IACC error

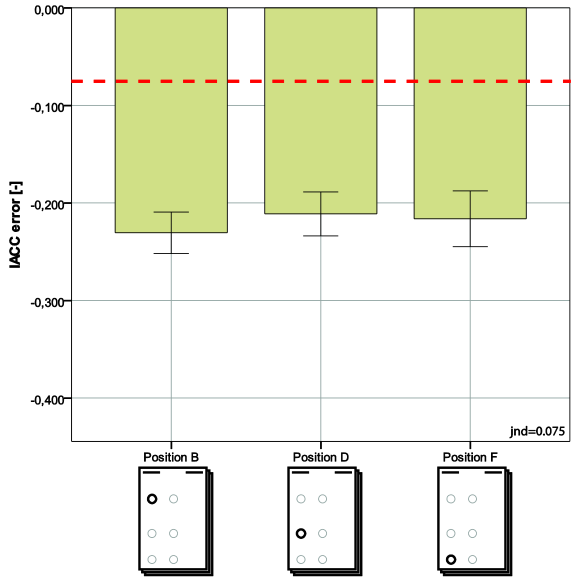


Figure E.35 *IACC error with SE per side position; all cinemas averaged; front loudspeakers; 500, 1000 Hz averaged*

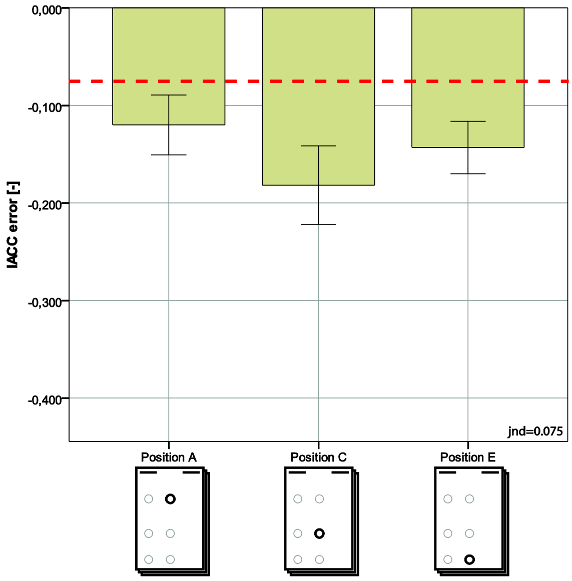


Figure E.36 *IACC error with SE per center line position; all cinemas averaged; front loudspeakers; 500, 1000 Hz averaged*

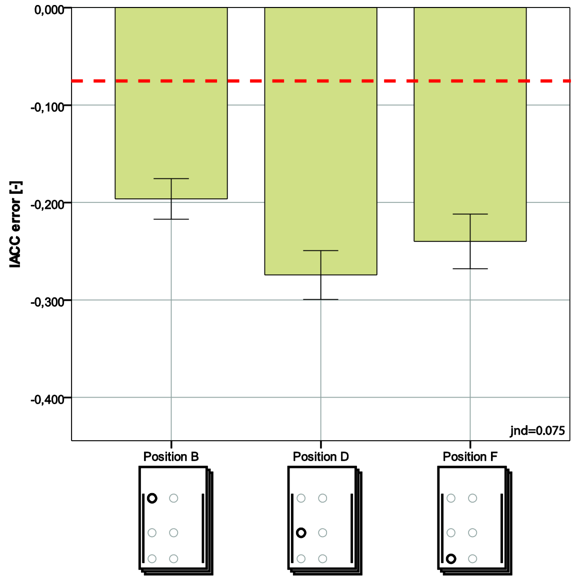


Figure E.37 *IACC error with SE per side position; all cinemas averaged; surround loudspeakers; 500, 1000 Hz averaged*

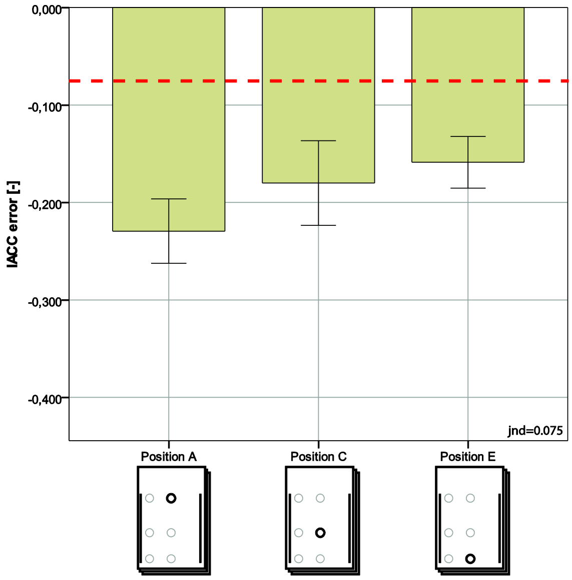


Figure E.38 *IACC error with SE per center line position; all cinemas averaged; surround loudspeakers; 500, 1000 Hz averaged*

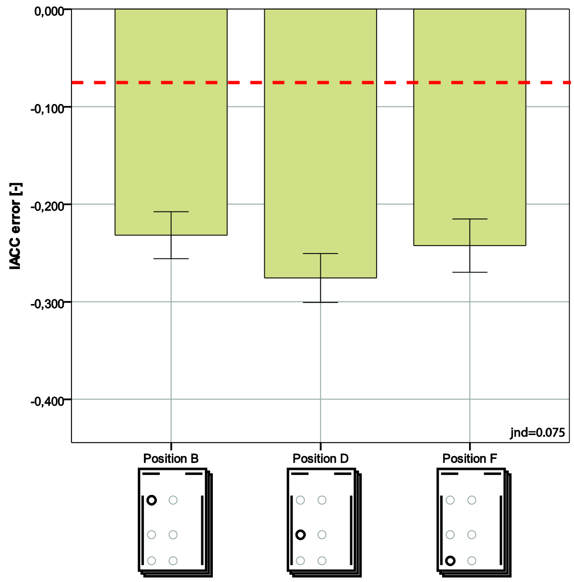


Figure E.39 *IACC error with SE per side position; all cinemas averaged; both front and surround loudspeakers; 500, 1000 Hz averaged*

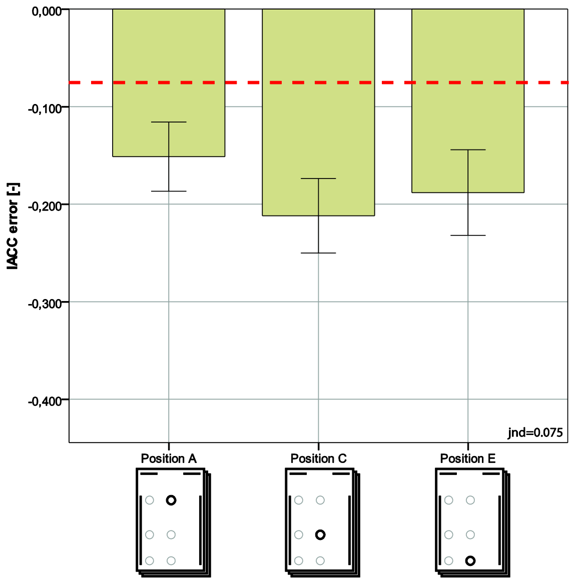


Figure E.40 *IACC error with SE per center line position; all cinemas averaged; both front and surround loudspeakers; 500, 1000 Hz averaged*

Crosstalk

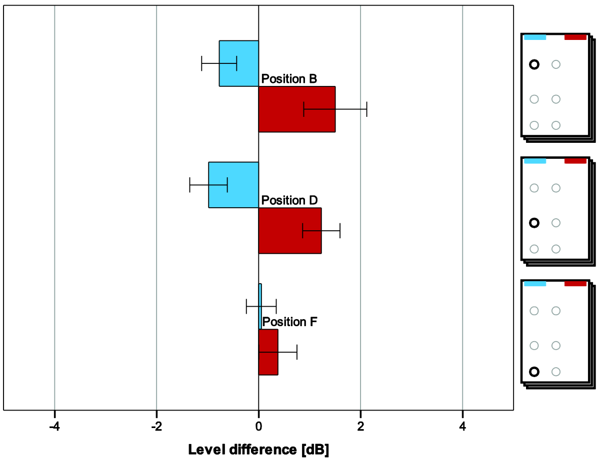


Figure E.41 *Crosstalk per side position; right ear - left ear; all cinemas average; front loudspeakers; 500, 1000 Hz averaged; blue: left loudspeaker only, red: right loudspeaker only*

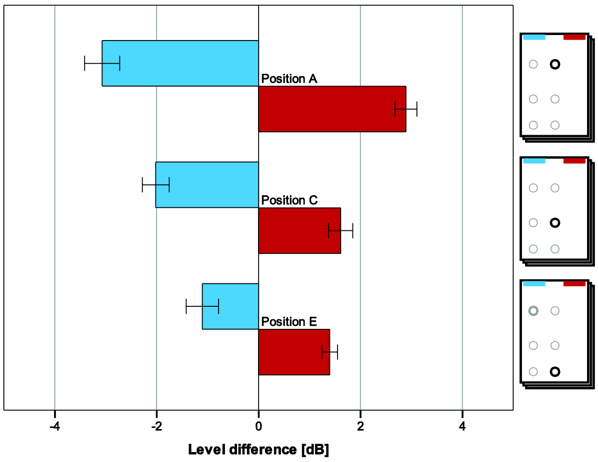


Figure E.42 *Crosstalk per center line position; right ear - left ear; all cinemas average; front loudspeakers; 500, 1000 Hz averaged; blue: left loudspeaker only, red: right loudspeaker only*

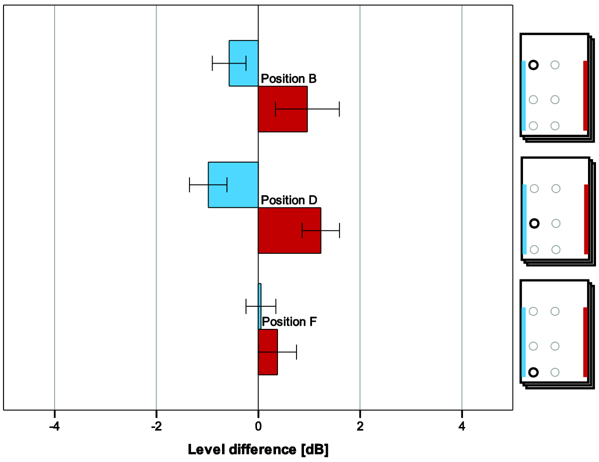


Figure E.43 *Crosstalk per side position; right ear - left ear; all cinemas average; surround loudspeakers; 500, 1000 Hz averaged; blue: left loudspeakers only, red: right loudspeakers only*

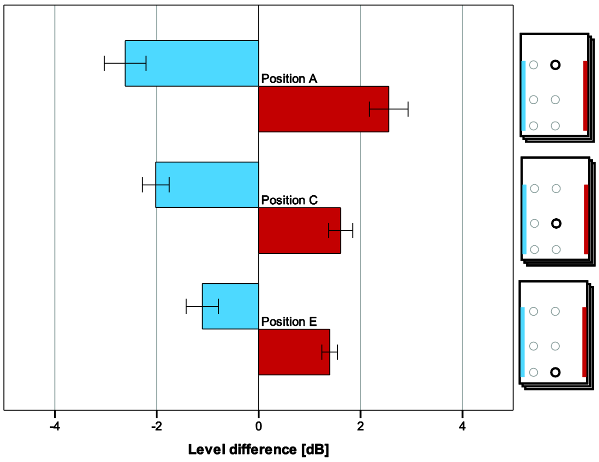


Figure E.44 *Crosstalk per center line position; right ear - left ear; all cinemas average; surround loudspeakers; 500, 1000 Hz averaged; blue: left loudspeakers only, red: right loudspeakers only*

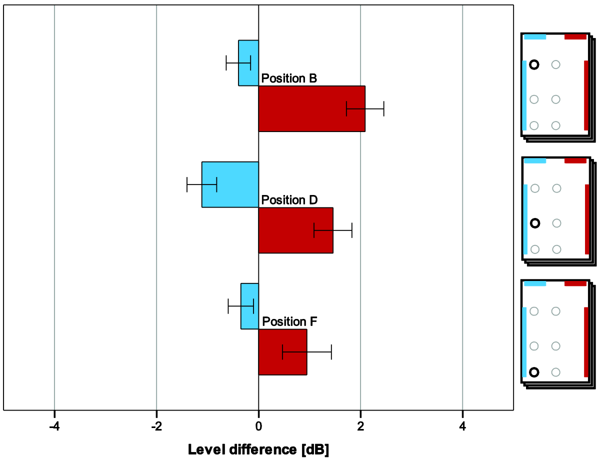


Figure E.45 *Crosstalk per side position; right ear - left ear; all cinemas average; both front and surround loudspeakers; 500, 1000 Hz averaged; blue: left loudspeakers only, red: right loudspeakers only*

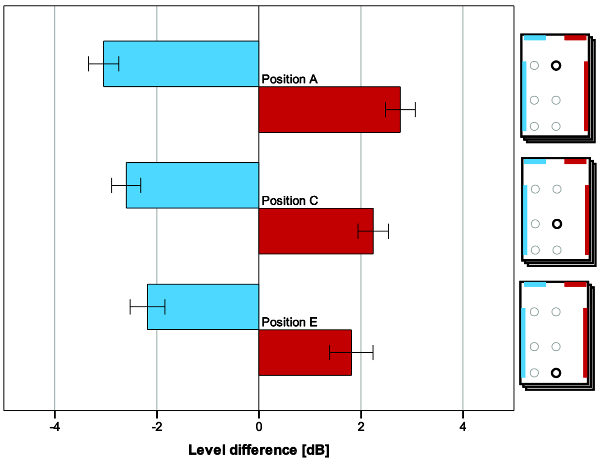


Figure E.46 *Crosstalk per center line position; right ear - left ear; all cinemas average; both front and surround loudspeakers; 500, 1000 Hz averaged; blue: left loudspeakers only, red: right loudspeakers only*

Appendix F: Measurement results

Speakers: Front

INR [dB] Average of 500Hz and 1000 Hz octaves, averaged for both ears

	Cinema 1	Cinema 2	Cinema 3	Cinema 4	Cinema 5	Cinema 6	Cinema 7	Cinema 8	Studio 1
Position A	48.75	58.25	52.50	56.25	59.00	56.75	53.25	63.50	
Position B	48.75	57.75	50.25	54.75	56.75	58.75	55.75	60.25	
Position C	50.25	56.00	50.25	57.50	60.00	55.75	53.50	61.50	59.00
Position D	49.75	51.75	52.50	55.50	59.75	59.00	54.25	61.00	58.35
Position E	51.25	55.50	51.25	59.75	54.25	56.50	55.25	62.00	58.05
Position F	51.50	56.25	51.50	57.00	53.25	56.50	55.50	59.50	58.93

T30 error [%] Average of 500Hz and 1000 Hz octaves, averaged for both ears

	Cinema 1	Cinema 2	Cinema 3	Cinema 4	Cinema 5	Cinema 6	Cinema 7	Cinema 8	Studio 1	Average
Position A	-0.92	-0.89	-0.03	0.79	0.91	0.89	0.10	-0.91		-0.01
Position B	-1.90	-0.59	-0.33	1.06	-0.28	1.91	1.56	0.96		0.30
Position C	-0.40	0.52	0.32	0.45	0.06	0.88	-0.37	-0.76	0.86	0.09
Position D	-2.36	1.08	0.93	0.46	-0.87	0.76	-2.66	0.39	0.46	-0.28
Position E	-0.63	2.21	-0.71	2.22	-1.29	1.03	0.66	-0.56	-1.26	0.37
Position F	-1.88	1.43	-0.58	1.40	0.47	0.07	-0.57	0.17	-0.23	0.06
Average	1.35	1.12	0.48	1.06	0.65	0.92	0.99	0.63	0.70	0.90

EDT error [%] Average of 500Hz and 1000 Hz octaves, averaged for both ears

	Cinema 1	Cinema 2	Cinema 3	Cinema 4	Cinema 5	Cinema 6	Cinema 7	Cinema 8	Studio 1	Average
Position A	7.43	12.15	7.60	-0.49	2.91	15.83	25.64	16.74		10.98
Position B	10.58	8.49	10.78	9.93	10.27	10.50	24.97	21.16		13.33
Position C	5.21	6.81	-1.62	5.58	4.12	11.44	28.94	20.85	-3.28	10.17
Position D	8.09	12.88	4.23	9.78	6.42	7.86	27.65	17.52	-1.17	11.80
Position E	12.30	7.64	4.81	5.06	5.52	8.10	21.32	12.80	8.10	9.69
Position F	10.77	8.35	0.73	5.89	1.04	9.26	21.68	15.06	-1.68	9.10
Average	9.06	9.39	4.96	6.12	5.05	10.50	25.03	17.35	3.56	10.93

C80 error [dB] Average of 500Hz and 1000 Hz octaves, averaged for both ears

	Cinema 1	Cinema 2	Cinema 3	Cinema 4	Cinema 5	Cinema 6	Cinema 7	Cinema 8	Studio 1	Average
Position A	-2.05	-2.30	-1.57	-2.04	-1.32	-2.84	-2.82	-3.50		-2.30
Position B	-1.78	-2.45	-1.13	-2.22	-2.72	-3.67	-3.58	-3.76		-2.66
Position C	-2.42	-3.65	-1.27	-1.57	-1.23	-2.56	-2.67	-3.13	-1.13	-2.31
Position D	-2.73	-2.89	-1.58	-2.14	-1.28	-2.00	-3.25	-3.83	-1.63	-2.46
Position E	-1.65	-2.07	-1.73	-1.82	-2.03	-2.08	-2.91	-0.92	-1.72	-1.90
Position F	-2.28	-2.53	-1.96	-1.81	-2.14	-1.97	-3.95	-2.57	0.01	-2.40
Average	-2.15	-2.65	-1.54	-1.93	-1.79	-2.52	-3.20	-2.95	-1.11	-2.34

MTI error [-] Average of 500Hz and 2000Hz octaves, best ear selected

	Cinema 1	Cinema 2	Cinema 3	Cinema 4	Cinema 5	Cinema 6	Cinema 7	Cinema 8	Studio 1	Average
Position A	-0.020	-0.025	-0.010	-0.025	-0.015	-0.050	-0.090	-0.050		-0.036
Position B	-0.055	-0.030	-0.005	-0.035	-0.050	-0.020	-0.040	-0.080		-0.039
Position C	-0.010	-0.025	-0.020	-0.035	-0.030	-0.010	-0.050	-0.040	0.005	-0.028
Position D	-0.015	-0.025	0.000	-0.040	-0.035	-0.040	-0.055	-0.040	-0.015	-0.031
Position E	-0.040	-0.020	-0.025	-0.025	-0.015	-0.010	-0.065	-0.035	-0.005	-0.029
Position F	-0.035	-0.005	-0.015	-0.030	-0.005	-0.015	-0.080	-0.045	0.020	-0.029
Average	-0.029	-0.022	-0.013	-0.032	-0.025	-0.024	-0.063	-0.048	0.00	-0.032

IACC error [-] Averages of 500Hz and 1000 Hz octaves

	Cinema 1	Cinema 2	Cinema 3	Cinema 4	Cinema 5	Cinema 6	Cinema 7	Cinema 8	Studio 1	Average
Position A	-0.165	-0.050	-0.005	-0.040	-0.220	-0.190	-0.075	-0.215		-0.120
Position B	-0.255	-0.230	-0.165	-0.305	-0.165	-0.255	-0.305	-0.165		-0.231
Position C	-0.310	-0.340	-0.045	-0.035	-0.160	-0.265	-0.155	-0.145	-0.192	-0.182
Position D	-0.285	-0.255	-0.215	-0.135	-0.155	-0.220	-0.290	-0.135	-0.148	-0.211
Position E	-0.210	-0.130	-0.095	-0.115	-0.145	-0.180	-0.260	0.010	-0.119	-0.141
Position F	-0.310	-0.180	-0.220	-0.250	-0.265	-0.285	-0.160	-0.060	-0.043	-0.216
Average	-0.256	-0.198	-0.124	-0.147	-0.185	-0.233	-0.208	-0.118	-0.13	-0.183

Speakers: Surround

INR [dB] Average of 500Hz and 1000 Hz octaves, averaged for both ears

	Cinema 1	Cinema 2	Cinema 3	Cinema 4	Cinema 5	Cinema 6	Cinema 7	Cinema 8	Studio 1
Position A	54.50	58.50	59.75	56.00	56.00	54.25	49.50	60.00	
Position B	56.50	58.25	59.75	53.25	55.75	56.00	50.75	58.00	
Position C	57.50	58.25	60.75	55.75	55.00	53.75	52.00	60.00	58.44
Position D	56.50	55.50	58.75	53.50	53.25	55.00	49.50	59.25	58.21
Position E	55.25	58.25	58.75	54.25	52.50	54.75	51.25	58.00	58.76
Position F	54.25	59.00	60.25	54.00	54.00	54.75	50.25	58.50	66.84

T30 error [%] Average of 500Hz and 1000 Hz octaves, averaged for both ears

	Cinema 1	Cinema 2	Cinema 3	Cinema 4	Cinema 5	Cinema 6	Cinema 7	Cinema 8	Studio 1	Average
Position A	-0.48	-0.59	0.37	0.13	-0.95	0.53	-0.42	1.08		-0.04
Position B	1.73	0.59	0.33	0.99	-0.51	0.18	-1.04	0.64		0.36
Position C	-0.98	0.48	1.43	0.60	-0.16	1.14	1.53	-0.48	-0.53	0.45
Position D	-1.37	0.05	0.45	0.47	-0.22	0.32	-0.85	2.71	0.28	0.20
Position E	0.53	-0.61	0.17	0.17	-2.20	1.71	0.37	2.61	1.29	0.34
Position F	1.04	-0.10	0.81	0.48	0.30	2.04	0.53	-0.42	0.65	0.58
Average	1.02	0.40	0.59	0.47	0.72	0.99	0.79	1.32	0.69	0.79

EDT error [%] Average of 500Hz and 1000 Hz octaves, averaged for both ears

	Cinema 1	Cinema 2	Cinema 3	Cinema 4	Cinema 5	Cinema 6	Cinema 7	Cinema 8	Studio 1	Average
Position A	10.86	14.64	6.62	15.10	-1.10	6.87	34.17	18.44		13.20
Position B	9.45	9.88	4.66	8.81	8.71	10.83	31.67	24.06		13.51
Position C	0.02	10.85	-0.30	1.56	5.98	3.90	13.31	18.32	-0.07	6.70
Position D	5.42	7.52	2.54	0.59	8.84	15.13	29.11	19.26	1.81	11.05
Position E	-0.89	10.93	-0.67	7.06	15.45	6.33	28.38	17.12	-0.18	10.47
Position F	6.23	10.67	-4.98	0.49	8.15	-0.36	30.18	21.38	10.68	8.97
Average	5.48	10.75	3.29	5.60	8.04	7.24	27.80	19.76	3.19	11.00

C80 error [dB] Average of 500Hz and 1000 Hz octaves, averaged for both ears

	Cinema 1	Cinema 2	Cinema 3	Cinema 4	Cinema 5	Cinema 6	Cinema 7	Cinema 8	Studio 1	Average
Position A	-3.44	-3.26	-2.53	-1.92	-0.55	-3.37	-5.46	-3.22		-2.97
Position B	-3.57	-3.00	-2.97	-2.42	-2.44	-3.76	-7.00	-5.98		-3.89
Position C	-2.44	-1.97	-1.59	-1.80	-1.78	-2.34	-2.33	-3.51	-1.27	-2.22
Position D	-3.12	-2.47	-2.92	-1.45	-3.10	-3.60	-4.49	-5.36	-2.03	-3.31
Position E	-2.56	-2.44	-2.58	-2.20	-2.96	-1.65	-4.28	-4.00	-0.80	-2.83
Position F	-3.24	-2.39	-1.99	-1.95	-1.94	-2.03	-5.32	-6.02	-2.39	-3.11
Average	-3.06	-2.59	-2.43	-1.96	-2.13	-2.79	-4.81	-4.68	-1.62	-3.06

MTI error [-] Average of 500Hz and 2000Hz octaves, best ear selected

	Cinema 1	Cinema 2	Cinema 3	Cinema 4	Cinema 5	Cinema 6	Cinema 7	Cinema 8	Studio 1	Average
Position A	-0.070	-0.055	-0.025	-0.050	0.015	-0.050	-0.100	-0.065		-0.050
Position B	-0.050	-0.030	-0.035	-0.030	-0.030	-0.040	-0.105	-0.060		-0.048
Position C	-0.020	-0.020	-0.020	-0.030	-0.020	-0.035	-0.040	-0.060	-0.010	-0.031
Position D	-0.040	0.000	0.000	-0.010	-0.055	-0.030	-0.060	-0.070	-0.010	-0.033
Position E	-0.035	-0.025	-0.010	-0.035	-0.060	-0.035	-0.100	-0.065	0.000	-0.046
Position F	-0.030	-0.015	0.005	-0.005	-0.040	-0.030	-0.105	-0.075	-0.020	-0.037
Average	-0.041	-0.024	-0.014	-0.027	-0.032	-0.037	-0.085	-0.066	-0.01	-0.041

IACC error [-] Averages of 500Hz and 1000 Hz octaves

	Cinema 1	Cinema 2	Cinema 3	Cinema 4	Cinema 5	Cinema 6	Cinema 7	Cinema 8	Studio 1	Average
Position A	-0.220	-0.320	-0.095	-0.120	-0.170	-0.265	-0.340	-0.305		-0.229
Position B	-0.240	-0.105	-0.250	-0.210	-0.205	-0.245	-0.210	-0.105		-0.196
Position C	-0.155	-0.250	0.000	-0.065	-0.355	-0.275	-0.085	-0.255	-0.169	-0.180
Position D	-0.305	-0.180	-0.205	-0.250	-0.310	-0.395	-0.320	-0.230	-0.253	-0.274
Position E	-0.185	-0.215	-0.085	0.025	-0.120	-0.225	-0.180	-0.235	-0.322	-0.153
Position F	-0.325	-0.155	-0.125	-0.315	-0.175	-0.280	-0.235	-0.310	-0.155	-0.240
Average	-0.238	-0.204	-0.127	-0.156	-0.223	-0.281	-0.228	-0.240	-0.22	-0.212

Speakers: Both Front & Surround

INR [dB] Average of 500Hz and 1000 Hz octaves, averaged for both ears

	Cinema 1	Cinema 2	Cinema 3	Cinema 4	Cinema 5	Cinema 6	Cinema 7	Cinema 8	Studio 1
Position A	48.50	67.28	51.25	55.50	58.50	55.50	52.25	60.25	
Position B	50.25	58.50	52.25	54.75	56.00	56.00	53.75	59.25	
Position C	50.75	58.00	51.00	57.25	58.00	54.50	53.75	63.50	59.20
Position D	53.00	56.25	51.00	55.25	56.50	57.00	53.75	60.50	58.43
Position E	51.25	57.75	52.75	55.00	50.49	55.25	53.50	62.00	58.36
Position F	53.25	58.75	54.00	55.25	55.50	56.50	53.25	61.50	58.06

T30 error [%] Average of 500Hz and 1000 Hz octaves, averaged for both ears

	Cinema 1	Cinema 2	Cinema 3	Cinema 4	Cinema 5	Cinema 6	Cinema 7	Cinema 8	Studio 1	Average
Position A	-0.73	-0.36	-0.45	0.07	0.07	-0.04	-0.21	-0.81		-0.31
Position B	-0.59	-0.59	0.26	0.62	-0.32	0.80	0.80	1.30		0.29
Position C	-0.63	1.26	0.03	0.62	0.23	1.27	1.44	-0.87	0.27	0.42
Position D	-2.17	-0.33	0.14	-0.21	-0.58	1.33	-1.88	0.46	-0.18	-0.41
Position E	0.91	-0.81	-0.21	1.21	-1.12	1.51	0.92	1.64	-0.06	0.51
Position F	-0.85	0.03	0.49	-1.18	0.65	-0.25	-0.44	1.11	0.93	-0.05
Average	0.98	0.56	0.26	0.65	0.49	0.86	0.95	1.03	0.36	0.72

EDT error [%] Average of 500Hz and 1000 Hz octaves, averaged for both ears

	Cinema 1	Cinema 2	Cinema 3	Cinema 4	Cinema 5	Cinema 6	Cinema 7	Cinema 8	Studio 1	Average
Position A	11.99	16.08	6.48	4.66	1.87	13.72	29.48	16.83		12.64
Position B	13.83	8.32	9.55	9.87	7.63	9.75	29.18	21.57		13.71
Position C	2.63	9.41	-1.74	6.32	1.65	4.67	17.15	26.87	-6.19	8.37
Position D	5.24	8.31	11.13	4.23	5.86	11.50	25.84	22.69	0.46	11.85
Position E	3.72	12.27	1.35	2.57	8.26	6.79	22.59	12.22	2.57	8.72
Position F	7.28	10.61	0.86	5.07	6.13	6.65	24.76	20.68	3.90	10.26
Average	7.45	10.83	5.19	5.45	5.23	8.85	24.84	20.14	3.28	11.00

C80 error [dB] Average of 500Hz and 1000 Hz octaves, averaged for both ears

	Cinema 1	Cinema 2	Cinema 3	Cinema 4	Cinema 5	Cinema 6	Cinema 7	Cinema 8	Studio 1	Average
Position A	-3.53	-2.99	-1.79	-2.13	-2.60	-3.22	-3.42	-3.65		-2.91
Position B	-3.41	-2.94	-1.43	-2.84	-2.61	-3.90	-4.16	-4.24		-3.19
Position C	-2.98	-2.02	-1.28	-1.80	-1.38	-2.41	-2.22	-5.32	-0.76	-2.42
Position D	-3.43	-2.66	-2.75	-2.20	-3.07	-3.45	-4.70	-7.80	-2.46	-3.76
Position E	-2.30	-2.72	-2.95	-1.68	-4.04	-2.68	-4.73	-6.87	-1.83	-3.49
Position F	-2.68	-2.83	-3.47	-2.60	-3.61	-3.17	-6.87	-10.94	-1.88	-4.52
Average	-3.05	-2.69	-2.28	-2.21	-2.88	-3.14	-4.35	-6.47	-1.73	-3.38

MTI error [-] Average of 500Hz and 2000Hz octaves, best ear selected

	Cinema 1	Cinema 2	Cinema 3	Cinema 4	Cinema 5	Cinema 6	Cinema 7	Cinema 8	Studio 1	Average
Position A	-0.040	-0.060	-0.020	-0.035	-0.020	-0.050	-0.095	-0.065		-0.048
Position B	-0.065	-0.020	-0.010	-0.020	-0.020	-0.015	-0.070	-0.080		-0.038
Position C	-0.015	-0.020	-0.015	-0.025	-0.030	-0.025	-0.015	-0.070	0.000	-0.027
Position D	-0.010	-0.015	-0.015	-0.020	-0.035	-0.025	-0.040	-0.065	-0.010	-0.028
Position E	-0.035	-0.030	-0.020	-0.030	-0.025	-0.045	-0.075	-0.050	-0.015	-0.039
Position F	-0.035	-0.020	0.000	-0.020	-0.030	-0.050	-0.065	-0.085	0.000	-0.038
Average	-0.033	-0.028	-0.013	-0.025	-0.027	-0.035	-0.060	-0.069	-0.01	-0.036

IACC error [-] Averages of 500Hz and 1000 Hz octaves

	Cinema 1	Cinema 2	Cinema 3	Cinema 4	Cinema 5	Cinema 6	Cinema 7	Cinema 8	Studio 1	Average
Position A	-0.195	-0.140	0.005	-0.050	-0.300	-0.190	-0.100	-0.240		-0.151
Position B	-0.285	-0.135	-0.205	-0.300	-0.275	-0.200	-0.305	-0.150		-0.232
Position C	-0.235	-0.280	-0.055	-0.110	-0.200	-0.250	-0.160	-0.405	-0.186	-0.212
Position D	-0.390	-0.200	-0.305	-0.250	-0.245	-0.365	-0.245	-0.205	-0.243	-0.276
Position E	-0.345	-0.255	-0.165	-0.065	-0.250	-0.255	-0.215	0.045	-0.327	-0.188
Position F	-0.305	-0.135	-0.150	-0.320	-0.200	-0.310	-0.210	-0.310	-0.176	-0.243
Average	-0.293	-0.191	-0.146	-0.183	-0.245	-0.262	-0.206	-0.211	-0.23	-0.217