Proceedings of 20th International Congress on Acoustics, ICA 2010

23-27 August 2010, Sydney, Australia

Reverberation Time – The Mother of All Room Acoustic Parameters

Magne Skålevik

Brekke & Strand, Oslo, Norway
and
www.akutek.info

PACS: 43.55, 43.55.Gx

ABSTRACT

Wallace Sabine introduced the reverberation time (RT) as a measure of acoustic conditions in rooms a century ago. After some decades of experience with RT it became evident that two rooms with similar RT could still be sounding differently. Until today, a large number of different parameters have been suggested to describe these differences. In an attempt to settle for a limited number of listener aspects, and a limited number of physical measures associated with each of them, a set of five aspects have been suggested. In the ISO standard 3382-1, the RT is not included in the group of physical measures associated with listener's aspects. It is tempting to jump to the conclusion that the reverberation time era has come to an end. However, from statistical analysis of 126 measurements in 11 European concert halls it is shown that RT is the underlying acoustical parameter governing 4 out of the 5 listener's aspects included in ISO 3382-1. In the work reported in this paper, it is concluded that the 4 listener aspects Level, Reverberance, Clarity and Listener Envelopment can be predicted from RT, volume and source-receiver distance. Thus the statement that RT is the underlying parameter of 4 of the 5 listener aspects still holds. Further investigations with more data should be carried out to increase the statistical confidence of the results.

INTRODUCTION

Since Wallace Sabine introduced the reverberation time (RT) as a measure of acoustic conditions in rooms a century ago, a large number of different parameters have been suggested. After some decades of experience with RT it became evident that two rooms could be sounding quite differently even if they had similar RT. The post-war design tendency towards wider concert halls led to acoustics with a lack of early reflections and a long initial time delay gap at many seats, an effect that could be measured by the initial time delay gap (IDTG) and the clarity parameters C, D, Ts. By introducing canopies under the ceiling, more early reflections were provided, inherently leading to a more vertical sound field, suppressing the already weak lateral reflections even more. This problem was associated with a lack of apparent source width ASW, which could be measured by the (Early) Lateral Fraction LF and 1-IACC. Since the 1980's the early decay time EDT has been used to measure the amount of reverberance, i.e. the perceived reverberation, in contrast to the full decay that usually is perceived only when the music stops. It has also been proved that listeners preference of halls relate to a proper sound level, motivating use of the G (Strength) parameter.

By today, acousticians have arrived at some consensus that even the listener's sense of envelopment LEV by sound is important to acoustics in a concert hall, and that this can be measured by the amount of late arriving energy. There are still discussions regarding the significance of lateral, vertical and rear directional content of this late energy. For the purpose of this paper we shall ignore these details and assume that LEVis associated with the total late (after 80ms) energy level. In an attempt to settle for a limited number of listener aspects and a limited number of physical measures, a set of five listener aspects with their corresponding acoustic quantities have been suggested.

The five listener aspects listed in Table 1 are to be considered local, i.e. receiver position dependent, in contrast to RT, which is considered a global parameter describing the overall acoustic properties of the room. In the ISO standard 3382-1, RT is not included in the group of physical measures associated with listener aspects. It may be tempting to jump to the conclusion that the reverberation time era has come to an end. However, from statistical analysis of measurements and computer simulations, and with Barron's Revised Theory, it can be shown that RT is the underlying acoustical parameter governing 4 out of the 5 important listener aspects. Besides, if any acoustician where allowed to ask for only one single number in order to obtain information about the acoustics of a concert hall, that would most likely be the mid-frequency RT. Rather than having become an obsolete physical quantity, the reverberation time may turn out to be more significant than ever, defending its position as the mother of all room acoustical parameters.

To study the role of the reverberation time, a statistical analysis of the 126 measurements from 11 European halls by Gade[1] in 1989 has been carried out. This paper reports the result of this study.

Table 1: The 5 listener aspects and acoustic quantities

Subjective listener aspect	**Acoustic quantity**	**Just Noticeable Difference (JND)**
Subjective level of sound	Sound Strength G, in dB	1dB
Perceived reverberance	Early Decay Time, EDT, in s	5%
Perceived clarity of sound	Clarity, C80, in dB	1 dB
Apparent source width, ASW	Early Lateral Energy Fraction, LF	0.05
Listener envelopment[1] LEV	Late Sound Level, G_{late} , in dB	1 dB

METHOD

The hypothesis is: The 4 listener aspects Level, Reverberance, Clarity and Listener Envelopment can be predicted from RT. In order to test the hypothesis, a set of 5 simplified prediction formulas based on RT, room volume V and Source-Receiver-Distance r, are designed, one for each of the 5 aspects above. 4 of the 5 prediction formulas depend on RT, while the 5th does not. RT and V are the global (hall specific) variables, while r is the spatial variable. The hypothesis can be rejected if it is shown that the 4 aspects cannot be predicted by RT. If not, the hypothesis and the statement that RT governs 4 listener aspects still hold. To assess the outcome of the simplified predictions, they are compared with predictions by the computer simulation software ODEON version 10, which has through round robin tests been proven to be a state-of-the art prediction tool.

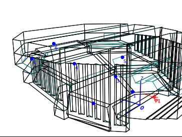
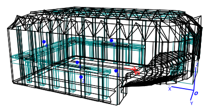
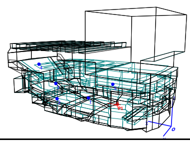
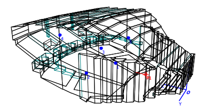
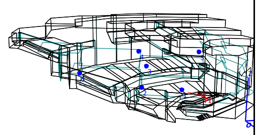
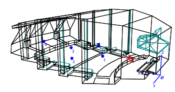
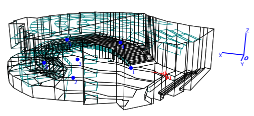
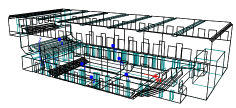
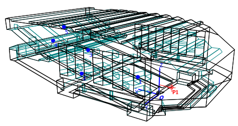
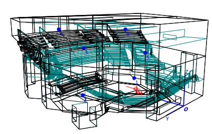
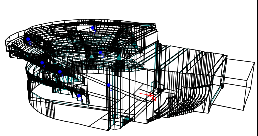
THE 126 MEASUREMENTS IN 11 HALLS

With its version 10, ODEON has released computer models of the 11 European Halls investigated and reported by Gade in 1989 [1]. While the overall results and data per hall has been published and referred to earlier [5], the 126 measurements together with their coordinates provide a unique set of data for the study reported in this paper. The same measurement data have been compared with simulated results in ODEON in order to evaluate the significance of surface resolution in computer models [2]. All measurements are in unoccupied halls, and the source-receiver constellations are made up by two source positions and 5 to 7 receiver positions in each hall.

The 11 halls vary significantly in volume and shape, which supports the validiy to the results of the study, see models in Figure 1. For example, the width of the halls varies in the range from 20 meters to 55 meters, the splay (angle between side walls) from 0 to 70 degrees, and the floor-rake from 5 to 20 degrees. The total number of measurements (and corresponding source-receiver positions) from the 11 halls are 126.

[1] The choice of G_{late} instead of the late lateral energy level (LG80) to describe Envelopment is due to evidence that late energy from all directions contributes more or less to perceived envelopment, Beranek (2008)[4].

Table 2. The eleven concert halls in the study

Concert hall	V(m^3)	RT	Model
Barbican, London	18000	2,0	
Concertgebouw, Amsterdam	19000	2,5	
Derngate, Northamton	13500	2,1	
Festspielhaus, Salzburg	15500	1,9	
Gasteig, Munich	30000	2,2	
Konserthus, Gøteborg	12000	1,7	
Liederhalle, Stuttgart	16000	2,1	
Musikverein, Vienna	15000	3,2	
Royal Festival Hall, London	22000	1,6	
St David, Cardiff	22000	2,2	
Usher Hall, Edinburgh	16000	2,0	

FIVE PREDICTION FORMULAE

The TVr-predictor

All levels are related to 0 dB being the direct free field sound pressure level at 10m distance from the source.

Formulas for the basic energy components direct energy, reflected energy, early energy and late energy are given from Barron Revised Theory in [6].

The corresponding energy levels are (Reverberation time *T*, Volume *V*, speed of sound *c*, and source-receiver-distance *r*) given in Table 3.

The set of predictive expressions based on the variables T, V and r will for simplicity be referred to as the **TVr-predictor**.

Table 3: Basic energy level components

Level component	**Symbol**	**Formula**
Direct energy level	Ld	$10\cdot\log(100/r^2)$
Reflected energy level	G,refl	$10\cdot\log(31200\cdot T/V) - r/c\cdot 60\text{dB}/T$
Total energy level	G	$10\cdot\log(10^{G,refl/10} + 100/r^2)$
Late reflected energy	GL	$G,refl - 60\text{dB}\cdot 80\text{ms}/T$
Early energy level	Ge	$10\cdot\log(10^{G/10} - 10^{GL/10})$

Combination of the energy level components in Table 3, together with an empiric estimate for LF, provides the 5 TVr–predictors given in

Table 4. If G and C80 are given from measurements or simulations, Glate can be calculated from

G – C80 – 10·log(1+10C80/10)

Table 4: The 5 aspects and their TVr predictors

Listener aspect	**Quantity**	**TVr – Predictor Formulae**	**Intrinsic variables**
SOUND LEVEL	G (dB)	G	T, V, r
REVERBERANCE	EDT (s)	**T**· [10dB-(G-G,refl)]/10	T, V, r
CLARITY	C80 (dB)	Ge – GL	T, V, r
APPARENT SOURCE WIDTH	LF (1)	**r**·0.18/18m if **r** ≤ 18m 0.18 if **r** > 18m	r
ENVELOPMENT	G_{late} (dB)	GL	T, V, r

RESULTS - TESTING THE PREDICTORS

The 5 predictors of the 5 listener aspects in

Table 4 are tested by computing the difference between predicted values and the 126 measured values after Gade's work, for each listener aspect. To provide a basis for assessing the quality of the predictors, the results are compared with differences between ODEON 10 simulation values and measured values. The units of difference are the corresponding JND (Just noticeable difference) in Table 1.

Results are presented in Table 5 and Figure 1. The global reverberation time used in this test is the average of measured RT's in each hall. All quantities are 500 and 1000Hz octave band averages, except LF which is 125-1000Hz average. Volume and RT is given in Table 2.

COMMENTS

As can be seen from Table 5, the TVr-predictors predicts the 5 aspects with even less difference from measured results than the corresponding ODEON predictions. The only purpose of comparing TVr results with ODEON results was to test the initial hypothesis: The 4 listener aspects Level, Reverberance, Clarity and Listener Envelopment can be predicted from RT. As long as TVr shows better prediction that a state-of-the-art prediction tool, then the hypothesis has stood this test. Note that this can not be taken as a proof of T,V,r prediction being superior to ODEON predictions. A comparison of prediction methods is outside the scope of this paper.

The 4 predictors including RT show better quality than the one (LF) not including RT, which is not surpising given the course algorithm.

Table 5: Differences in JND between predicted values and measured values for the 126 source-receiver combinations in the 11 halls; T,V,r – predictor and ODEON-prediction.

Listener aspect	**Quantity**	**T,V,r – re measured (JND)**	**ODEON re measured (JND)**
SOUND LEVEL	G (dB)	1,62	2,25
REVERBERANCE	EDT (s)	0,78	1,14
CLARITY	C80 (dB)	1,40	1,81
APPARENT SOURCE WIDTH	LF (1)	1,25	1,33
ENVELOPMENT	G,late (dB)	0,81	1,32
ALL FIVE ASPECTS	**-**	**1,20**	**1,57**

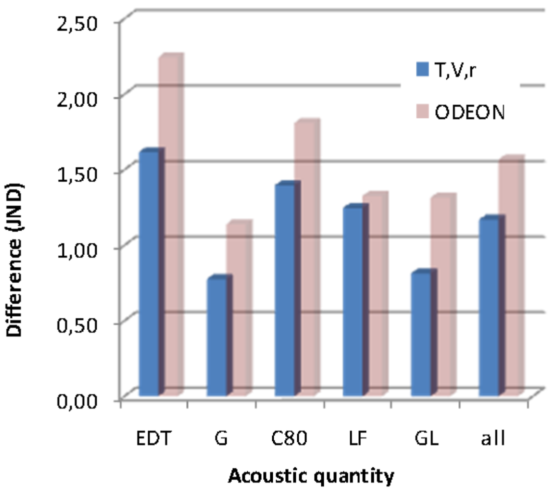


Figure 1 Differences (in JND units) between prediction and measurement, T,V,r-predictor and ODEON 10

CONCLUSION

The 4 listener aspects Level, Reverberance, Clarity and Listener Envelopment can be predicted from RT, with the TVr-predictor.

The statement that RT is the underlying parameter for 4 of the 5 listener aspects still holds.

Further investigations with more data should be carried out to increase the statistical confidence of the results.

FURTHER WORK

It cannot be concluded from this test that the T,V,r-predictor is superior to ODEON-predictions. However, there is reason to pursue the quite promising result. It will in further work also be pursued the fact that the 5 listener aspects depend on only 3 variables, two global ones and one spatial. This is interesting in light of the search for so-called orthogonal parameters. The LF-predictor should be studied further to see if it can be improved in accuracy. In the test reported above, the measured RT was used. If the T,V,r-predictor proves to be one that can be applied to halls in general, it will become increasingly important to develop the methods for predicting the RT itself during the planning of halls.

A brief study showed that exchanging the RT-input in the T,V,r-predictor from measured RTs to RTs from ODEONS's Global Estimate, made the overall difference (1.20 in Table 5) raise to 1.22. This is an interesting result because it is considerably closer to measured results than the direct ODEON-predictions and measured results. If this is a trend that can be confirmed by expanding the study, it opens up for a new way to predict room acoustics.

REFERENCES

[1] A. C. Gade, "Acoustical Survey of Eleven European Concert Halls", DTU Report No.44, 1989, ISSN 0105-3027

[2] Hiroyoshi SHIOKAWA and Jens Holger RINDEL, "Comparisons between Computer Simulations of Room Acoustical Parameters and Those Measured in Concert Halls", Report of the Research Institute of Industrial Technology, Nihon University Number 89, 2007, ISSN 0386-1678

[3] ISO 3382:1997, ''Acoustics — Measurement of the reverberation time of rooms with reference to other acoustic parameters'' (1997)

[4] L.Beranek, Concert Hall Acoustics—2008, J. Audio Eng. Soc., Vol. 56, No. 7/8, 2008 July/August http://www.leoberanek.com/pages/concerthalls2008.pdf

[5] L Beranek: Concert Halls and Opera Houses, second edition, Springer, 2003

[6] M Barron, Auditorium Acoustics and Architectural Design (E & FN Spon, London, 1993).

[7] M Barron, Using the standard on objective measures for concert auditoria, ISO 3382, to give reliable results, Acoust. Sci. & Tech. 26, 2 (2005)

[8] http://www.akutek.info/concert_hall_acoustics_files/parameters.htm