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EXPERIENCE WITH NEW AUDITORIUM ACOUSTIC MEASUREMENTS

by J.S. Bradley

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RÉSUMÉ

Comme le temps de réverbération est un paramètre inadéquat pour déterminer la qualité d'un auditorium, beaucoup de nouveaux paramètres ont été proposés. Parmi ceux-ci les rapports sons en avance - sons en retard et la corrélation inter-aurale sont des paramètres généralement acceptés pour quantifier les deux principaux critères de qualité acoustique. La présente étude comprend un grand nombre de mesures de ces paramètres dans des salles de 200 à 2 500 sièges. Le but de l'étude est de rendre plus familiers les nouveaux paramètres, de publier plus de données et d'analyser l'interdépendance de ces paramètres avec les autres. Les variations des nouveaux paramètres ont été examinées à l'intérieur des salles. Des salles qui ont un temps de réverbération semblable montrent des différences nettes lorsque l'on utilise comme paramètre le rapport sons en avance - sons en retard.

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Experience with new auditorium acoustic measurements

J. S. Bradley

Division of Building Research, National Research Council Canada, Ottawa, Canada K1A 0R6

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As the inadequacy of reverberation time as a predictor of the acoustical quality of auditoria has been recognized, many new measures have been proposed. Of these, early-to-late sound ratios and interaural cross correlations are generally accepted as correlates of two major aspects of acoustical quality. Accordingly, the present work includes a large number of measurements of these quantities in halls ranging from 200 to 2500 seats. The purpose of the work was to improve familiarity with the newer measures, to provide more published data, and to explore the dependence of these measures on other quantities. Variations of the new measures were examined within and among halls. Halls that are apparently similar in terms of reverberation times showed clearly identifiable differences when early-to-late sound ratios were considered.

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INTRODUCTION

Reverberation time was for a long time regarded as the principal objective quantity in the acoustical design of halls and auditoria. It is now generally accepted that it is not the sole design quantity, and Jordan,¹ for example, has referred to "... the utter insufficiency of RT as an acoustical criterion for large halls ...". In the last two or three decades a large number of new measures have been proposed, with the result that there is now a confusing array of acoustical measures with quite varied degrees of support in the literature. Some have merely been proposed as "good ideas," while others have been tested in subjective studies. Although one can certainly not claim that the acoustical design of auditoria is completely understood, there does appear to be a developing consensus regarding the types of acoustical measures that should be made.

There are probably four important types of measure. First, those of clarity or definition that relate to the concept of speech intelligibility for speech sounds and can be considered as monaural effects. Acceptable clarity, definition, or speech intelligibility relate to sufficient early sound energy. Too much early sound leads to a lack of fullness and blend in music sounds; too little early sound creates a muddy sound. Second, there are measures of what Barron² has termed spatial impression that relate to binaural hearing phenomena, including a sense of envelopment in the sound, and subjectively perceived source broadening. This is the feeling of being immersed in the sound and not just "looking" at it, and can be compared with the difference between listening to monaural and stereophonic sound reproduction. Adequate spatial impression relates to sufficient early lateral sound energy. As third and fourth types of measures, the overall strength of the sound in the room and the tone color imparted by the room seem to be important,³ but these are less clearly defined. The first two of the four types of measure have received the most attention, and it is these that are considered in this paper.

A. Monaural measures

After the pioneering work of Haas,⁴ the subjective importance of early reflected sound has been appreciated as

contributing to the intelligibility of speech sounds and to the clarity or definition of musical sounds. Shortly after Haas' work, Thiele⁵ proposed the quantity *Deutlichkeit* (D) as a measure of clarity:

$$D = \frac{\int_0^{0.05} p^2(t) dt}{\int_0^{\infty} p^2(t) dt}. \quad (1)$$

As defined, *Deutlichkeit* is the ratio of the early sound energy in the first 50 ms after the arrival of the direct sound to the total sound energy. Thiele reported extensive measurements of *Deutlichkeit*^{5,6} in a number of rooms nearly 30 years ago. Schultz⁷ published measurements of a quantity R that he referred to as a reverberant-to-early sound ratio:

$$R = 10 \log \left(\frac{\int_{0.05}^{\infty} p^2(t) dt}{\int_0^{0.05} p^2(t) dt} \right). \quad (2)$$

Reverberant energy in this context has not the conventional meaning, but actually refers to late-arriving sound energy following after the early sound. Assuming that the sound arriving after the first 0.5 s contributes a negligible amount of sound energy, it is readily shown that R is related to *Deutlichkeit* by the following expression:

$$R = 10 \log(1/D - 1). \quad (3)$$

Schultz refers to his reverberant-to-early sound ratio as a measure of the balance between definition and blend. A number of other ratios of early-to-late-arriving sounds have been considered, including Reichardt's⁸ measure of clarity that incorporates an 80-ms limit for early sound:

$$C_{80} = 10 \log \left(\frac{\int_0^{0.08} p^2(t) dt}{\int_{0.08}^{\infty} p^2(t) dt} \right). \quad (4)$$

This early sound limit was intended to be more suitable for music than the 50-ms limit. There is evidence that a variety of measures are similarly indicative of the relative strength of early reflections and are intercorrelated.^{3,9} These include measurements of rise time, early decay times, and various ratios of early- and late-arriving sounds. In this paper measurements were made in terms of Schultz' reverberant-to-early ratio because it seemed the most appropriate for overall comparison of rooms in which both speech and music are performed, and because it allowed easy comparison with published data from both Schultz and Thiele.

B. Binaural measures

Consideration of the binaural phenomena associated with spatial impression due to adequate early lateral sound has developed more recently and has not reached the same level of consensus. After earlier related work with Lochner,¹⁰ Keet¹¹ in 1968 demonstrated the relation between spatial impression and apparent source width. He also showed that the short-term interaural cross correlation between signals at the two ears during the first 50 ms after the arrival of the direct sound is linearly related to spatial impression. At about the same time West,¹² and later Marshall,¹³ suggested that the ratio of height to width of a hall contributes to an appropriate spatial impression. More recently Ando^{14,15} has continued the investigation of interaural cross correlations (IACC) and demonstrated with synthesized sounds that IACC values are related to the subjective preference for sound fields. In a large subjective comparison of a number of European halls, Gottlob⁹ found IACC values to be of particularly high subjective relevance independent of reverberation times. Although Barron's results² again demonstrated that the IACC related to subjectively perceived spatial impression, in more recent work¹⁶ he has preferred to consider lateral energy fraction L_f , the ratio of early lateral energy (over the first 80 ms) to total early energy. Similarly, Reichardt and Lehman⁸ have used a measure of room impression that involves early- and late-arriving sound measurements, using directional microphones. In the present work short-term IACC values were measured since this seemed to be the best-established measure of spatial impression. In addition, directional microphone arrays were used to obtain early-to-late sound ratios in the lateral and medial planes that would allow examination of the interrelation of such measures of spatial impression and IACC values.

In reviewing the literature it was concluded that measures of clarity or definition and measures of spatial impression are generally important correlates of at least two of the major dimensions of the acoustical quality of halls and auditoria. Further, it was assumed that although a variety of physical measures have been proposed, most are closely related to each other in one of the two groups. In short, there was a sort of consensus, but in a number of areas practical information is lacking. Most published work has been in the form of research studies and practical measurement procedures have not always been established. There are generally very few published data for any type of measured early-to-late sound ratios in actual halls, and measurements relating to spatial impression are even more difficult to find. As these quantities are all relatively new, there is no evidence of an understanding of how they are related to other physical and acoustical properties of rooms, and there is not the general appreciation of these quantities that exists among acousticians for reverberation time data. Finally, there appears to have been no consideration as yet of how to design a new hall so as to achieve the desired values of these quantities.

The present work is an attempt to provide more information in a number of these areas. Reverberant-to-early sound ratios (R) were measured with omnidirectional and directional microphones, and interaural cross correlations

(IACC) were also measured. These were made at a number of positions in halls of a very large range of sizes, from 200 to 2500 seats. It was intended to provide more and a broader range of data than has previously existed. It was also hoped that it would be possible to derive an improved understanding of the physical relations among these and various other geometrical and acoustical measures. Ultimately it was anticipated that this type of information would enable quantitative design procedures to be developed.

I. MEASUREMENTS AND PROCEDURES

Measurements were made at between six and nine receiver positions in each of 11 rooms. Omnidirectional reverberant-to-early sound ratios (R values) were measured as well as reverberant-to-early ratios in the lateral and medial planes. In addition, interaural cross correlations (IACC) were measured at each position. Measurement procedures were as much as possible a practical compromise, incorporating common acoustical equipment where possible. This included the tape recording of pistol shots and the use of octave band filters. Although the data were processed by computer, the calculations could have been performed by a small microcomputer.

A 0.38 caliber blank pistol was used as the sound source. Each measurement at each position was an average of the results of three pistol shots, which were recorded using inexpensive 1-cm electret microphones that had a flat-frequency response ± 2 dB over the range of interest (from 80 Hz to 10 kHz). The response was only slightly irregular in the highest octave band of interest, the 8-kHz band. As will be seen, little use was made of the measurements in the 8-kHz band. A line array of five microphones with a 6.3-cm spacing between microphones was used to record lateral and medial plane results. The lateral plane was considered to be the one parallel to the floor through the listener's ears. The medial plane was considered to be that perpendicular to it, bisecting the plane of symmetry of the head of a listener facing the center of the stage or the front of the room. The beam widths of the line array were measured at 1000, 2000, and 4000 Hz to be 49°, 26°, and 15°, respectively, between the -3 -dB points. In the worst case, at 4000 Hz, side lobes were no greater than -14 dB relative to the mainlobe.

The tape-recorded pistol shots were processed by computer by digitizing the parallel outputs of the seven octave filters from 125 Hz to 8 kHz. Thus all early-to-late sound ratios and reverberation times were calculated numerically in octave bands. Early sounds were those arriving in the first 50 ms after the direct sound. Late-arriving sounds were those arriving in the period 50–500 ms after the direct sound. Reverberation times were calculated from least-squares fits to the late-sound energy decay envelope, considered in terms of the logarithm of the rms pressure versus time.

IACC's were calculated from dual-channel pistol shot recordings obtained with microphones positioned at the ear canal entrances of a live subject. The A-weighted pistol shot recordings were low-pass filtered with an upper limit of 4000 Hz. The signals were again processed by computer and the autocorrelation functions for each signal were produced as

TABLE I. Details of eleven halls.

Hall	Vol (m ³)	No. of Seats	RT (500–2000 Hz)
1	900	200	1.06
2	1,050	424	0.67
3	1,390	248	1.25
4	1,420	450	0.80
5	1,900	382	1.17
6	3,110	370	0.76
7	3,620	693	0.90
8	9,340	1,800	1.37
9	13,880	2,500	1.67
10	14,530	2,300	2.00
11	31,430	2,181	1.80

well as the cross correlations between the signals at the two ears. Only the early sound, that is, the sound arriving in the first 50 ms after the direct sound, was considered, and the maximum time shift used was ± 1.0 ms. The maximum value of the cross correlation function within this range was the IACC value. This procedure closely followed that of Gottlob.⁹

II. RESULTS

A. Basic data

Table I gives basic information for the 11 halls, including volume, number of seats, and mid frequency reverberation time. The reverberation times are overall averages from all receiver positions and are averages of the results obtained in three octave bands, 500, 1000, and 2000 Hz. All measurements were made in unoccupied halls, and they were not at all representative of the acoustical conditions of occupied halls. Accordingly, the individual halls are not identified, but were located in London, Hamilton, and Toronto, Canada. Four were used strictly for speech, while the remaining seven were to some extent multipurpose. They were selected to provide the widest possible range of hall sizes.

B. Monaural effects

The omnidirectional reverberant-to-early ratios were considered to be related to the monaural subjective effects of speech intelligibility and to music clarity and definition. One

can consider the variation of these omnidirectional ratios both within and among halls.

1. Within-hall variations

Table II gives the measured mean and range of seat-to-seat variation, in each octave band for all 11 halls, of the omnidirectional reverberant-to-early ratios (R). Hall 9 quite consistently had the largest within-hall ranges for all but one octave band. For all halls the ranges were larger in the lowest two octave bands. In all but one hall the within-hall ranges were largest in the 125-Hz octave. Even in the 1000-Hz octave band within-hall variations of up to 8.2 dB are indicated in Table II.

In attempting to determine the cause of within-hall variations the spatial standard deviations were correlated with various quantities for the 1000- and 2000-Hz results. These quantities were volume, mean width, and mean height. In addition, the 2000-Hz spatial standard deviations were correlated with the 2000-Hz R values and the 2000-Hz reverberation times. None of these correlations produced statistically significant results. One can expect that both small and large halls may exhibit similar seat-to-seat variations. For example, hall 11, with the largest volume, had a range of R values at 1000 Hz of only 1.8 dB, while halls 6 and 7, with approximately 1/10 the volume of hall 11, had much larger within-hall variations (4.8 and 5.2 dB, respectively).

Figure 1 plots R values versus frequency for the nine measurement positions in hall 8. In this form the data serve only to illustrate the general pattern and overall magnitude of the within-hall variations for this auditorium; the 2000-Hz R values for it are plotted on the floor plan in Fig. 2. As in many other cases, there is a tendency for R values to be greatest at positions near the center and towards the rear of the room owing to lack of early reflected sounds at these positions. Positions 7, 8, and 9, for which data are presented in Fig. 1, were in the balcony above positions 6, 5, and 3, respectively.

In an attempt to present the data in a less confusing form, Fig. 3 shows the R values in a manner that permits one to infer seat-to-seat variations in spectral balance. Here the R values were averaged over two low-frequency octave bands (250 and 500 Hz) and over two high-frequency octave bands (2000 and 4000 Hz) and plotted as a function of receiver

TABLE II. Mean (M) and range (R) of octave band reverberant-to-early sound ratios.

Hall	125		250		500		1000		2000		4000		8000	
	M	R	M	R	M	R	M	R	M	R	M	R	M	R
1	2.1	5.7	3.4	6.3	3.2	2.6	3.3	3.0	3.1	2.5	1.9	1.6	0.4	2.8
2	−3.0	7.1	−0.1	4.7	−1.6	2.7	−1.1	2.5	−0.9	0.9	−0.4	2.6	−2.9	2.5
3	1.5	5.3	4.7	3.8	2.9	4.9	2.6	1.5	3.2	1.0	3.1	1.4	0.7	1.4
4	1.6	5.7	1.8	3.4	0.5	4.2	1.1	2.9	1.2	1.9	1.4	1.3	−1.6	1.1
5	3.3	6.0	3.4	6.5	2.5	2.8	2.5	1.6	2.5	1.5	3.0	1.3	−0.4	1.5
6	1.1	7.0	−0.3	5.8	0.4	4.6	0.2	4.8	1.2	5.0	2.0	3.4	−0.8	4.4
7	0.9	8.7	−0.6	6.8	−1.0	6.4	−0.6	5.2	0.3	5.1	1.5	3.1	−1.0	3.0
8	3.3	12.5	3.2	5.8	2.9	5.7	3.3	4.8	4.0	4.8	3.6	4.5	1.2	3.2
9	1.4	9.0	1.9	7.3	3.3	7.4	3.0	8.2	3.6	6.1	2.8	6.4	1.8	7.0
10	6.0	6.6	3.6	3.3	4.3	5.0	4.3	1.5	5.4	2.4	4.5	1.5	0.5	1.8
11	2.2	10.5	0.4	4.3	0.7	3.9	0.6	1.8	2.0	3.0	1.0	2.2	−1.4	2.6

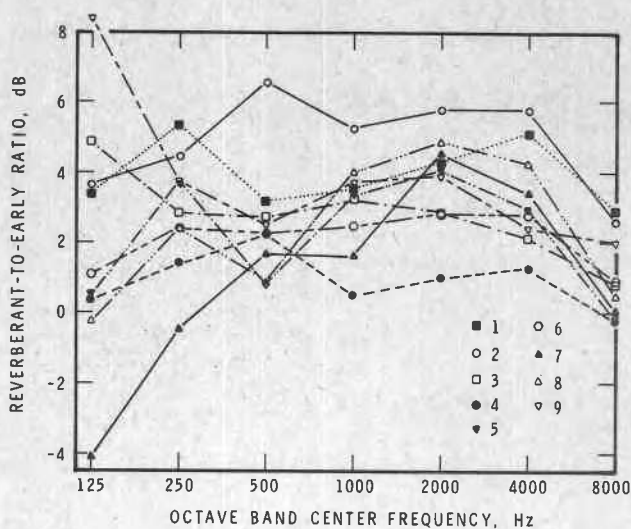


FIG. 1. R values versus octave band center frequency for nine positions in hall 8.

er position. One can see two types of effect: overall general seat-to-seat variations, where low- and high-frequency R values behave similarly, and changes in spectral balance where low- and high-frequency R values behave quite differently. One can interpret the overall variations as deleterious in that one would prefer some constant optimum R value throughout the hall. Hall 10, in particular, illustrates such undesirable overall general seat-to-seat variations. One can also interpret changes in spectral balance as unwanted, again

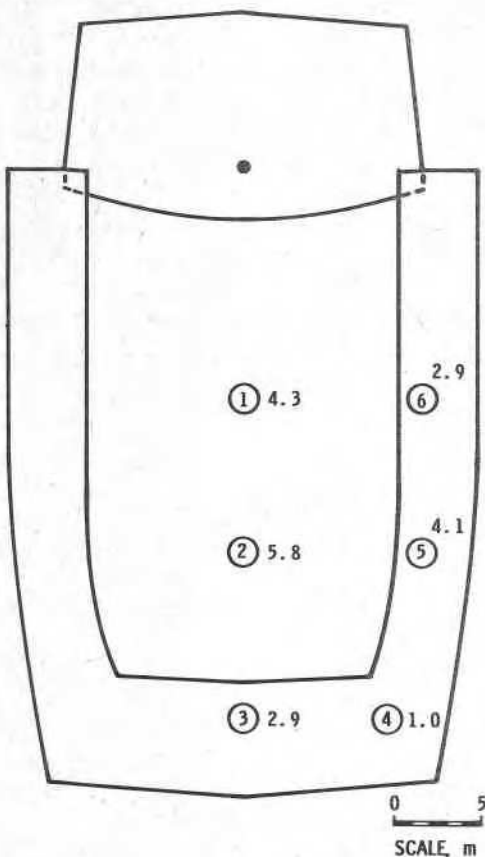


FIG. 2. R values at 2000 Hz in hall 8.

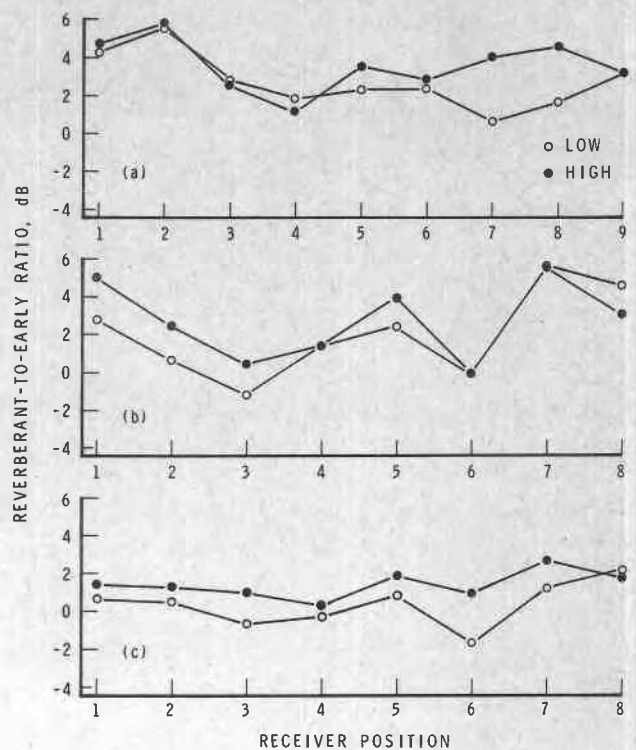


FIG. 3. Low (250 and 500 Hz) and high (2000 and 4000 Hz) R values versus position, (a) hall 8, (b) hall 10, and (c) hall 11.

because one would prefer some presumed optimum value throughout the hall. Position 6 in hall 11, and positions 7 and 8 in hall 8 are examples where the spectral balance seems to change when compared with other seats in the hall. At these three positions the high-frequency R values are higher than the low-frequency values. This was thought to be due to reduced, early high-frequency energy that caused the R values to increase. Although it may be premature to rate auditoria accurately by these criteria, the amount of overall variability and the variability in the spectral balance of R values may be related to the overall acoustical quality of the hall. Minimizing these variations in existing halls could presumably lead to improved subjective ratings if an appropriate mean value could be approached.

Comparisons of present within-hall variations can be made with Thiele's and Schultz' results. Schultz⁷ reported within-hall ranges in R values of 2 and 3 dB at 1000 and 2000 Hz, respectively. These measurements were limited, however, to the centerline of one hall. Thiele⁵ reported within-hall ranges of Deutlichkeit that correspond to R values of 2.9 to 5.3 dB in several auditoria and 7.7 dB in a large church. Thiele made broadband measurements with a spark source. In a second paper¹⁷ he reported detailed measurements of Deutlichkeit at large numbers of positions in five different halls. The ranges of measured Deutlichkeit values correspond to ranges in R values between 5.5 and 6.8 dB. From Table II it may be seen that at 1000 Hz within-hall ranges varied from 1.5 to 8.2 dB and at 2000 Hz from 0.9 to 6.1 dB. The greater within-hall variations in the present work probably result from the fact that Thiele selected a smaller range of more nearly similar, well liked halls. Certainly, much

larger within-hall variations than those reported by Schultz do occur.

It is also possible to investigate the effect of varied source position as a form of within-hall variation. In the present study this was only done for hall 10 in which the effect of varied source positions was investigated at one central receiver position and for five different source positions distributed over half the stage area. At 1000 Hz R values varied by a maximum of 1.8 dB at the one receiver position. Thiele⁵ reported the effect of varied source positions in two halls. Over many receiver positions at which measurements were made the maximum change in Deutlichkeit corresponded to a change in R of 3.5 dB. Averaged over 12–18 receiver positions, the hall mean Deutlichkeit varied by amounts equivalent to R value changes of 0.2 and 0.8 dB in the two halls. Although there are quite limited data to consider, both Thiele's data and the present results suggest that the influence of source position is quite small, particularly when averaged over a number of receiver positions.

2. Between-hall variations

From Table II one can see how the mean R values varied between halls: at 1000 Hz, from -1.1 to 4.3 dB, a range of 5.4 dB. At 2000 Hz the range of between-hall mean R values was 6.3 dB. At the same frequencies Schultz⁷ reported variations of up to 6.8 dB among four unoccupied halls. Thiele⁶ reported differences in hall average Deutlichkeit values that correspond to a range of R values of 8.7 dB. Thus all three studies suggest relatively similar variations among halls. It should be pointed out that the maximum within-hall variations discussed in the previous section were approximately the same as the between-hall variations in average R values.

Thiele⁶ attempted, unsuccessfully, to relate Deutlichkeit to room volume. In the present work, in attempting to relate R values to a number of geometrical and acoustical quantities, some success was achieved in relating R values to the logarithm of the reverberation time. Figure 4 plots mean R values at 2000 Hz versus the logarithm of RT values for

the 11 halls. Also shown by the dashed line is the theoretical result for an ideal continuous exponential decay. It is readily approximated by a straight line in the range 0.5 – 2.5 s RT with an error of less than 0.2 dB. The equation of this straight line approximation, also shown in Fig. 4, is

$$R = 12.8 \log(RT) - 0.1. \quad (5)$$

The measured mean R values shown in the figure are roughly parallel to the above straight line, but about 2 dB above it. Thus for real rooms where the early sound is not continuous the early energies were lower and the resulting ratios, on average, were about 2 dB larger than the ideal case. There were clearly exceptions; for example, for one hall the mean R value was lower than the ideal case, indicating stronger early-sound components. One should realize that although the mean R values were approximately related to the logarithm of RT, this would not necessarily be true for the complete data, which included large within-hall variations.

3. Comparison with other ratios

Although 50 ms was taken as the division between early- and late-arriving sound, other division points have been proposed. Noteworthy among these was Reichardt's early-to-late energy ratio C_{80} [Eq. (4)], which incorporates an 80 -ms early-sound limit. It is clearly desirable to be able to convert, at least approximately, from one set of ratios to another. Equation (3) permits direct conversion from Deutlichkeit to R values. Approximate conversions to other ratios were obtained from the measured data.

Unfortunately, 80 -ms early-to-late energy ratios were not calculated in the original processing of the present data. Late-to-early ratios were calculated for 35 -, 50 -, 75 -, and 100 -ms early-sound energy time limits. Regression analyses were performed by plotting each of these other ratios versus the 50 -ms R values. Figure 5 illustrates the results for the 75 -ms late-to-early ratios. The slope of the regression line is extremely close to 1.0 and the intercept is -2.9 dB. The other regression analyses similarly resulted in regression lines with slopes very close to 1.0 . It was therefore possible to

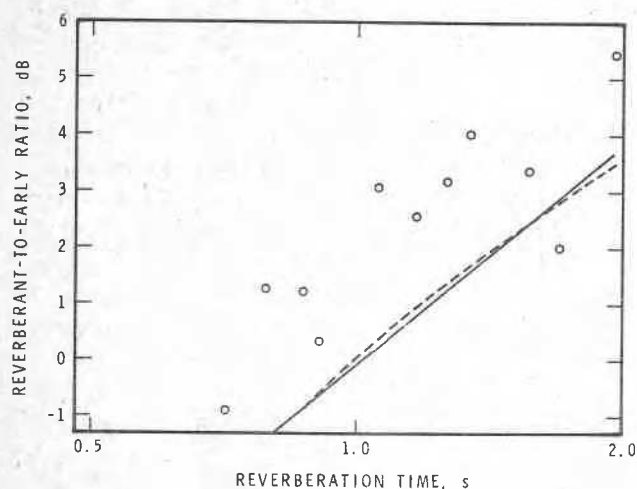


FIG. 4. Mean hall R values at 2000 Hz versus $\log(RT)$, $\circ \circ \circ$, measured, —, Eq. (5), - - - - -, ideal exponential theory.

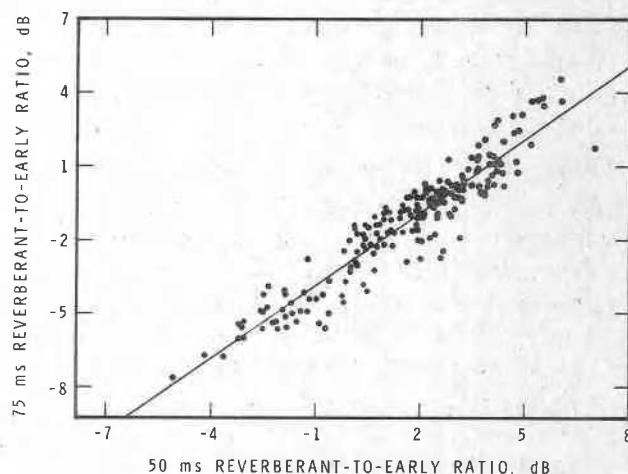


FIG. 5. 75 -ms reverberant-to-early ratios versus 50 -ms reverberant-to-early ratios for measured values at 1000 Hz and regression line.

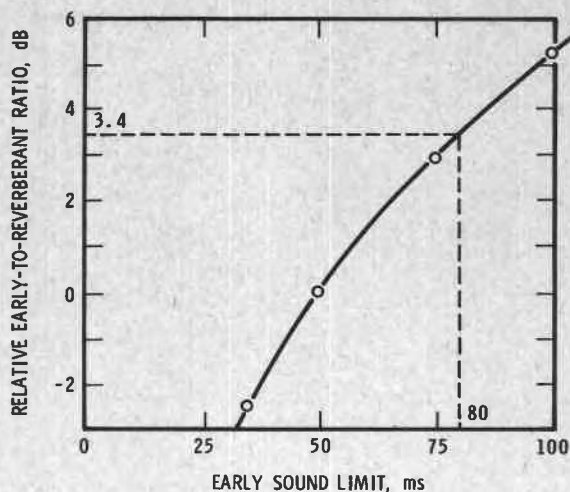


FIG. 6. Correction to be added to 50-ms early-to-late ratios to obtain other ratios as a function of early time limit.

convert, approximately, between the different ratio values by adding or subtracting a constant given by the intercept of the regression lines. Figure 6 plots the value of this constant as a function of the time limit for early sound. It may be seen, for example, that to make an approximate conversion from 50-ms early-to-late ratios to an 80-ms ratio a value of 3.4 dB must be added. To obtain a quantity equivalent to Reichardt's C_{80} from R values one would also have to change the sign because this ratio is an early-to-late energy ratio, not a late-to-early one. As the various ratios considered here were quite strongly correlated, one would expect them to be somewhat equivalent predictors of subjective judgments. This is supported by Gottlob,⁹ who found that the 50-ms early time limit was not very critical.

4. Interpretation of reverberant-to-early ratios

From subjective studies using synthesized sound fields Reichardt determined a range of C_{80} values that relate to an acceptable degree of clarity. Using the approximate conversions shown in the previous section it is possible to arrive at an acceptable range of R values based on Reichardt's work. It is first necessary, however, to modify the measured values to make them representative of occupied conditions. This was achieved by using Schultz¹⁸ regression equations for relating occupied and unoccupied RT values. For 1000 Hz his relation for the change in RT is

$$\Delta(RT) = 0.6959 RT(\text{unocc}) - 0.9354. \quad (6)$$

The estimated occupied 1000-Hz RT values for halls 8 to 11 were calculated to be 1.4, 1.4, 1.5, and 1.5 s from the unoccupied RT values of 1.37, 1.64, 1.96, and 1.77 s, respectively. The approximate relation of Eq. (5) was used to adjust measured R values to be representative of expected occupied conditions. These expected R values are shown on Fig. 7 along with Reichardt's acceptable clarity region. For each hall the mean occupied R value of 1000 Hz is shown, as is the range of values within each hall.

Only for hall 11 do the R values fall into a relatively narrow range close to the center of the acceptable region.

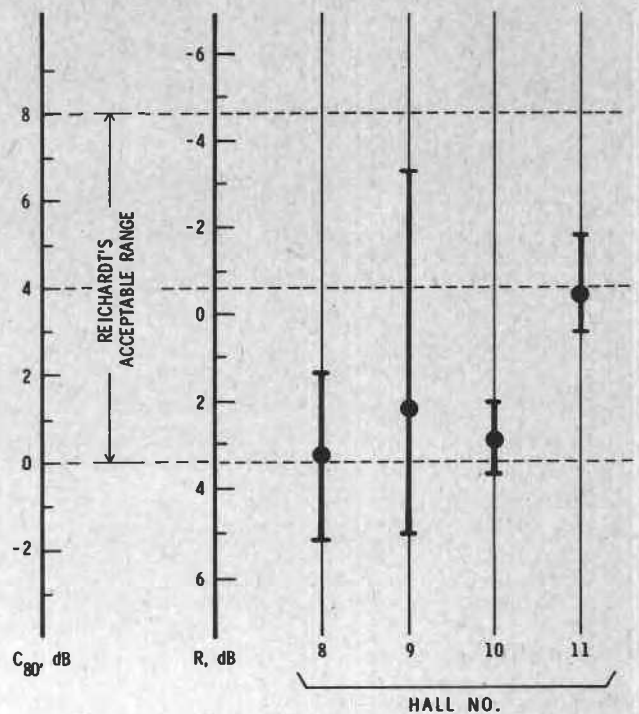


FIG. 7. Comparison of mean and within-hall ranges of R values for halls 8, 9, 10, and 11 with Reichardt's acceptable clarity region.

The other three halls tend to have larger R values and are only partly within the acceptable region. Hall 9 and, to a lesser extent, hall 8 seem to exhibit excessive within-hall variations of R values. Thus it seems possible to differentiate among the four halls on the basis of this criterion. This is not apparent from the expected occupied reverberation times, which were all reasonable compromises for multipurpose halls of these volumes. One would normally consider such reverberation times to be a little short for music, usually relating to insufficient late-arriving energy. It is clear from Fig. 7 that this is not at all the case. For three of the four halls the R values seem to be too large. One must therefore conclude that in each of the three halls there is less early sound energy than would be ideal. Where conventional reverberation times suggest comparable acceptable conditions, R values show distinct differences with respect to both the mean R values and the within-hall range of R values.

TABLE III. Mean IACC values and within-hall ranges.

Hall	IACC	
	Mean	Range
1	0.18	0.12
2
3	0.17	0.095
4
5
6
7	0.22	0.23
8	0.28	0.22
9	0.34	0.22
10	0.41	0.24
11	0.33	0.23

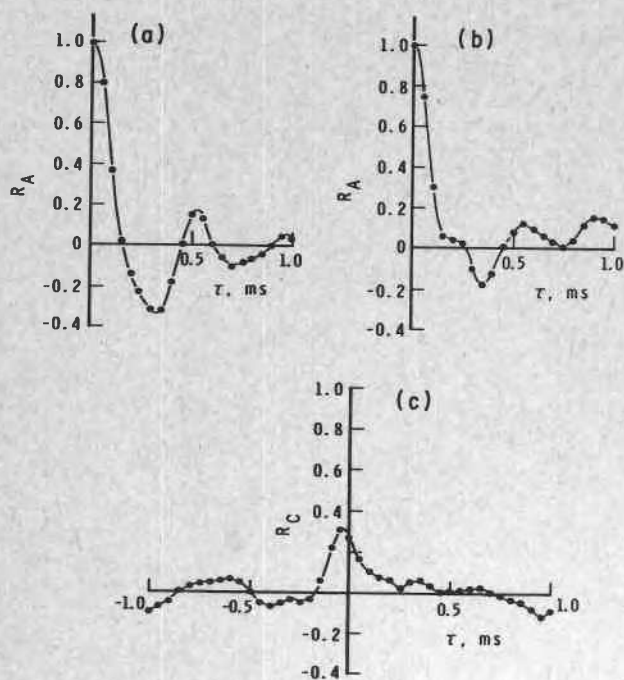


FIG. 8. Example correlation functions in hall 2, (a) autocorrelation left ear, (b) autocorrelation right ear, and (c) cross correlation.

C. Binaural effects

Table III gives the mean IACC values and the range of IACC values among seats for seven of the 11 halls. Some of the smaller lecture theaters were not measured because binaural effects such as spatial impression, which has been shown to be related to IACC values, are only thought to be relevant with respect to musical performances. Figure 8 shows typical autocorrelations of the signals at each ear and an example of a cross-correlation function of the recordings at the two ears. The IACC value for this example, taken from hall 11, is 0.30. Few published data of IACC values in real halls were found. Gottlob⁹ measured IACC values, but only mentioned a specific value of 0.23 for the mean of a group of subjectively preferred sound fields. The measured data in Table III for the larger halls 8 to 11 are all a little larger than this value. These differences could be due to different measuring techniques or could indicate lower spatial impression

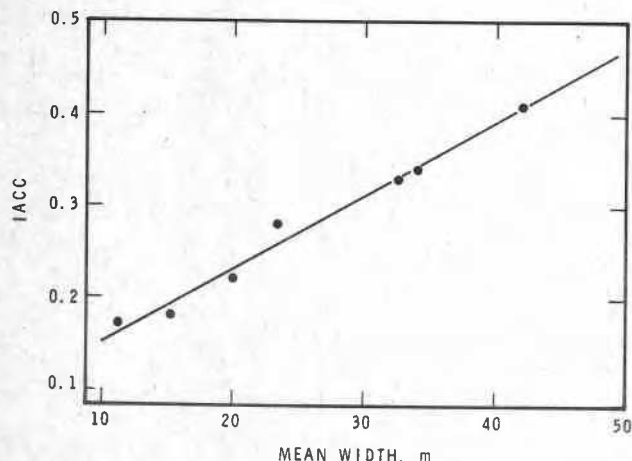


FIG. 9. Mean hall IACC values versus mean hall width.

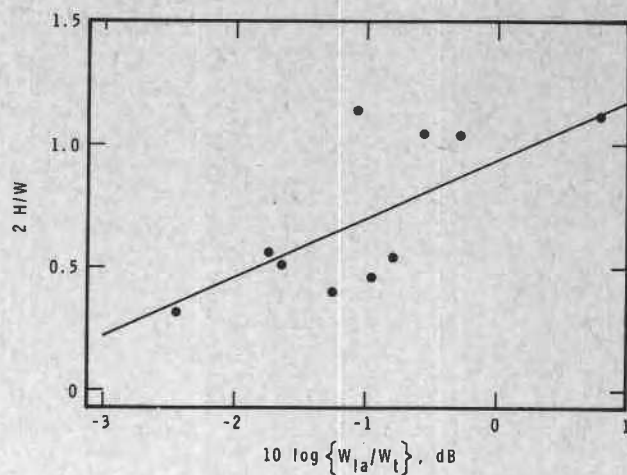


FIG. 10. Ratios $2H/W$ vs $10 \log (W_{la}/W_t)$.

for the present data. Clearly, more data are required and more firmly established optimum values are needed before meaningful comparisons can be made.

Possible relations between IACC values and other variables were considered. As shown in Fig. 9, there was a highly significant relation between mean width and the measured mean IACC values. Gottlob⁹ also found IACC values significantly correlated with a measure of hall width. The relation shown in Fig. 9 is sufficiently strong to suggest use of the mean width to predict IACC values. The observed increase in IACC with increasing width is consistent with the explanation that as width increases direct sound becomes increasingly dominant in the 50-ms early-sound window and thus that signals at the two ears become more nearly similar.

Gottlob suggested from an analytical derivation that IACC is related to the fraction of early sound that is lateral in orientation:

$$10 \log (W_{la}/W_t) = 10 \log (1 - \text{IACC}), \quad (7)$$

where W_{la} = early lateral energy, W_t = total early energy. Gottlob did not confirm the relation experimentally, but this has been attempted in the present work. The ratios of early lateral to early total sound were obtained from the corresponding late-to-early ratios, assuming the late components to be equal. Differences in reverberation times for lateral array and omnidirectional results indicated that differences did exist in reverberant energies and would lead to errors. Further, it was observed that additive errors of only 0.5 dB in each of the two ratio values used could produce a change in the related IACC values corresponding to the full range of measured IACC values. It was not surprising, therefore, that the measured data failed to confirm this relation. One must conclude that Eq. (7) is not a practical method for predicting IACC values. At least for the present data in Fig. 9, the mean width of the hall appears to be a more suitable predictor of mean IACC values.

West¹² and Marshall¹³ have suggested that the ratios of height to width ($2H/W$) relate to the adequacy of early sound to a desirable spatial impression. Gottlob found that although IACC values were of high subjective importance, the ratio $2H/W$ had no particular relevance. In support of Gottlob's results, no relation was found between IACC values

and the ratios $2H/W$ in the present work. The ratios $2H/W$ were, however, found to be significantly related to the ratios of early lateral to total early sound energy, as illustrated in Fig. 10.

III. CONCLUSION

Omnidirectional reverberant-to-early sound ratios, R , measured in a wide range of halls have been observed to vary approximately as much within some halls as the hall averages vary among halls. Such large within-hall variations have been presumed to degrade acoustical quality because optimum R values were clearly not approached at all points. In some cases such variations depended on frequency and would cause variations in the spectral balance from seat to seat. It was demonstrated for four of the larger halls that although reverberation times suggested they were similarly suitable for multipurpose use, the R values indicated differences among halls as well as acoustical flaws not suggested by RT data.

To a first approximation, hall average reverberant-to-early ratios can be expected to relate to the logarithm of the reverberation times. Mean IACC values, which have in the past been shown to correlate with subjective ratings of spatial impression, are now shown to relate strongly to the mean width of the hall. Relations between IACC values and ratios of early lateral to early total sound were investigated but not clearly established.

The present work provides expanded insight of a practical nature as well as representative values of new auditorium acoustic measures established by other researchers.

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