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OBJECTIVE MEASUREMENTS IN DANISH CONCERT HALLS.

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INTRODUCTION

During 1982-83 a survey was carried out in which the room acoustic conditions were investigated in halls of major importance for the performance of symphonic music in Denmark [1]. The survey included collection of structural data and measurement of objective room acoustic parameters in 21 halls. Among these were halls mainly built for concerts as well as multi-purpose halls and sports halls occasionally used for musical performances. The size of the halls varied between 3000 and 18000 m^3 and the number of seats between 400 and 2100. 14 halls had rectangular shape, 4 were fanshaped, 2 were haxagonal, and 1 had eliptical shape. The halls were measured in the empty state with the reverberation times covering the range 1,2 to 2,8 s.

Besides supplying up to date acoustical data for concert halls in Denmark, the purpose of the investigation was to look for statistical relationships between the acoustic parameters and aspects of the hall design. Below, the results of these statistical analyses are described after a brief review of the measurement technique.

MEASUREMENT TECHNIQUE

<u>Impulse response registrations</u>
All room acoustic parameters were evaluated from impulse response registrations. For recordings in the halls a sweep signal

$$s(t) = w(t)\cdot\cos(\pi\cdot r\cdot t^2) \quad (1)$$

was used. Here w(t) is a window function which determines the duration and frequency range of s(t) while r is a constant guiding the sweep rate. A key property of s(t) is that

$$s(t) * s(t) = \delta'(t) \quad (2)$$

where $\delta'(t)$ is a band-pass limited Dirac function and "*" is the convolution symbol. If h'(t) denotes the impulse response h(t) limited to the same frequency range as $\delta'(t)$, then

$$h'(t) = h(t) * \delta'(t) = h(t) * s(t) * s(t) \quad (3)$$

With s(t) emitted by a loudspeaker h(t) * s(t) was recorded in the hall while the second s(t)-convolution was carried out in the laboratory. Thus the second convolution acted as a compression in time of the sweep response signal as well as a band-pass filtering process. By using this technique the energy emitted in the hall could be increased by a factor comparable to the ratio between the duration of s(t) and $\delta'(t)$ without increased demands on loudspeaker power. This meant that the recording became far less sensitive to background noise in the hall and in the field-recording equipment. Corrections for the linear distortion in the measurement equipment was only attempted by equalizing the loudspeaker amplitude response. The more complicated phase correction as included in the adapted filtering [2] or FFT methods [3] turned out to be unnecessary. Anyway phase corrections would not be possible above the 1 kHz octave where the loudspeaker polar response became frequency dependent.

The loudspeaker consisted of 20 full-range units evenly distributed on a sphere 50 cm in diameter. The computer-generated 1/1 octave sweep signals with centre frequencies from 125 to 4000 Hz were pre-recorded on one channel of a four-channel FM-recorder while the 3 other channels were used for recording of sweep responses.

The calculation of h'(t) per 1/1 octave (time domain convolution), of decay curves (Schroeder method) and of room acoustic parameter values were done by a PDP8/E computer in the laboratory.

Acoustic parameters

The acoustic parameters measured in the survey are listed in Table 1. RT was evaluated from the -5 to -25 dB interval of the decay curve whereas EDT is based on the interval 0 to -10 dB. C denotes the dB-ratio between the energy before and after 80 ms in the impulse response. t_s has been suggested in an attempt to avoid

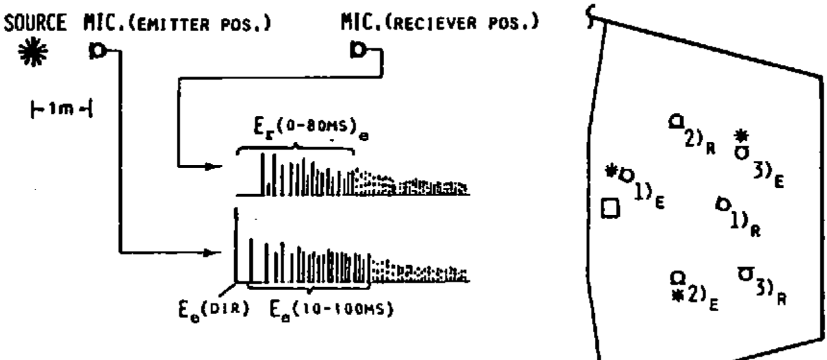
Table 1. Acoustic parameters measured in the Danish halls

Acoustical Parameter	Symbol	Associated subjective quality	References
Audience area			
Reverberation time	RT	reverberance (standard)	
Early decay time	EDT	reverberance/clarity	[5]
Point of gravity time	t_s	reverberance/clarity	[6]
Clarity	C	reverberance/clarity	[7]
Total energy measure	G	level	[8][1]
Lateral energy fraction	LEF	spatial impression	[9]
Variation of RT and G with frequency	RT(f), G(f)	timbre	
Platform area			
Early decay time	EDT_p	reverberance	
Support	ST	ease of playing	[4]
Early ensemble level	EEL	possibility of hearing each other	[4]

the sharp level or time limits in the other reverberance/clarity measures. G is defined as the ratio in dB between the total impulse response energy and the direct sound 10 m from the source. LEF is the ratio between the energy of lateral reflections before 80 ms picked up by a fig. 8 microphone and the energy of direct sound and early reflections from all directions arriving within the same time interval.

As indicated in the table special parameters were included for measurement of the performers' conditions. ST measures how much the early reflections assist the musician's own efforts (as heard by himself) while EEL describes the efficiency of early energy transmission between musicians in the orchestra. The definitions of ST, EEL, and the choice of measurement positions on the platforms are illustrated in Figure 1.

Figure 1. "Support" and "Early Ensemble Level": Definitions and measurement positions on orchestra platforms



$$ST = 10 \cdot LOG \frac{E_e(10\text{-}100MS)}{E_e(DIR)} \qquad EEL = 10 \cdot LOG \frac{E_r(0\text{-}80MS)_e}{E_e(DIR)}$$

<u>Measurement positions and frequency ranges</u>

The audience parameters were measured in 3 positions in the main floor area plus in one position on rear and side balconies, if any. For each audience position two source positions on the platform were used. The values for EDT, t_s, C, G, and ST were averaged over the 250 to 2000 Hz octaves whereas the intervals for LEF and EEL were 125-1000 Hz and 500-2000 Hz, respectively. Except for the discussion of within-hall-variation, the parameter values were position-averaged before the analyses described in the following.

RESULTS

<u>Mutual correlations among the parameters</u>

The mutual correlation coefficients are listed in Table 2. Only coefficients indicating a relationship significant at a 5% level are shown.

Table 2. Significant mutual parameter correlations

	audience parameters						platform parameters		
	RT	EDT	t_s	C	G	LEF	EDT_p	EEL	ST
RT	1,00	0,95	0,89	-0,64	-	-	0,75	-	-
EDT		1,00	0,98	-0,78	-	-	0,78	-	-
t_s			1,00	-0,88	-	-	0,75	0,44	-
C				1,00	-	-	0,54	-	-
G					1,00	0,63	-	-	0,69
LEF						1,00	-	-	-
EDT_p							1,00	-	-
EEL								1,00	0,68
ST									1,00

It is seen that a high degree of dependence only occurs between parameters intended to describe the same aspect of the subjective room acoustic impression (the reverberance/clarity parameters, see Table 1). Thus, for a thorough acoustical analysis of an auditorium, measurement of parameters for each subjective aspect is necessary.

Also with respect to variation with frequency C and RT were often found to be independent of each other. Consequently, evaluation of tonal colour of a hall may yield quite different results, depending on whether RT or G versus frequency is regarded. A more detailed look at data and halls indicated that different behaviour of the G and RT curves could often be related to the frequency characteristics of absorbing surfaces close to the source (or receiver). Thus, in two halls with orchestra enclosures made of rather thin and bass-absorbing wooden panels, the G-versus-frequency curves indicated weak bass in the audience area, whereas the RT curves did not. Judged from listening experience in these halls it is felt that the information obtained from G is the most relevant.

Within-hall variation of G

Compared to the between-hall-variation, the variation of parameter values with position was generally highest for parameters focusing on the early energy in the impulse response (C, LEF, EEL). An exception from this rule was G, which in fact showed the highest position variation of all the parameters. The variation consisted of a steady decrease of the G-value with increased source/receiver distance - also beyond the reverberation distance. The correlation between G and the logarithm to the source/receiver distance was above 0,9 in 75% of the halls and on average the slope was -2 dB per doubling of the distance. Recently this phenomenon in concert halls has also been observed by other authors [10,11] and Michael Barron has suggested a theory to explain it [10].

Relationships between acoustic parameters and hall design

Explanations for the varying acoustic properties of the halls were looked for by means of linear regression analyses. The acoustic parameters were compared with their expected values (according to classical statistical theory and the measured RT): $par._{exp.}$ as well as with geometrical properties of the spaces. Also the deviation of the parameters from the predictions: $\Delta par. = par.-par._{exp.}$ were compared to the geometry. Correlation coefficients found to be significant at a 5% level have been listed in Table 3.

Reverberance/clarity parameters. Table 3 indicates that these parameters are mainly related to their statistical predictions. However, there is also a weak but consistent tendency of a relationship with α: reverberation becomes weaker or clarity higher when the slope of the audience floor is increased.

As to t_s and C the relationship with geometry becomes slightly more apparent when Δt_s and ΔC are considered, i.e. when the RT-related part of the variance has been removed. The tendency is that reverberation is weak or clarity high in wide halls. (This phenomenon might be related to Barron's finding of weak reverberation in halls of wide fan shape.)

No geometry dependence of ΔEDT was found probably because the deviations from statistical values are small and comparable with measurement errors as seen on Figure 2. This Figure also shows that $EDT_{exp.}$(=RT) is a very good prediction for EDT.

Table 3. Correlation coefficients between objective parameters and statistical prediction formulae/geometric variables

AUDIENCE PARAMETERS

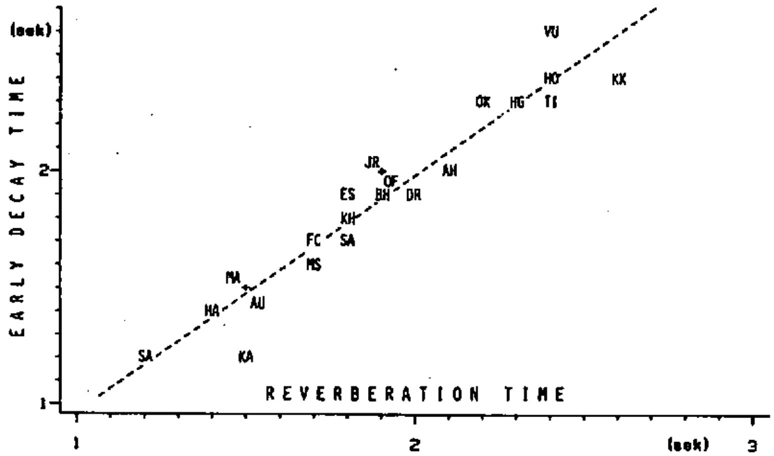
		EDT	ΔEDT	t_s	Δt_s	C	ΔC	L	ΔL	LEF
	$par._{exp.}$	0,96	/	0,91	/	0,65	/	0,88	/	/
	V	0,47						-0,81*		
audience area geometry	W	0,56			-0,62		0,49*	-0,53*		-0,84
	H							-0,66*		
	D							-0,67*		-0,47
	W·H	0,45			-0,46			-0,74*		-0,83
	W/H				-0,52		0,51*			-0,47
	D/(W·H)									0,51
	α	-0,45		-0,47		0,46				
platform area geometry	$W_p \cdot H_p \cdot D_p$	0,43			-0,48				0,58	0,58
	$D_p \cdot W_p$	0,48								

PLATFORM PARAMETERS

		EDT_p	ΔEDT_p	EEL	ΔEEL	ST	ΔST
	$par._{exp.}$	0,75	/	0,49	/	0,74	/
	V		-0,64	-0,48*	0,83	-0,76*	0,47
platform area geometry	H_p			-0,59*		-0,74*	
	$D_p \cdot W_p$	0,43					
	$W_p \cdot H_p \cdot D_p$	0,43		-0,66*		-0,63*	
	$Min(W_p, H_p, D_p)$			-0,71*		-0,61*	
	β_p					-0,48	

Notes to Table 3: $par._{exp.}$ = statistically expected value; Δpar. = par.-$par._{exp.}$; V = volume; W = mean width between side walls; H = mean ceiling height; D = distance from platform front to rearmost seat; α = mean slope of floor; suffix "p" denote equivalent measure on the platform (D_p = distance from platform front to rear wall behind the platform.); β_p = horizontal angle of side walls in platform area. A "*" denote correlation with the logarithm to the geometrical variable.

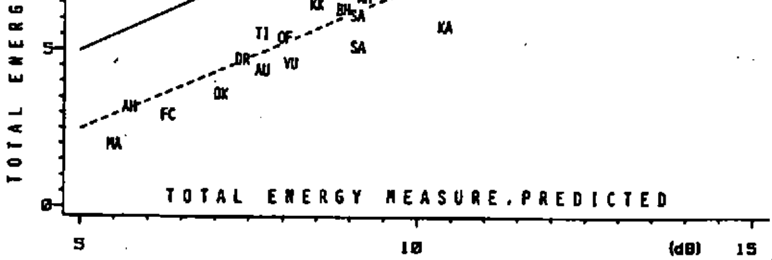
Figure 2. EDT versus RT for 21 halls. Dashed line: regression line



Total energy measure. Also G is strongly related to its predicted value. However, as shown in Figure 3, G is on average about 2,5 dB lower than $G_{exp.}$ (in accordance with Barron's findings and theory).

G is also correlated with dimensions of the hall. However, through V these are already considered in $G_{exp.}$ which showed the highest correlation with G. The fact that ΔG does not correlate with the geometric variables also indicates that the average value of G in a hall is not related to hall geometry apart from the V-relationship dealt with in G_{exp}.

Figure 3. G versus $G_{exp.}$ for 21 halls. Dashed line: regression line; solid line: $G = G_{exp.}$



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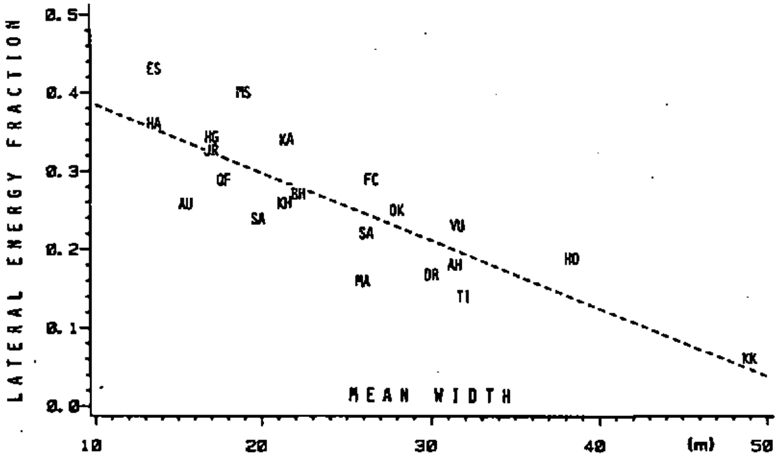
Lateral energy fraction. According to Table 3 LEF is strongly related to hall width and the often stated reduction of lateral reflection energy with increased width is neatly illustrated by the data in Figure 4. Among the halls investigated especially MÅ, DR and IT were pronouncely fan shaped. As expected, these halls are seen to have slightly lower LEF-values than the rectangular halls of comparable width.

Figure 4. LEF versus mean width for 21 halls. The regression line is drawn dashed



Platform parameters. EDT_p is rather closely related to RT, but always about 20 to 40% lower than RT or EDT in the audience area.

EEL and ST follow the same pattern as G by being related to the expected values as well as to geometric variables: the dimensions of the platform. However, the high correlations with V and expected values are more likely to be caused by the fact that small platforms are found in small halls rather than early reflection energy being predicted well by diffuse field theory. Thus it seems resonable to interpret the results as support and ease of ensemble playing being promoted by close reflecting surfaces around the orchestra platform.

CONCLUDING REMARKS

Although parameters related to different subjective aspects are practically uncorrelated, many of them are seen to be closely related to statistical predictions based on RT and V. Therefore RT will remain the basic room acoustic parameter - despite the higher subjective relevance of the other newer parameters.

Concerning the influence of room geometry the statistical analyses have demonstrated the importance of hall width for spatial impression and reverberance, the influence of floor slope on reverberance/clarity, and the need for close reflecting surfaces in the platform area for the benefit of musicians.

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The relationships found can be summarized in the following prediction formulae based on the statistical regression lines for the highest correlations:

$$EDT = RT \tag{4}$$

$$C = C_{exp.} - 3{,}3 \cdot \log \frac{W/m}{30} \text{ dB}; \; C_{exp.} = 10 \cdot \log(e^{1,1/T} - 1) \text{ dB} \tag{5}$$

$$G = G_{exp.} - 2{,}5 \text{ dB}; \; G_{exp.} = 10 \cdot \log \frac{RT/s}{V/m^3} + 45 \text{ dB} \tag{6}$$

$$LEF = 0{,}47 - 0{,}0086 \cdot W/m \tag{7}$$

$$EDT_p = 0{,}3 \text{ sec.} + 0{,}55 \cdot EDT \tag{8}$$

$$EEL = -3{,}0 \text{ dB} - 10 \cdot \log(\mathrm{Min}[W_p, H_p, D_p]/m) \tag{9}$$

$$ST = -4{,}2 \text{ dB} - 9{,}3 \cdot \log(H_p/m) \text{ dB} \tag{10}$$

However, especially for C and the platform parameters a substantial part of the total parameter variance could not be explained by any of the statistically emerging relationships (the correlation coefficients were fairly low). This situation is caused by the great number of possible geometrical factors and interactions influencing the parameter values - combined with the limited number of halls represented in this survey. Finally it should be repeated that these results relate to the position-averaged parameter values only. Thus for C and G, which on average are closely related to the statistical values, within-hall variations are nearly as large as the between-hall variation.

ACKNOWLEDGEMENTS

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