The Effect of the Acoustics of Sound Control Rooms on the Perceived Acoustics of a Live Concert Hall Recording

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Abstract: - Live recordings of music and speech in concert halls have acoustical properties, such as reverberation, definition, clarity and spaciousness. Sound engineers play back these recordings through loudspeakers in sound control rooms for audio CD or film. The acoustical properties of these rooms influence the perceived acoustics of the live recording. To find the practical impact of a sound control room on the acoustical parameter values of a concert hall, combinations of concert hall impulse responses and sound control room impulse responses have been investigated using convolution techniques. It can be concluded that the ITU-recommendations used for sound control room design are sufficient for reverberation and speech intelligibility judgement of concert hall recordings. Clarity judgement needs a very high decay rate, while judgement of spaciousness can only be done by headphone.

Key-Words: Sound control, Sound studio, Control room, Room acoustics, Concert hall, Recording, Playback, Convolution, Head and torso simulator, HATS

1 Introduction

From experience and an earlier investigation [1] it is clear that a recorded reverberation time can only be heard in a room having a reverberation time shorter than the one in which the recording was made. The smallest details and the finest nuances with regard to colouring, definition and stereo image can only be judged and criticized when there is little acoustical influence from the playback acoustics on the recorded acoustics. However, usually the listening or playback room in combination with the used sound system affects the recorded acoustics. This happens in class rooms, congress halls, cinemas and even in sound control rooms.

The impact of the control room acoustics on live recorded acoustics has been investigated, using the acoustic measurement program DIRAC. To this end the convolution function has been applied to binaural impulse responses of six control rooms, a symphonic concert hall, a chamber music hall and a professional headphone. The impact on reverberation, speech intelligibility, clarity and inter-aural cross-correlation has been investigated. From the results, a first step is made to judge the quality of a sound control room using this new approach, starting from the JND (Just Noticeable Difference) as allowable error.

2 Procedure

Starting from a set of 6 binaural control room impulse responses, 1 binaural headphone impulse response and 4 binaural concert hall impulse responses, 28 pairs of impulse responses are defined. From each pair ($\boldsymbol{h_1}$, $\boldsymbol{h_2}$) the first is considered as a concert hall impulse response and the other as a control room impulse response. Each pair ($\boldsymbol{h_1}$, $\boldsymbol{h_2}$) is convolved (see Section 4) to obtain the impulse response $\boldsymbol{h_{12}}$, heard when playing back the recorded concert hall impulse response in the sound control room. $\boldsymbol{h_{12}}$, thus representing $\boldsymbol{h_1}$ affected by $\boldsymbol{h_2}$, is then compared to $\boldsymbol{h_1}$, with respect to the reverberation time T_{30}, the clarity C_{80}, the modulation transfer index MTI and the inter-aural cross-correlation coefficient IACC [2,3].

3 Room acoustic parameters

Many room acoustic parameters are derived from the room's impulse responses. Examples of such parameters are the reverberation time, which is related to the energy decay rate, the clarity, the definition and the centre time, which are related to early to late energy ratios, the speech intelligibility, which is related to the energy modulation transfer characteristics of the impulse response and the latereral energy fraction, the late lateral sound energy and the inter-aural cross-correlation, which are related to the lateral impulse response measurements.

Four of them have been investigated, being the reverberation time T_{30}, the clarity C_{80}, the modulation transfer index MTI and the inter-aural cross-correlation. The JND-values of these parameters are presented in table 1.

3.1 Reverberation time T

The reverberation time T is calculated from the squared impulse response by backwards integration [4] through the following relation:

$$\boldsymbol{L}(\boldsymbol{t}) = 10\lg\frac{\int_{t}^{\infty}\boldsymbol{p}^2(\boldsymbol{t})\boldsymbol{dt}}{\int_{0}^{\infty}\boldsymbol{p}^2(\boldsymbol{t})\boldsymbol{dt}} \quad [\boldsymbol{dB}] \tag{1}$$

where L(t) is the equivalent of the logarithmic decay of the squared pressure. For this investigation the T_{30} with its evaluation decay range from -5 dB to -35 dB is used to determine T.

3.2 Clarity C_{80}

The parameter C_{80} [5] is an early to late arriving sound energy ratio intended to relate to conditions for music and is calculated from the impulse response using the following relation:

$$\boldsymbol{C}_{80} = 10\lg\frac{\int_{0}^{80\boldsymbol{ms}}\boldsymbol{p}^2(\boldsymbol{t})\boldsymbol{dt}}{\int_{80\boldsymbol{ms}}^{\infty}\boldsymbol{p}^2(\boldsymbol{t})\boldsymbol{dt}} \quad [\boldsymbol{dB}] \tag{2}$$

3.3 Modulation Transfer Index

The Modulation Transfer Function m(F) [6] describes to what extent the modulation m is transferred from source to receiver, as a function of the modulation frequency F, which ranges from 0.63 to 12.5 Hz. The m(F) is calculated from the squared impulse response using the folowing relation:

$$\boldsymbol{m}(\boldsymbol{F}) = \frac{\int_{-\infty}^{\infty}\boldsymbol{p}^2(\boldsymbol{t})\cdot\boldsymbol{e}^{-j2\pi\boldsymbol{F}\boldsymbol{t}}\boldsymbol{dt}}{\int_{-\infty}^{\infty}\boldsymbol{p}^2(\boldsymbol{t})\boldsymbol{dt}} \quad [-] \tag{3}$$

The m(F) values for 14 modulation frequencies are averaged, resulting in the so called modulation transmission index MTI [7], given by:

$$\boldsymbol{MTI}(\boldsymbol{F}) = \frac{\sum_{n=1}^{14}\boldsymbol{m}(\boldsymbol{F}_n)}{14} \quad [-] \tag{4}$$

3.4 Inter-aural cross-correlation coefficient IACC

Although the IACC is still subject to discussion and research, the parameter IACC [8] is used to measure the "spatial impression" and is calculated from the impulse response using the following relation:

$$\boldsymbol{IACF}_{t_1,t_2}(\boldsymbol{\tau}) = \frac{\int_{t_1}^{t_2}\boldsymbol{p}_l(\boldsymbol{t})\cdot\boldsymbol{p}_r(\boldsymbol{t}+\boldsymbol{\tau})\boldsymbol{dt}}{\sqrt{\int_{t_1}^{t_2}\boldsymbol{p}_l^2(\boldsymbol{t})\boldsymbol{dt}\int_{t}^{t_2}\boldsymbol{p}_r^2(\boldsymbol{t})\boldsymbol{dt}}} \quad [-] \tag{5}$$

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 inter-aural cross-correlation coefficient IACC is given by:

$$\boldsymbol{IACC}_{t_1,t_2} = |\boldsymbol{IACF}_{t_1,t_2}(\boldsymbol{\tau})|_{\max} \quad \text{for } -1\text{ms} < \boldsymbol{\tau} < +1\text{ms} \tag{6}$$

For this investigation only the interval between $t_1 = 0$ and $t_2 = 80$ ms (early reflections) is used.

Table 1. *JND (Just Noticeable Difference).*

T_{30}	C_{80}	MTI	IACC
10 %	1 dB	0.1	0.075

4 Impulse responses and measurements

4.1 Measurement conditions

All measurements, both the single channel and the dual channel, were performed using a HATS or an artificial head [9]. The decay range (INR) [10] for all measured impulse responses had a minimum exceeding 52 dB for all octave bands used.

4.1.1 Large and small concert hall

Impulse response measurements were performed in the large and small concert hall of "The Frits Philips Muziekcentrum Eindhoven" with a volume of approx. 14,400 m^3, an unoccupied stage floor and $T_{empty} \approx 2$ s for the large hall and a volume of approx. 4000 m^3, an unoccupied stage floor and $T_{empty} \approx 1.5$ s for the small (chamber music) hall. Figures 1 en 2 give an impression of the halls and the schematic floorplans with the source position S as indicated, placed on the major axis of the hall, and the microphone positions R1 and R2, where R1 is placed at approx. 5 m from the source, equal to the critical distance, and R2 is placed at approx. 18 m (diffuse field). More specifications of both concert halls are presented in table 2, using the total average over both microphones (ears) of the HATS, the 500 and 1000 Hz octave bands and the receiver positions R1 and R2. The INR for all measured symphonic and chamber music hall impulse responses had an average of 60 dB for all used octave bands, with a minimum exceeding 54 dB.

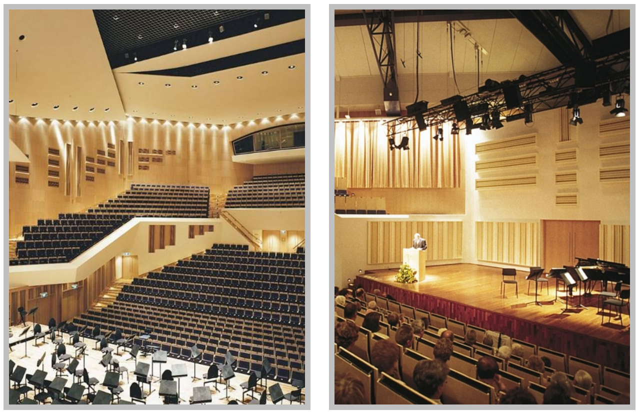


Fig 1. *Measured symphonic and chamber music hall.*

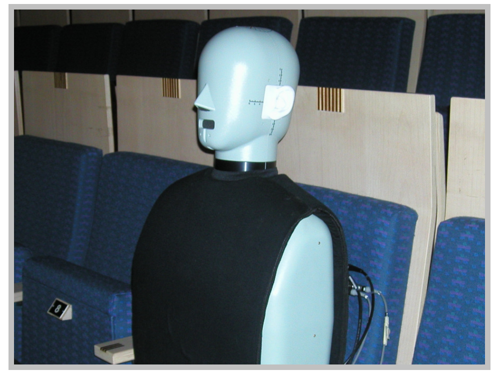
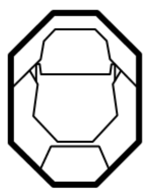


Fig 3. *Concert hall measurement using a Head and Torso Simulator (HATS).*

Table 2. *Concert hall specifications.*

Hall type	Symphonic music	Chamber music
Floor plan (10 m)		
Volume	14400	4000
Number of Seats	1250	385
Stage area [m²]	200	70
T_{avg} [s]	2.0	1.5
$C80_{avg}$ [dB]	1.1	2.7
MTI [-]	0.51	0.57
IACC [-]	0.58	0.44

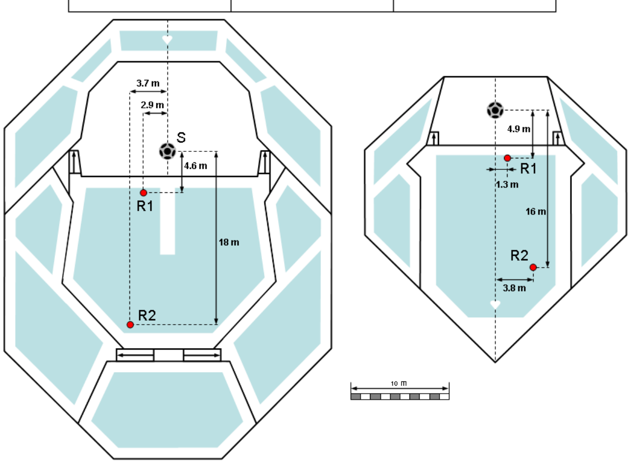


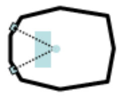
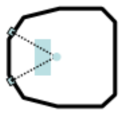
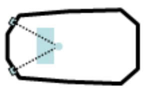
Fig 2. *Sound source S and microphone R positions.*

4.1.2 Control rooms

The control rooms under test are all Dutch control rooms and qualified as very good by the sound engineers as well as the designers. For the sake of privacy the measured control rooms are marked from CR1 to CR6. The control rooms were measured extensively with microphone positions placed on a grid consisting of 15 measurement positions [11]. Based on these measurements several important room acoustical parameters were computed. The results of the reverberation time measurements revealed that in the lower frequencies all control rooms under test met the generally used ITU recommendation [12]. In the higher frequencies only control room CR2 met this criterion. Specifications of all control rooms under test are presented in table 3. The control room impulse response measurements were performed at the sound engineer position, known as the 'sweet spot', the focal point between the main (wall mounted) loudspeakers. Control room CR5 was only suitable for near field monitoring. The INR for all measured control room impulse responses had an average of 57 dB for all used octave bands, with a minimum exceeding 52 dB.

Fig 4. *Sweet spot measurement using a Head and Torso Simulator (HATS) or an artificial head.*

Table 3. *Control room specifications.*

Control room	Floor plan (5m)	Floor area m^2	Vol. m^3	T_{avg} s
CR 1		33	103	0.32
CR 2		33	98	0.22
CR 3		35	100	0.20
CR 4		40	120	0.19
CR 5		25	75	0.14
CR 6		25	75	0.14

4.1.2 Headphone

To complete the set of impulse responses a pure free field measurement was performed using the HATS and a high quality headphone as shown in figure 5. The minimum INR for the measured impulse response reached a value of 88 dB for both the 500 Hz and the 1 kHz octave band.

Fig 5. *Headphone transfer measurement using a HATS.*

4.2 Measurement equipment

The measurement equipment consisted of the following components:

- *Head And Torso Simulator:* used in concert halls and control rooms. (B&K - Type 4128C);
- *artificial head:* used in control rooms (Sennheiser - MZK 2002)
- *microphones:* used with artificial head (Sennheiser - MKE 2002)
- *power amplifier:* used in concert halls (Acoustics Engineering - Amphion);
- *sound source:* omnidirectional, used in concert halls. (B&K - Type 4292);
- *sound device:* USB audio device (Acoustics Engineering - Triton);
- *headphone:* used as a reference source; (Philips: SBC HP890)
- *measurement software:* DIRAC (B&K - Type 7841)

5 Convolution

The convolution $\boldsymbol{y}$ of signal $\boldsymbol{s}$ and system impulse response $\boldsymbol{h}$ is written and defined as:

$$\boldsymbol{y}(t) = \boldsymbol{s}(t) * \boldsymbol{h}(t) \tag{7}$$

or

$$\boldsymbol{y}(t) = (\boldsymbol{s} * \boldsymbol{h})(t) = \int_{-\infty}^{\infty} \boldsymbol{s}(t) \cdot \boldsymbol{h}(t-\tau) d\tau \tag{8}$$

In words: the convolution is defined as the integral of the product of two functions $\boldsymbol{s}$ and $\boldsymbol{h}$ after one is reversed and shifted. From a room acoustical point of view ***s(t)*** is a piece of music that is recorded in a concert hall and played back in a sound control room, ***h(t)*** the impulse response of the control room and ***y(t)*** the convolved sound as it is heard in that control room. When the control (listening) room is reverberant, smoothing of the sound occurs. The room acoustics in the music recording that we want to judge will be affected by the acoustics of the sound control (listening) room. With a double convolution by which an impulse response from the concert hall is convolved with a dry recording of music and afterward the result is convolved with the impulse response of a sound control room, it is possible to hear how a recording, made in the concert hall, sounds when played back in the control room. The result is a more or less smoothed sound signal. By using a pure impulse (Dirac delta function) instead of a normal sound signal to be convolved with both room impulse responses (eq 9 and 10) we can examine what the control room does with the concert hall concerning the values for the room acoustic parameters (eq 11). Therefore it is possible to derive a 'room in room' acoustic parameter value from the more or less smoothed impulse response. Mathematically:

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$$h(t) * \delta(t) = \delta(t) * h(t) = h(t) \qquad (9)$$

Where:
h(t) = room impulse response
δ(t) = Dirac delta function (ideal impulse)

$$h_{12}(t) = \delta(t) * h_1(t) * h_2(t) = h_1(t) * h_2(t) \qquad (10)$$

Where:
$h_{12}(t)$ = 'total' impulse response room1 room2
$h_1(t)$ = impulse response room 1
$h_2(t)$ = impulse response room 2

Substituting equation (10) into equation (7) results in:

$$y_{12}(t) = s(t) * h_{12}(t) \qquad (11)$$

Where:
$y_{12}(t)$ = convolution of a random sound signal with the 'total' impulse response
$s(t)$ = random sound signal

6 Measurement results

In Figure 6 through 13 the results of the convolutions are depicted as an average over the 500 and 1000 Hz octave band. Each graph shows the difference between 2 values of a parameter, one calculated from $\boldsymbol{h_{12}}$, the convolution of the concert hall with the control room and one from $\boldsymbol{h_1}$, the impulse response of the concert hall. On the x-as the control rooms CR1 to CR6 are given in order of the decay rate. The differences are calculated for four acoustical parameters: T_{30}, C_{80}, MTI and IACC.

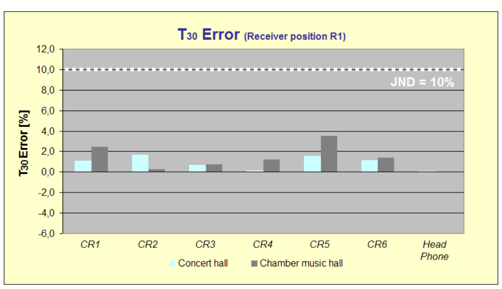

Fig 6. *Percentual difference between $T_{h_{12}}$ and T_{h_1} (T_{30} error) measured at (hall) position R1*

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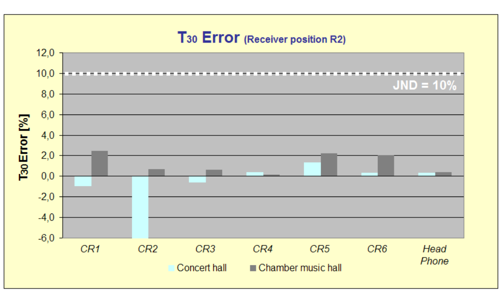

Fig 7. *Percentual difference between $T_{h_{12}}$ and T_{h_1} (T_{30} error) measured at (hall) position R2.*

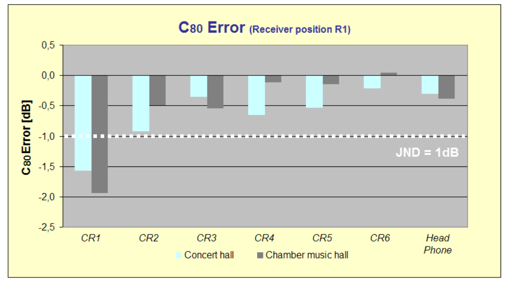

Fig 8. *Difference between $C_{80}h_{12}$ and $C_{80}h_1$ (C_{80} error) measured at (hall) position R1.*

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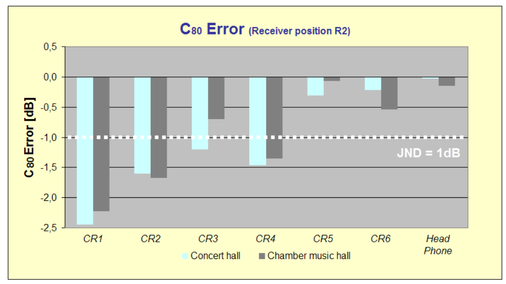

Fig 9. *Difference between $C_{80}h_{12}$ and $C_{80}h_1$ (C_{80} error) measured at (hall) position R2.*

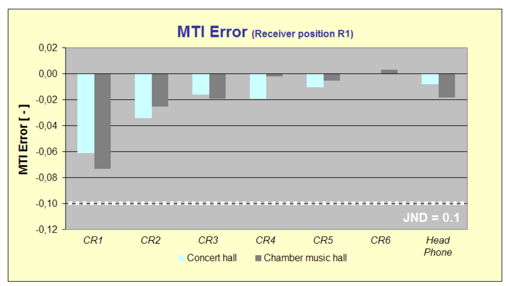

Fig 10. *Difference between $MTI_{h_{12}}$ and MTI_{h_1} (MTI error) measured at (hall) position R1.*

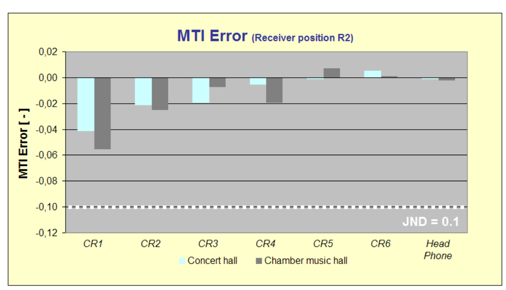

Fig 11. *Difference between $MTI_{h_{12}}$ and MTI_{h_1} (MTI error) measured at (hall) position R2.*

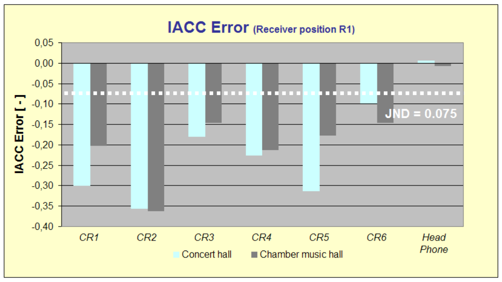

Fig 12. *Difference between* $IACC_{h_{12}}$ *and* $IACC_{h_1}$ *(IACC error) measured at (hall) position R1.*

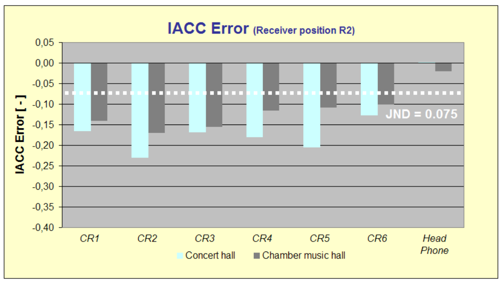

Fig 13. *Difference between* $IACC_{h_{12}}$ *and* $IACC_{h_1}$ *(IACC error) measured at (hall) position R2.*

7 Conclusion

Starting with six qualified good, more or less standardised sound control rooms, two concert halls and the Just Noticeable Difference of four calculated room acoustic (ISO/IEC) parameters it can be concluded:

- The ITU-recommendations for sound control room design are adequate for evaluation of reverberation in concert hall recordings.
- When it is important to asses the details of sound definition of a concert hall recording, you need a control room with a very high decay rate. Only the control rooms with a reverberation time below 0.15 s can be used.
- The ITU-recommendations for sound control room design are adequate for evaluation of speech intelligibility in concert hall recordings.
- An accurate judgement of spaciousness of a binaural concert hall recording apparently requires the use of headphones. This requires further investigation.

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