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Journal of the Acoustical Society of America, 96, 6, pp. 3525-3535, 1994

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NRCC-37817

Bradley, J.S.

May 1994

A version of this document is published in / Une version de ce document se trouve dans:
Journal of the Acoustical Society of America, 96, (6), pp. 3525-3535, 94

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Comparison of Concert Hall Measurements of Spatial Impression

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Received _____

Abstract

Two different types of measures of spatial impression, lateral energy fractions and interaural cross correlations, were measured at a number of locations in 14 different concert halls. The mean and range of the hall-average values of these quantities give an indication of typical conditions to be expected in other larger concert halls. Comparisons of hall-average values of the two types of quantities showed them to be significantly related at medium and lower frequencies in good agreement with theoretical expectations. Individual position measurements were less well related and showed that other factors had a major influence on the individual position measurements. In some halls the two types of quantities varied quite differently with increasing source-receiver distance. At a particular seat location, the two types of measures cannot always give similar indications of expected spatial impression. Calculating hall-average values from a small number of measurement locations is shown to introduce significant errors.

Introduction

Interaural cross correlations, IACC, and lateral energy fractions, LF, are quite different objective measures that have both been related to subjective judgments of spaciousness^{1,2,3}. Spaciousness is normally assumed to relate to the apparent source width and to the degree of envelopment experienced by listeners in a concert hall. Several authors have produced theoretical relationships between the two types of quantities^{5,6}. Previous objective measurements of these quantities suggested that they were not related⁴, but these previous results were based on measurements in a single hall.

This paper reports the results of comparisons between values of the two types of measures obtained in 14 different concert halls. Analyses are performed in terms of both hall-average values as well as individual position measurements.

I. Measurement Details

Lateral energy fractions are the linear ratio of the early lateral energy to the early total energy of a room impulse response. Barron^{2,3} demonstrated that spaciousness was related to the lateral energy fraction and defined "early" as the first 80 ms after the arrival of the direct sound. Thus, the lateral energy fraction can be defined as follows,

$$LF = \int_0^{0.08} p_L^2(t) \cdot dt / \int_0^{0.08} p^2(t) \cdot dt, \quad dB \quad (1)$$

where $p_L(t)$ is the lateral pressure response from the figure-of-eight

microphone, and $p(t)$ is the response from the omni-directional microphone. Subjective judgments of spatial impression increase with increasing LF values.

The lateral energy is usually measured using a figure-of-eight microphone with its directional null pointing towards the source to measure the lateral response. This quite effectively eliminates the direct sound energy from the lateral sound signal. Barron suggested that the summation of the early lateral energy (the numerator of equation (1)) should start 5 ms after the arrival of the direct sound and not at 0 ms after as shown in equation (1). This variation was also calculated and is referred to as LF5. Although this procedure does help to ensure that the direct sound energy is eliminated from the lateral microphone signal, attempting to window out the first 5 ms of the signal may introduce errors in some frequency bands. In practice LF and LF5 values are almost identical because the directional pattern of the figure-of-eight microphone quite effectively eliminates the direct sound energy from the lateral microphone response.

Barron's subjective studies indicated that spatial impression varies with the cosine of the horizontal angle of arrival of lateral reflections. When LF measurements are made using a figure-of-eight microphone, the measured pressures are cosine weighted and then squared to get an energy related quantity. Thus, the lateral energy sum includes a cosine squared rather than a cosine weighting. Kleiner⁷ has suggested a procedure for obtaining an approximation to a cosine weighting while using a figure-of-eight microphone. This involves multiplying the lateral microphone signal by the omni-directional microphone signal rather than squaring the lateral microphone signal in the numerator of equation (1).

In the present study four variations of LF were measured. These were the four combinations of: cosine, or cosine squared directionality, and summing lateral energy from 0, or from 5 ms after the direct sound. They are listed in the table below.

Lateral Energy Fraction	Lateral Energy Integration Limits	Angular Weighting
LF	0-80 ms	(cosine) ²
LF5	5-80 ms	(cosine) ²
LF_c	0-80 ms	(cosine)
LF5_c	5-80 ms	(cosine)

IACC values are derived from the cross correlation function of the impulse responses at the two ears of a dummy head as defined by equation (2).

$$\Phi_{lr}(\tau) = \frac{1/(T_2 - T_1) \cdot \int_{T_1}^{T_2} p_l(t) \cdot p_r(t+\tau) \cdot dt}{\sqrt{\Phi_{ll}(0) \cdot \Phi_{rr}(0)}}, \quad |\tau| \leq 1 \text{ ms} \quad (2)$$

where, Φ_{ll} and Φ_{rr} are the auto correlations of the left and right ear signals respectively, T_1 and T_2 , the limits of the integration, vary according to whether the early, late or total IACC is being determined and are included in the table below.

For the present concert hall measurements of IACC values, the internal microphones of a Bruel and Kjaer Head and Torso Simulator were used. The cross correlation is performed for a maximum time shift of ± 1 ms (to include the maximum interaural time delay) and the maximum absolute value of the cross correlation function over this range is the IACC value. The lower the IACC value, the more different the signals at the two ears, and the more spacious

the sound field would be. IACC values were calculated for the early, late and total parts of the binaural impulse responses. "Early" was again defined as the first 80 ms, and "late" was the period from 80 ms to 1 s after the direct sound. "Total" IACC values were calculate from both the early and late parts of the impulse response.

Interaural Cross Correlations	Impulse Response Segment
IACC (E)	0 - 80 ms
IACC (L)	80 - 1000 ms
IACC (T)	0 - 1000 ms

Two different computer based measurement systems were used to obtain values of the two types of quantities. Both programs used Maximum Length Sequence, MLS, signals and Fast Hadamard Transform procedures to obtain impulse responses. In both cases the sound source was a dodecahedron loudspeaker. The RAMSoft-II program used to measure LF values also measures a number of other room acoustics quantities from measured impulse responses such as decay times and early/late ratios. The program samples the signal at 12.7 kHz and provides results in the 6 octave bands from 125 to 4000 Hz. The binaural program, BRAM, sampled the signals at 32 kHz so that the binaural impulses could also be used in subjective studies. IACC values were calculated for the 6 octaves from 125 to 4000 Hz.

The measurements were obtained from 14 concert halls listed in Table 1. Data for 15 halls is included in some of the following analyses because one hall was measured for two different positions of its acoustically absorbing banners. Eleven of the halls were relatively large concert halls with between 1400 and about 3000 seats. Three smaller halls were also included in some of the analyses. In most of the halls the IACC measurements were made for only one

The LF values (with cosine squared directionality) in Figure 2(a) tend to be smaller than the corresponding cosine directionality LF5_c values in Figure 2(b). This is because the cosine directionality leads to a broader directional pattern than the cosine squared directionality. Neither lateral fraction measure exhibits the large variation with frequency found for IACC values. However, the range of these hall-average values is again quite small, and quite careful measurements are required to precisely define differences between halls. Data for LF5 values were very similar to LF values and LF_c values were very similar to LF5_c. That is, shifting the start of the integration of the lateral energy had very little effect. (Differences in overall average octave band LF and LF5 values were less than 0.007).

Data from the three smaller halls tended to have higher LF values and smaller IACC values. These data were not included because three halls were not considered to be a representative sample of smaller halls.

(b) Correlation of LF and IACC values

The relationships between IACC(E) values and LF values were first examined by comparing hall-average values of $1 - \text{IACC}(E)$ and hall-average LF values. For each octave, the quantity $1 - \text{IACC}(E)$, (sometimes referred to as the degree of incoherence), is plotted versus LF values along with best fit linear regression lines in Figures 3(a), (b), and (c). The corresponding regression equations are included in Table 2. Table 3(a) and (b) gives the correlation coefficients between IACC(E) values and all four LF measures.

At 125 Hz there is a quite small variation in the $1 - \text{IACC}(E)$ quantity for a wide

range of LF values. However, the scatter about the regression line is quite small, and as indicated in Table 3(a) the relationship is highly significant. ($p < 0.001$). (Here p is the probability of this correlation occurring by chance. Thus it is highly significant and there is less than a 1 in one thousand probability of this occurring by chance). The greatest variation of 1-IACC(E) with LF values occurs in the middle 500 and 1000 Hz octaves shown in Figure 3(b). Although there seems to be a trend for 1-IACC(E) values to increase with increasing LF values in the 2 and 4 kHz octaves shown in Figure 3(c), the trends are not statistically significant ($p < 0.01$).

The relationships between hall-average LF and IACC values were also examined by correlation analysis. Table 3(a) shows the resulting correlation coefficients from correlations between 1-IACC(E) values and all four variations of the lateral fraction measure. (1-IACC(E) values were used so that positive correlations were obtained). Table 3(a) indicates that in the lowest 4 octaves all correlations between IACC(E) and the four lateral fraction measures were statistically significant. However, in the 2 and 4 kHz octaves the IACC(E) values are not significantly related to any of the lateral fraction values. That is, in these two highest octaves the two types of measure do not evaluate the same aspect of the sound fields.

IACC(E) values are most strongly correlated with cosine squared measures (LF, LF5) in the 125 and 250 Hz octaves, and most strongly correlated with cosine pattern measures (LF_c, LF5_c) in the 500 and 1000 Hz octaves. Among the significant correlations, the influence of the starting point of the lateral energy integration did not seem to have a systematic effect.

Table 3(b) shows that there were a number of significant correlations between IACC(L) values and the lateral fraction measures. The significant correlations are mostly found in the 250 and 500 Hz octave results. These relationships are surprising in that IACC(L) values are calculated from the late part of the impulse responses and the lateral fraction measures are obtained from the early part of the impulse responses.

Correlations between hall average IACC(T) values and the four LF values were similar to the pattern of correlations for IACC(E) values.

These results demonstrate that there are some quite strong relationships between hall-average IACC(E) and lateral fraction measures. That is, in the 125 to 1000 Hz octaves the hall-averages of the two types of measures seem to assess similar aspects of the sound fields of these concert halls. At the higher 2 and 4 kHz octaves there is a trend for the same pattern of relationships, but it is not statistically significant. Thus, there are other factors that modify the values of at least one of these two types of acoustical measures and cause them to be less well related at these higher frequencies.

III Comparisons with Barron's Theory

Barron⁵ determined a theoretical relationship between $1 - \text{IACC(E)}$ and the lateral fraction, LF, but made no attempt to experimentally verify this relationship. He assumed that low frequencies are of interest and that head shadowing could be ignored. His derivation resulted in the following relationship.

$$(1 - \text{IACC(E)}) = K \cdot \text{LF} \quad (3)$$

theoretical relationships that assume diffuse field conditions up to the 1000 Hz octave band even though only the early part of the signal is included. However, the dummy head results agree best with the 0.30 m separation results and not with the 0.15 m separation results. The physical separation of the ears of the dummy head are approximately 0.15 m, but the acoustical separation seems to be equivalent to approximately 0.3 m. Thus, it seems more appropriate to use a $\tau_{\max}$ value related to this separation in calculating Barron's relationship between LF and 1-IACC(E).

Accordingly, a $\tau_{\max}$ of 0.97 ms (the same as used in calculating IACC values) was used to calculate the averages of the auto-correlation functions and values of the K parameter in equation (3). Similarly K values were determined from the slopes of regression equations of 1-IACC(E) versus LF values given in Table 2. Both are compared in Figure 5. The agreement between measured and calculated K values is good at low frequencies but the agreement decreases with increasing frequency.

In the highest two octaves, 2000 and 4000 Hz, the measured values are considerably different than theoretical predictions using Barron's procedure. This may well be due to Barron's assumption of no head-shadowing. While this assumption would be approximately valid up to 500 or 1000 Hz, at higher frequencies the wavelength of the sound becomes increasingly smaller than the dimensions of the head, and shadowing must occur and would be expected to modify the IACC(E) values.

The lack of agreement between measured and theoretical K values may also be due to ignoring a residual minimum 1-IACC(E) that is always present. The regression

The relationships between IACC and lateral fraction values were considered in more detail in terms of the 124 individual position measurement results. Octave band values of $1-IACC(E)$ are plotted against LF values in Figures 6(a), (b), and (c) for the individual position data. Tables 4(a) and (b) show the correlation coefficients from the correlations of $IACC(E)$ values with the four types of LF measures for the individual position measurements.

The scatter about the regression lines in Figures 6(a), (b), and (c) is much greater than the maximum variation indicated by the mean trend of the regression lines. Thus, although the relationships are statistically significant (see Table 4(a)), they are not of much practical use. That is, knowing the value of a particular LF would not allow one to make an accurate estimate of the corresponding $IACC(E)$ value.

An overview of the pattern of relationships between the two types of measures is given by the calculated correlation coefficients. Table 4(a) shows the results of correlations between $IACC(E)$ values and the four lateral fraction measures. The pattern of correlation coefficients is similar to those for the hall-average data in Table 2(a), except that correlation coefficients are largest in the 125 and 1000 Hz octaves. Correlation coefficients in the highest two octaves are smallest for all lateral fraction measures. The cosine squared pattern lateral fraction values (LF and LF5) are most strongly correlated with $IACC(E)$ values in the lowest two octaves, and the cosine pattern measures (LF_c and LF5_c) are most strongly correlated with $IACC(E)$ values in the 500 and 1000 Hz octaves.

Because of the much larger number of data points, all of the correlation

coefficients in Table 4(a) are statistically significant ($p < 0.01$ or better).

However, the magnitudes of the correlation coefficients are much smaller than for the hall-average data and the scatter about the associated regression lines is much greater.

Table 4(b) shows the results of correlations between IACC(L) values and the four lateral fraction measures. Significant correlations are limited to the 250, 500, and 1000 Hz octaves whereas for the hall-average values they were limited to only the 250 and 500 Hz octaves. The pattern of correlations between IACC(T) and the four LF values was similar to that for IACC(E) values.

While the hall-average values of these two types of measures were quite closely related, the individual position measurements were not. Thus, there must be other factors that influenced the relationships and that varied on a seat-to-seat basis. Some clear examples of quite different seat-to-seat variations of the two measures were found in some halls. Figure 7(a) plots 1000 Hz LF and 1-IACC(E) values versus source-receiver distance for data from Boston Symphony Hall. While there is not much variation of LF values with distance, the 1-IACC(E) values increase rapidly with increasing source-receiver distance. This data suggests not one, but a range of possible relationships between LF and IACC(E) values varying with source-receiver distance.

A quite different trend is seen for the 1000 Hz data from E.J. Thomas hall in Figure 7(b). Both LF and 1-IACC(E) values are relatively constant with source-receiver distance. The E.J. Thomas hall is a wide fan shaped hall and the Boston Symphony Hall is a relatively narrow rectangular shoe box shaped hall. However, these two different types of within-hall variation of IACC(E) values

do not seem to be related to the basic hall shapes. For example, data from the wide fan shaped Kleinhans Music Hall were similar to the Boston data in Figure 7(a) despite the great differences in plans. Results from some rectangular halls were quite different from the Boston Symphony Hall results in Figure 7(a).

The LF measure is based on the sums of the energy arriving within the first 80 ms. In concert halls both the early lateral energy and the total early energy tend to decrease with increasing source-receiver distance. If both components decrease at approximately the same rate, it is possible for LF values to not vary greatly with source-receiver distance. Although IACC(E) values are also influenced by the fraction of early lateral energy, they will also be influenced by the relative importance of the direct sound. Where the direct sound is relatively important, the sound fields at the two ears of the dummy head will be more similar and IACC(E) values will be high. As the receiver is moved away from the source and the relative importance of the direct sound diminishes, IACC(E) values will also decrease as in Figure 7(a).

Although values of the direct to reflected sound ratios were not available, C35 values describing the early/late energy ratio with a 35 ms early time limit were measured. Because there are usually few reflections in the first 35 ms, these ratios should be close to a direct-to-reverberant ratio. In Figure 8 the 1000 Hz C35 values are plotted versus source-receiver distance for the Boston Symphony Hall and the E.J. Thomas Hall measurements. In Boston Symphony Hall, these 1000 Hz C35 values vary by approximately 10 dB from the front to the rear of the hall. However, in the E.J. Thomas Hall the C35 values vary by only 5 dB over similar distances. These variations seem to parallel, and help to explain

the variation of $1-IACC(E)$ values with distance in these two halls.

V Relationships with Other Measures

To better understand the measured LF and IACC values, statistical analyses were performed to determine how they were related to other acoustical measures.

Initially LF and IACC values were correlated with other measures for both the hall-average and the individual position data. Subsequently, multiple regression analyses were performed to examine multiple predictors of the measures of spatial impression. The other acoustical measures are defined in Table 5 below.

Table 6(a) summarises the significant relationships with hall-average LF values. Because the particular correlation coefficients are not of much interest, only the levels of significance are presented to give a simple overview of the main trends of the results. (In these analyses DIST is the average source-receiver distance for all measurements in a particular hall). Since LF values are the ratio of the lateral to the total early sound energy, one would expect LF values to be correlated with GEL (the early lateral energy) and G80 (the total early energy). Although LF values were strongly correlated with GEL values in all 6 octaves, only weaker correlations occurred with G80 values and only in two octave bands. Surprisingly, high frequency LF values (calculated from the early part of the impulse responses) were correlated with the late arriving energy as measured by G_{late} .

The significant relationships with hall-average $IACC(E)$ values are given in Table 6(b). There are few significant correlations and most are relatively weak

correlations. There are significant correlations with GEL values in the three mid-frequency octave bands. In comparing Tables 6(a) and 6(b), the pattern of significant correlations is quite different indicating that there are important differences between hall-average LF and IACC values.

Hall-average IACC(L) values were only significantly related to DIST and GEL values and only in the 250 and 500 Hz octaves.

Tables 7(a) and (b) summarise correlations with individual position LF and IACC(E) values. These individual position data lead to a larger number of significant correlations than occurred for the hall-average data. LF values are significantly correlated with both G80 and GEL values in most octave bands. There are also a number of significant correlations with DIST, G, and G_{late} values. There are fewer significant correlations with individual position IACC(E) values. GEL values are significantly correlated with IACC(E) values in the lowest 4 octaves. Only DIST was significantly related to high frequency IACC(E) values.

Fewer significant correlations were found with individual position IACC(L) values. Significant correlations with G_{late} values were found in the 125, 250, and 500 Hz octaves. GEL values were significantly related to IACC(L) values in the 250 and 500 Hz octaves and G80 values in the 500 Hz octave.

Multiple regression analyses were performed to find the best combinations of predictors of LF and IACC values. No significant multiple predictors of hall-average LF values were found. Individual position LF values were found to relate most strongly to combinations of GEL and G80. This is to be expected

coefficients from the stepwise multiple regression analyses. The correlations from the various models show how one can improve the prediction of IACC(E) values from the simple case based on only LF values.

The second column of Table 8 shows the multiple correlation coefficient when GEL and G80 values are used as the only two predictors. The third column builds on this model by adding C35, and DIST values as predictors in the highest three octaves. Even this quite simple model predicts IACC(E) almost as accurately as the stepwise multiple regression analyses.

VI Influence of Measurement Locations on Average Values

The averages of LF and IACC values for each hall will depend on the individual measurement locations that are included. In most of the halls included in this study measurements were made using one centre stage source position and 6 to 10 receiver positions. In two halls (Massey Hall and Mechanics Hall) measurements were made at the combinations of 3 source positions and 9 or 12 receiver positions. Other authors⁹ have quoted results from just 3 representative seats. The more extensive measurements in Massey and Mechanics Halls make it possible to estimate the likely errors of using fewer measurement positions to obtain hall-average values of LF and IACC values.

Hall-average values for data from these halls were calculated: (1) using all measured combinations of source and receiver positions, (2) for all receivers with only the centre source position, and (3) for the centre source position and three representative seats (two from the main floor and one from the balcony). Figure 9 compares these average values for IACC(E) values in

Mechanics Hall. The curve labelled "all sources" is the average of the 24 combinations of 8 receiver positions and 3 source positions. The source positions included the centre stage source position as well as a stage right and a stage left position. This average is assumed to be the best estimate of the actual hall-average values. The average for only the centre source position measurements is quite similar and only differs a little from the all-source data at higher frequencies. The average for the three representative seats is significantly different, especially when compared with the range of hall-average values for all 11 large halls in Figure 1. Although the choice of positions will influence the average, it is clearly not reliable to estimate hall-average values of IACC(E) values from measurements at only three positions.

Figure 10 presents a similar comparison for IACC(L) values. The average values from the three representative seats are again most different from the other average values, but the differences are quite small. In this case the errors due to averaging over only a few positions are relatively small compared to the range of hall-averages shown in Figure 1.

The hall-averages of LF values are compared in Figure 11. For this measure the averages from the centre source measurements are quite different from the all-source averages and these differences are greatest at low frequencies. The average LF values from the 3 representative receiver locations are even more different from the all-source averages. Again these differences are quite large compared to the range of hall-average LF values in Figure 2.

These results clearly demonstrate that it is very important to use an adequate

number of measurement positions to obtain an accurate estimate of hall-average values of IACC(E) and LF values. Hall-average IACC(L) values are less sensitive to the choice of measurement positions. Analyses of the Massey Hall data led to similar conclusions. It is suggested that one should average results from the combinations of 3 source and 8 or more receiver positions to accurately represent hall-average LF and IACC(E) values.

VII Conclusions

Measurements in 11 large concert halls have given an indication of the mean and range of the LF and IACC measures of spatial impression.

Hall-average LF values are significantly related to hall-average IACC(E) values in the 125, 250, 500, and 1000 Hz octaves. These measured relationships are in reasonable agreement with Barron's theoretical relationship for these measures. Hall-average LF and IACC(E) values are not significantly related in the 2000 and 4000 Hz octave bands. Thus, either may reasonably successfully assess the average spatial impression of a concert hall. However, they do not both assess the same average characteristics in the higher 2000 and 4000 Hz octaves.

Individual position LF and IACC(E) values are significantly related in all 6 octave bands, but there is considerable scatter about the mean trends. For IACC(E) values the within-hall variations are considerably greater than the between-hall variations. For individual position LF values, within-hall variations were similar in magnitude to between-hall variations.

Differences between individual position LF and IACC(E) values were seen to vary

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Figure Captions

Figure 1. Mean (solid line) and range of hall-average IACC values from 11 large concert halls.

Figure 2. Mean (solid line) and range of hall-average LF and LF5_c values from 11 large concert halls.

Figure 3(a) Hall-average values of 1-IACC(E) versus LF values for the 125 and 250 Hz octaves.

Figure 3(b) Hall-average values of 1-IACC(E) versus LF values for the 500 and 1000 Hz octaves.

Figure 3(c) Hall-average values of 1-IACC(E) versus LF values for the 2000 and 4000 Hz octaves.

Figure 4. Comparison of IACC(E) values measured in a reverberation chamber with calculated values for microphone separations of 0.15 and 0.30 m.

Figure 5. Comparison of the K parameter from hall-average measurements and Barron's theory.

Figure 6(a). Individual position values of 1-IACC(E) versus LF values for the 125 and 250 Hz octaves.

Figure 6(b). Individual position values of 1-IACC(E) versus LF values for the 500 and 1000 Hz octaves.

Figure 6(c). Individual position values of 1-IACC(E) versus LF values for the 2000 and 4000 Hz octaves.

Figure 7(a). Comparison of the variation with distance of 1000 Hz LF and 1-IACC(E) values in Boston Symphony Hall.

Figure 7(b). Comparison of the variation with distance of 1000 Hz LF and 1-IACC(E) values in the E.J. Thomas Hall.

Figure 8. Comparison of 1000 Hz C35 values versus distance in the E.J. Thomas Hall and Boston Symphony Hall.

Frequency	Regression Equation
125	$(1-IACC(E)) = 0.197 \cdot LF + 0.022$
250	$(1-IACC(E)) = 0.811 \cdot LF + 0.044$
500	$(1-IACC(E)) = 1.613 \cdot LF + 0.251$
1000	$(1-IACC(E)) = 1.352 \cdot LF + 0.284$
2000	$(1-IACC(E)) = 0.314 \cdot LF + 0.557$
4000	$(1-IACC(E)) = 0.232 \cdot LF + 0.602$

Table 2. Regression equations corresponding to the regression lines on Figure 3.

(a) 1-IACC(E)		Frequency, Hz				
	125	250	500	1000	2000	4000
LF	.798 **	.852 **	.803 **	.750 **	.368	.250
LF5	.788 **	.844 **	.794 **	.785 **	.377	.293
LF_c	.639 *	.804 **	.890 **	.819 **	.389	.324
LF5_c	.669 *	.760 **	.880 **	.877 **	.480	.369
(b) 1-IACC(L)						
LF	.419	.834 **	.726 *	.574	.281	.359
LF5	.415	.836 **	.711 *	.563	.260	.351
LF_c	.415	.774 **	.772 **	.621 *	.226	.313
LF5_c	.403	.735 **	.677 *	.624 *	.179	.319

Table 3 Correlation coefficients of half-average lateral fractions with, (a) 1-IACC(E), and (b) 1-IACC(L) values.
 (* $p < 0.01$, ** $p < 0.001$)

(a) 1-IACC(E)		1-IACC(E)				
	125	250	500	1000	2000	4000
LF	.617 **	.477 **	.530 **	.619 **	.297 **	.255 *
LF5	.618 **	.474 **	.525 **	.636 **	.310 **	.270 *
LF_c	.500 **	.382 **	.591 **	.703 **	.425 **	.369 **
LF5_c	.491 **	.356 **	.572 **	.758 **	.481 **	.412 **
(b) 1-IACC(L)						
LF	.188	.364 **	.406 **	.349 **	.082	.088
LF5	.190	.362 **	.406 **	.352 **	.083	.085
LF_c	.196	.318 **	.375 **	.367 **	.050	.079
LF5_c	.178	.311 **	.370 **	.362 **	.051	.076

Table 4 Correlation coefficients of individual position lateral fractions with, (a) 1-IACC(E) and, (b) 1-IACC(L) values.
(* $p < 0.01$, ** $p < 0.001$)

DIST	Source-receiver distance, m
RT	Reverberation time, s
G	Relative sound level (relative to the level of the same source at a distance of 10 m in a free field), dB
G80	G value for the total early arriving sound up to 80 ms after the arrival of the direct sound, dB
GEL	G value of the early arriving lateral sound arriving up to 80 ms after the arrival of the direct sound, dB
G _{late}	G value of the late sound arriving more than 80 ms after the arrival of the direct sound, dB

Table 5. Definitions of other acoustical measures tested as predictors of IACC and LF values.

	Frequency	DIST	G80	GEL	G _{late}	G	RT
(a)	125	**	*	**		*	
	250	*		**		*	
	500	**		**			**
	1000	**		**			**
	2000	*		**	*		**
	4000	**	*	**	**		*
(b)	125	*					**
	250			*		*	
	500			*		*	
	1000			*		**	
	2000					*	
	4000					*	

Table 6 Summary of significant correlations with hall-average,
(a) IACC(E), and (b) IACC(L) values.
(* $p < 0.01$, ** $p < 0.001$)

	Frequency	DIST	G80	GEL	G _{late}	G	RT
(a)	125	**		**	**	*	
	250			**	**	*	
	500	**	**	**	**	**	
	1000		**	**	**	**	
	2000	**	**	**	**	**	*
	4000	**	**	**	**	**	
(b)	125			**			**
	250			**			
	500	*		**	**	**	
	1000	*		**	**		
	2000	**					
	4000	*					

Table 7 Summary of significant correlations with individual position, (a) IACC(E), and (b) values. (* $p < 0.01$, ** $p < 0.001$)

ictors.

Figure 1. Mean (solid line) and range of hall-average IACC values from 11 large concert halls.

Figure 2. Mean (solid line) and range of hall-average LF and LF5_c values from 11 large concert halls.

Figure 3. Hall-average values of $1-IACC(E)$ versus LF .

Figure 4. Comparison of $IACC(E)$ values measured in a reverberation chamber with calculated values for microphone separations of 0.15 and 0.30 m.

Figure 5. Comparison of the K parameter from hall-average measurements and Barron's theory.

Figure 6. Individual position values of $1-IACC(E)$ versus LF .

Figure 7. Comparison of the variation with distance of 1000 Hz LF and 1-IACC(E) values, (a) Boston Symphony Hall, (b) E.J. Thomas Hall.

Figure 8. Comparison of 1000 Hz C35 values versus distance in the E.J. Thomas Hall and Boston Symphony Hall.

Figure 9. Comparison of half-average IACC(E) values in Mechanics Hall.

Figure 10. Comparison of hall-average IACC(L) values in Mechanics Hall.

Figure 11. Comparison of hall-average LF values in Mechanics Hall.