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MEASURED EARLY LATERAL ENERGY FRACTIONS IN CONCERT HALLS AND OPERA HOUSES

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In the 30 years since early lateral reflections were first suggested as important for concert halls, spatial impression and source broadening have become almost universally accepted as essential characteristics of halls with good acoustics. Two objective measures of source broadening have been proposed. Measured values of the best defined of these measures, the early lateral energy fraction (*LF*), are considered here. Results from two independent measurement surveys are discussed. Comparisons of *LF* values by hall show a significant link between hall mean *LF* and hall width. There is however considerable overlap between measured *LF* values in different halls so the relevance of describing halls by their mean early lateral energy fraction values is questionable. The behaviour of *LF* values within auditoria is discussed for different concert hall plan forms and within opera houses. A measure of source broadening including sound level is proposed and results considered in the context of auditorium design.

1. INTRODUCTION

During the 1960s, several acousticians felt that design form was of only minor importance for concert hall acoustics and that most shapes could be made to work well acoustically. Marshall [1] contested this view with the suggestion that some design forms worked better than others and that the secret lay in early lateral reflections. Experiments using simulation apparatus in an anechoic chamber [2] showed that the effect, labelled "spatial impression" at the time, was related to the proportion of early sound energy arriving from the side. The objective measure finally proposed [3] was the early lateral energy fraction (*LF*), which was also thought to be linearly related to the subjective effect. It was defined by

$$LF_c = \int_{0\cdot005}^{0\cdot08} p^2(t)\cos\phi\,\mathrm{d}t \bigg/ \int_{0}^{0\cdot08} p^2(t)\,\mathrm{d}t, \tag{1}$$

where $p(t)$ is received acoustic pressure and t is the arrival time after the direct sound. The listener is assumed to be facing the source and ϕ is the angle of incident sound to the axis passing through the listener's ears.

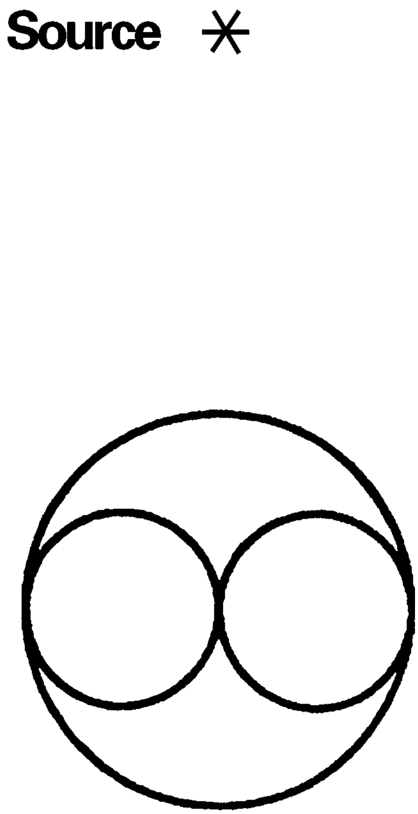

Figure 1. Microphone directivities and orientation for measurement of the lateral fraction.

As indicated in equation (1), subjective experiment showed the directional sensitivity for energy to be proportional to $\cos\phi$. To measure the fraction, a microphone with variable directivity with both an omni-directional and figure-of-eight characteristic is generally used. The null of the figure-of-eight is pointed towards the source; see Figure 1. However, a figure-of-eight microphone has a directional characteristic with *pressure* proportional to $\cos\phi$, so that for a measured lateral fraction

$$LF = \int_{0\cdot005}^{0\cdot08} p^2(t)\cos^2\phi\,\mathrm{d}t \Bigg/ \int_{0}^{0\cdot08} p^2(t)\,\mathrm{d}t$$

$$= \frac{\text{Early energy from figure-of-eight microphone from 5 to 80 ms}}{\text{Early omni-directional energy from 0 to 80 ms}}. \qquad (2)$$

For the lateral fraction at a seat position, the mean of values in octave bands at 125, 250, 500 and 1000 Hz is used. To distinguish the subjective from the measured lateral fraction, the former has the suffix *c*. The values for each measure in a diffuse field are: $LF_c = 0{\cdot}50$ and $LF = 0{\cdot}33$. Reference to the diffuse field offers the simplest solution for conversion from one type of lateral fraction to another: $LF_c = 1{\cdot}5 \times LF$.

Since Marshall's original suggestion, spatial impression has become almost universally accepted as a characteristic of good concert halls. More recently, it has been suggested that spatial impression encompasses two spatial effects: source broadening and envelopment (see section 1.2). An alternative objective measure for spatial impression based on cross-correlation has also been used by many (see section 1.3).

This paper considers lateral fraction measurements made in 17 British music spaces and 13 North American halls. Details of the British halls are given in Table 1; plans and sections, photographs and discussion of their acoustics can be found in reference [4]. The data for North American halls came from a report by Bradley [5], which contains all the measured data on floppy disk. Details of the halls measured are listed in Table 2; several halls are described in reference [6].

1.1. SPATIAL IMPRESSION, SOURCE BROADENING AND ENVELOPMENT

As already mentioned, the spatial effect of lateral reflections was initially called "spatial impression". This was generally considered to be associated with early reflections though it was clear that later reverberant sound also created a spatial effect that was different in character from that associated with early reflections. The term "envelopment" was also used and considered synonymous with spatial impression.

In 1993, Morimoto and Iida [7] proposed that envelopment might be linked to the front/back energy ratio (further elaborated in reference [8]). Two years later, Bradley and Soulodre [9] suggested that there were two distinct spatial effects. The early sound produced the sense that the source size increased while the later sound alone was able to provide the sense of being surrounded by sound. In other words, spatial impression encompassed two sensations: source broadening and envelopment. Source broadening can be quantified in terms of an apparent source width (ASW); the corresponding acronym for envelopment is LEV, for listener envelopment. Bradley and Soulodre used a temporal cut-off between ASW and LEV as 80 ms after the direct sound and have proposed the late lateral sound level as a measure for listener envelopment [10].

In the literature before 1990, spatial impression generally refers to what we now call source broadening. The discussion in this paper will be limited to source broadening produced by early reflections. The term spatial impression will be used here only when spatial effects in general are being considered.

1.2. EARLY LATERAL ENERGY FRACTION VERSUS INTERAURAL CROSS-CORRELATION

From the beginning there have been two objective measures which are considered relevant to source broadening: the early lateral energy fraction and cross-correlation measures [11]. Regarding the latter, the interaural cross-correlation coefficient (*ICC*) is most commonly used nowadays. Both measures have their advocates who defend the superiority of their preferred measure, see e.g., reference [12]. Both measures are defined in the 1997 ISO

TABLE 1

Basic details of the 17 British concert spaces; the second number under "Seating capacity" refers to choir seating

Hall	Label	Year of completion	Seating capacity	Volume (m^3)	Mean width (m)	Plan form
Royal Festival Hall, London	F	1951	2645 + 256	21950	32	Parallel-sided
Royal Albert Hall, London	A	1871	4670 + 419	86650	47	
Queen Elizabeth Hall, London	Q	1967	1106	9600	23	Parallel-sided
Barbican Concert Hall, London	R	1982	2026	17750	34	
Wigmore Hall, London	G	1901	544	2900	13	Parallel-sided
Fairfield Hall, Croydon	C	1962	1539 + 250	15400	26	
Wessex Hall, Poole	P	1978	1473 + 120	12430	30	Parallel-sided
Colston Hall, Bristol	B	1951	1940 + 182	13450	22	Parallel-sided
St. David's Hall, Cardiff	D	1982	1687 + 270	22000	34	
Assembly Hall, Watford	W	1940	1586	11600	22	
Music School Auditorium, Cambridge	S	1977	496	4100	20	Parallel-sided
Royal Concert Hall, Nottingham	N	1982	2315 + 196	17510	26	
Free Trade Hall, Manchester	M	1951	2529	15400	22	
Philharmonic Hall, Liverpool	L	1939	1767 + 184	13560	27	Parallel-sided
Usher Hall, Edinburgh	E	1914	2217 + 333	16000	29	
Conference Centre, Wembley	Y	1976	2511	24000	50	Fan-shape
Butterworth Hall, Warwick University	K	1981	1152 + 177	12100	30	Parallel-sided

Table 2

Basic details of the 13 *North American halls surveyed by Bradley* [5]

Hall	Label	Year of completion	Seating capacity	Volume (m^3)	Mean width (m)	Plan form
EJ Thomas Performing Arts Hall, Akron, OH, U.S.A.	a	1973	2969	19 800	42	Fan-shape
Joseph Meyerhoff Symphony Hall, Baltimore, MD, U.S.A.	m	1982	2465	21 500	31	
Boston Symphony Hall, Boston, MA, U.S.A.	b	1900	2631	18 740	24	Parallel-sided
Kleinhans Music Hall, Buffalo, NY, U.S.A.	k	1940	2839	18 220	43	Fan-shape
W. Manitoba Centennial Auditorium, Brandon, Manitoba, Canada	r	1969	867	12 390	28	Fan-shape
Severence Hall, Cleveland, OH, U.S.A.	c	1931	1890	15 700	28	
Orchestra Hall, Detroit, MI, U.S.A.	d	1919	2022	15 700	27	
Tanglewood Music Shed, Lenox, MA, U.S.A.	l	1938	5121	42 450	57	Fan-shape
Academy of Music, Philadelphia, PA, U.S.A.	p	1857	2984	15 720	27	
Troy Music Hall, Troy, NY, U.S.A.	t	1875	1255	11 320	30	Parallel-sided
Kennedy Center Concert Hall, Washington, DC, U.S.A.	s	1971	2759	19 300	28	Parallel-sided
Manitoba Centennial Auditorium Winnipeg, Manitoba, Canada	g	1966	2304	28 750	31	Fan-shape
Mechanics Hall, Worcester, MA, U.S.A.	w	1857	1400	10 760	25	Parallel-sided

Standard 3382. The early lateral energy fraction was proposed as a practical measure for use in music auditoria. Yet it is clear that spatial impression is caused by diferences between the signals at the two ears; a situation with identical reflections from each side has a lateral fraction but produces no spatial effect. In this respect the ICC is superior, but identical signals at the two ears are not significant in practice and can be avoided in measurements in symmetrical halls by not having both the source and receiver on the line of symmetry.

The interaural cross-correlation coefficient is the maximum value of the normalized cross-correlation function in the time interval ± 1 ms. But whereas the early lateral energy fraction was defined from the start in terms of octave-band measurements and microphones with particular directivities, there has been no such unanimity regarding measurement of ICC. Many researchers have used a single measurement with a broadband signal, Ando [13] for example. Some apply A-weighting, some do not. Some measure with dummy heads at the ear drum, some at the entrance to the ear canal. Some measure in octave bands and average the results.

Theoretical analysis [14] suggests that LF_c and ICC are related by:

$$LF_c = (1 - ICC)/k, \tag{3}$$

where k is determined by the autocorrelation function of the source signal. Analysis also shows that the autocorrelation function is linked to the variation of the ICC with reflection direction. This suggests that most broadband measurements are unlikely to represent the correct directional sensitivity for lateral reflections.

Blauert [15] and colleagues have proposed a model for our hearing system to extract source broadening. This works with many frequency bands being processed in parallel. Thus measurements of ICC in several frequency bands, such as octave bands, looks preferable to broadband measurements. But there is the problem that at low frequencies the ICC hardly varies, whereas these frequencies seem important for source broadening (see section 3.3).

Bradley [16] has made parallel measurements in 14 halls of both LF and ICC, each measured in octave bands. He found support for a relationship such as equation (3) when mean hall data is used. However the scatter with individual position measurements was high.

2. MEASUREMENT PROCEDURES

Both measurement surveys used omni-directional loudspeakers at a central position close to the front of the stage and with microphones of variable directivity placed at ear height. The 17 unoccupied British halls were measured with an average of 11 microphone positions per hall. The source was placed 3 m from the stage front. The British survey used single-cycle sine pulses as signals with the impulse responses being recorded on analogue tape. The microphone used was an AKG C414EB; careful calibration of the relative sensitivities of the two directivities is needed with this sort of microphone. The responses were analyzed by computer to produce results in the four octaves between 125 and 1000 Hz. Further details about the measurement procedure are given in reference [17].

Bradley's measurement technique in 13 American halls [5] used maximum length sequence signals processed by fast Hadamard transform. Bradley measured with three source positions on stage, but for the results reported here only values for the central source have been used. The central source position was approximately 2 m from the stage front. For compatibility, values for the octaves 125–1000 Hz alone were used.

3. COMPARISON OF LATERAL FRACTIONS IN THE TWO CONCERT HALL DATA SETS

3.1. MEAN *LF* VALUES

The mean values of the early lateral energy fractions are shown in Table 3 as 0·19 for the British halls and 0·15 for the American data. Both these values are significantly less than the theoretical value for a diffuse sound field of 0·33. The presence of the direct sound is a major reason for the mean being below the diffuse value.

Values in British halls are slightly higher on average. With only 17 British halls and 13 American halls, a lack of complete randomness in the range of hall shapes tested is to be expected. The average age of the American halls is greater: with an average year of completion of 1929 compared with 1953. One obvious difference is the number of fan-shaped plan halls; these halls tend to have low values of the lateral fraction. Whereas there was one fan-shaped plan among the British halls, there were five in the American survey. In addition, two halls in Britain had particularly high lateral fractions (Usher Hall, Edinburgh, and the Free Trade Hall, Manchester).

There are further differences between British and American halls associated with the stage arrangements. Many of the American halls, namely six out of 13, are multi-purpose to the extent that they have flytowers and use an orchestral enclosure for concerts. At the stage end this introduces a fan shape in both plan and section. On the other hand, none of the British halls have flytowers or orchestral enclosures. Ten of the 17 British halls have choir seating behind the orchestra

TABLE 3

Measured early lateral energy fraction and measurement data

	British concert halls	American concert halls	Diffuse
Mean *LF*	0·19	0·15	0·33
Standard deviation	0·085	0·056	—
Number of halls tested	17	13	—
Number of results	189	138	—
Number of fan-shaped halls	1	5	—

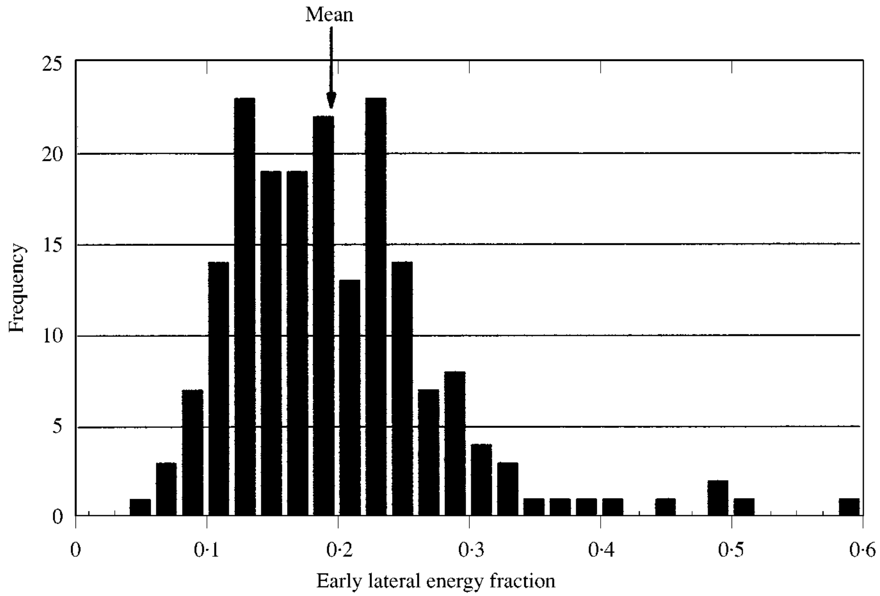

Figure 2. Distribution of measured early lateral energy fraction values in British concert halls.

platform, which is a feature not found in the American halls. Thus, the American stage platforms are more enclosed whereas the norm in British halls is to have a more open-stage arrangement. One might reasonably expect these design differences to contribute to the lower early lateral fractions to be found in the American halls.

An alternative cause of differences between the mean values of the two data sets could be calibration differences. In the light of the above discussion regarding the character of the halls in the two surveys, any calibration differences are likely to be small.

3.2. DISTRIBUTION OF MEASURED EARLY LATERAL ENERGY FRACTIONS

The distribution of measured values of the early lateral energy fraction has been analyzed for the British data. Measured *LF* values range from 0·04 to 0·60; Figure 2 indicates the frequency of individual values. A test on the statistical normality of the data using the χ^2 test shows it to be "almost certainly not normal" with a confidence limit of over 0·1%. Pelorson *et al.* [18] applied more sophisticated statistical analysis and also found non-normal distributions for the early lateral energy fraction.

3.3. EARLY LATERAL ENERGY FRACTIONS BY FREQUENCY

The importance of low frequencies to spatial impression was realized early [19] and has subsequently been confirmed [3, 20]. Further evidence of subtle spatial

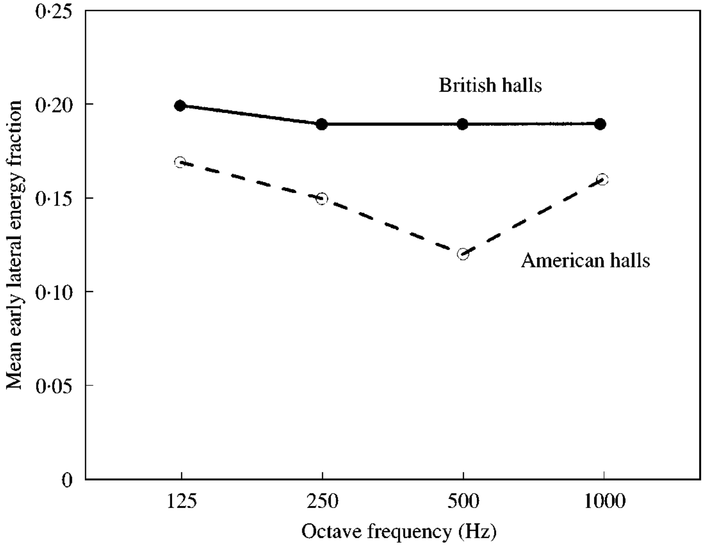

Figure 3. Mean *LF* values by frequency for the British and American concert hall data sets.

variations as a function of frequency have been reported by Blauert and Lindemann [21]. Attenuation at grazing incidence, the seat-dip effect, was also discovered in the 1960s and the possible influence of this low-frequency attenuation on spatial hearing was investigated by Marshall [19]. Does attenuation at grazing incidence influence *LF* values in general?

Figure 3 shows the mean values of the lateral fraction by frequency for the two data sets. For the British data and the mean value is constant, whereas the American data shows a minimum value at 500 Hz. The reason for the small variation with frequency in the American data is not obvious. But what these two data sets show is that whereas due to attenuation at grazing incidence we might expect lower lateral fractions at 125 Hz, the measured data shows no such trend on average.

The constancy of the lateral fraction with frequency may not be so surprising since both the direct sound and reflections from side walls are affected by grazing incidence attenuation. Grazing incidence certainly appears to influence the early sound level [22]. At individual positions, variations of the lateral fraction with frequency do of course occur. For good source broadening, reflection on paths remote from the audience are desirable. Individual surfaces should also be large enough to reflect low frequencies. This last point may be important in halls following the vineyard terrace concept; in these halls surfaces dividing seating blocks should preferably be sufficiently high for this reason.

4. EARLY LATERAL ENERGY FRACTIONS BY HALL

When the early lateral energy fraction is averaged within halls, the hall mean values range from 0·10 to 0·30; see Figure 4. A typical range of *LF* within a hall is 0·20 so there is considerable overlap between halls. (The average standard deviation

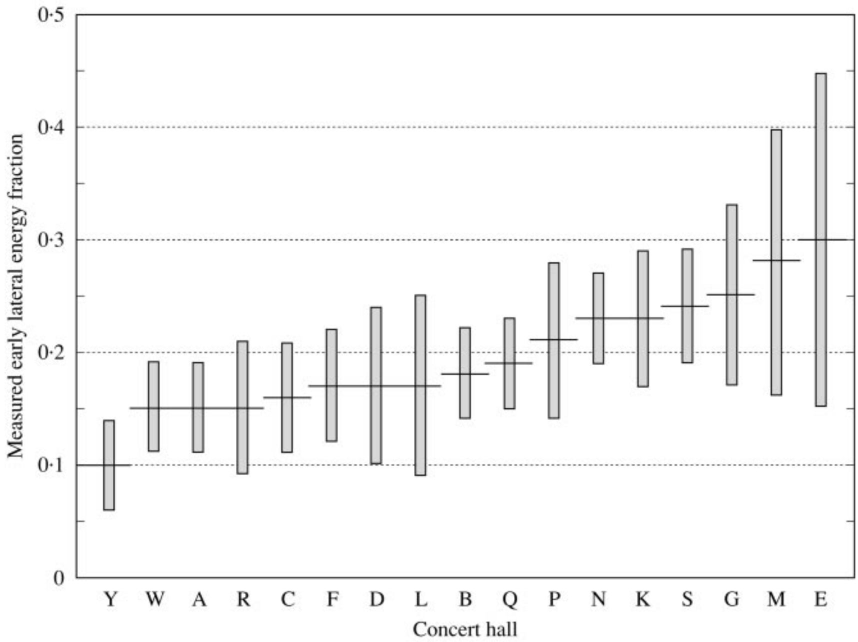

Figure 4. Means and spread (± one standard deviation) of measured early lateral energy fractions in 17 British concert halls. Hall labels according to Table 1.

of values within halls is 0·06.) The considerable overlap between halls raises the question of the value of a single number to describe source broadening in a hall. In many halls, there are regions with high and low values which can be attributed to design details particular to the different seating areas ([4], see for example St. David's Hall, Cardiff).

The British hall with the largest mean value as well as the largest spread of values is the Usher Hall, Edinburgh (label: E). This proves to be a rather special case [4] with a lack of early frontal sound. The Free Trade Hall, Manchester (label: M) has some reverse-splay profiles in plan; the Wigmore Hall (label: G) is a small hall which is the narrowest of the halls tested here. At the opposite extreme, Wembley Conference Centre (label: Y) has the smallest mean value; the plan form of this hall is semi-circular which is an extreme example of a fan shape. Again the reason for the low proportion of lateral sound with this plan form is discussed in reference [4].

4.1. HALL MEAN LATERAL FRACTIONS AND HALL WIDTH

The idea that early lateral reflections might be important started from the perception that the concert hall cross-section might be significant [23, 1]. Architectural drawings summarising a hall design usually comprise plans and a long section; the cross-section is generally omitted. West [23] had access to the data from Beranek's 1962 survey [24] and found a good correlation

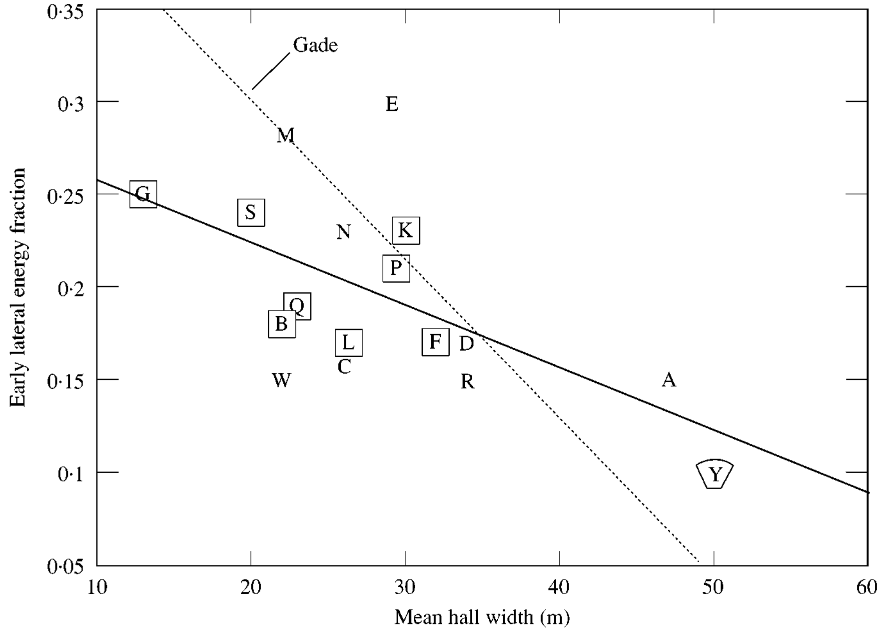

Figure 5. Mean hall early lateral energy fractions as a function of mean hall width in 17 British concert halls. Solid line is line of best fit. Hall labels according to Table 1. □, parallel-sided halls, ▽, fan-shaped halls.

($r = 0{\cdot}71$) between the subjective categories and the cross-section ratio (= height/width).

The rectangular (shoebox) hall is eminently simple to model by using an image model. All room surfaces are made reflecting with the exception of the floor which is made fully absorbing. Reflections are calculated within 80 ms of the direct sound and the early lateral energy fraction is calculated from the impulse response. Analysis of the lateral fraction [25, 26] keeping the plan form constant but varying the height showed that ceiling height has virtually no influence on the early lateral fraction. This is not in fact surprising when one realizes that the images of the source lie in just two horizontal planes: the plane of the source and the reflection of this plane in the ceiling. The proportion of lateral sound in each image plane is basically the same.

The simple image model does however indicate a correlation between mean lateral fraction and hall width. Several authors, such as Gade [27] using data measured in 32 European halls, have found relationships between width and measured early lateral fractions.

Figures 5 and 6 show the relationship between mean hall width and mean hall lateral fraction for British and North American halls. In each figure, parallel-sided halls are indicated by squares and fan-shape halls by simple fan shapes. The slopes of lines of best fit and correlation coefficients are listed in Table 4. In the case of the British halls, the equation for the line of best fit is

$$\text{Mean } LF = 0{\cdot}29 - 0{\cdot}0033 \times \text{mean hall width.}$$

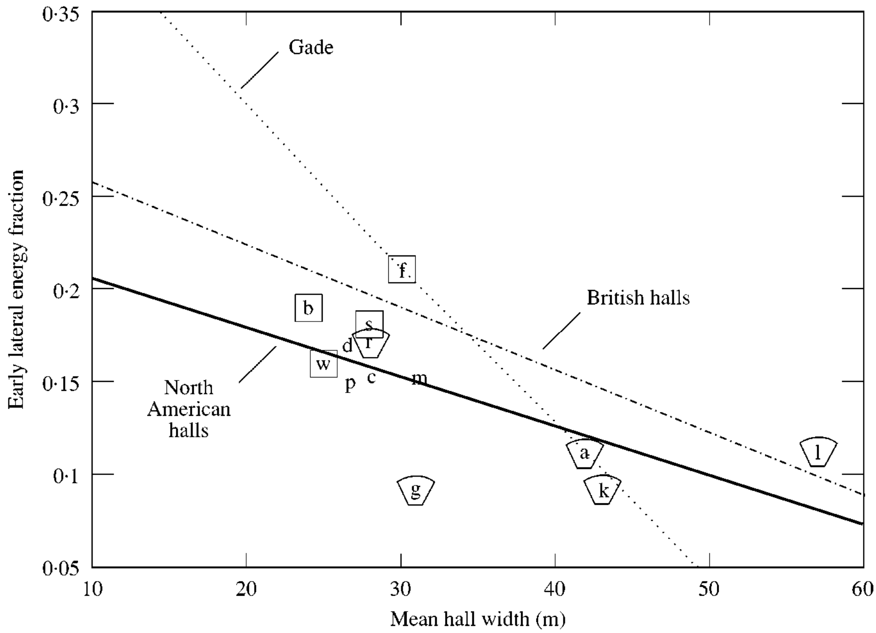

Figure 6. Mean hall early lateral energy fractions as a function of mean hall width in 13 American concert halls. Lines are best fit regression lines. Hall labels according to Table 2. □, parallel-sided halls, ▽, fan-shaped halls.

TABLE 4

Regressions between mean hall early lateral fractions and mean hall width

Data set	Slope: change in *LF* for 10 m change in hall width	Correlation coefficient, *r*
17 British halls	0·033	– 0·59
13 North American halls	0·026	– 0·65
8 British parallel-sided halls	0·027	– 0·54

The slopes of the lines of best fit for the British and American data are similar with a modest slope. This slope implies a change of only 0·03 in the lateral fraction for the substantial change of 10 m in the width of a hall. Gade's line is considerably steeper, but the reason for this is not obvious. Perhaps the predominance of smaller spaces among Gade's halls is significant.

One notes in Figures 5 and 6 that fan shapes have the lowest values in both surveys, though one fan-shaped hall (label: r in Figure 6) behaves well. A surprise though is that the mean *LF* values in fan-shape plans conform to the general trend regarding width for all hall shapes; again there is an exception, one American hall (label: g) performs badly.

Thus, most fan-shape plans perform according to their mean width, which happens to be large and so is responsible for small values of the lateral fraction.

Parallel-sided halls tend to perform well regarding *LF* but again not significantly better than other shapes. The slope of the regression line for British parallel-sided halls is similar to that for all halls in both surveys. (Note that two British halls have parallel side walls but have not been so designated in Figure 5; the Fairfield Hall, Croydon (label: C) has fins on the side walls which block lateral reflections and in Watford Town Hall (label: W) there are absorbing curtains over portions of the side walls producing the same effect.)

To summarize the influence of hall width: though parallel-sided halls are associated with higher lateral fractions and fan-shaped plans with lower lateral fractions, both plan forms conform to a general relationship between mean hall lateral fraction and hall width. The relationship with hall width is however rather weak. Design details, such as those already mentioned in section 4.1 in the Usher Hall, Edinburgh and the Free Trade Hall, Manchester, can influence lateral fractions independent of the hall width.

5. EARLY LATERAL ENERGY FRACTIONS WITHIN HALLS

Results from the simple image model discussed in section 4.2 above can provide a feel for the variation of lateral fraction in a simple plan form such as the rectangular plan. Figure 7 shows contours for the calculated lateral fractions in a hall of dimensions 45 × 32 × 17 m high. (In this case the early lateral fraction is the subjectively more accurate LF_c.) Figure 7 indicates that the lateral fraction is reasonably constant throughout the audience space except close to the source where it decreases markedly. The influence of the direct sound on the early energy fraction is obvious from its definition.

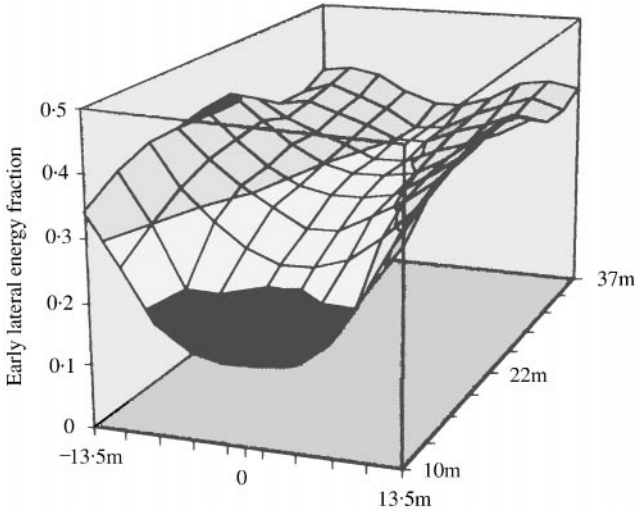

Figure 7. Computed early lateral energy fractions (LF_c) in the seating area of a rectangular room according to a simple image model. Bottom scale is lateral distance from the axis of symmetry, right-hand scale is longitudinal distance from the source: ■, 0·4–0·5; □, 0·3–0·4; □, 0·2–0·3; □, 0·1–0·2.

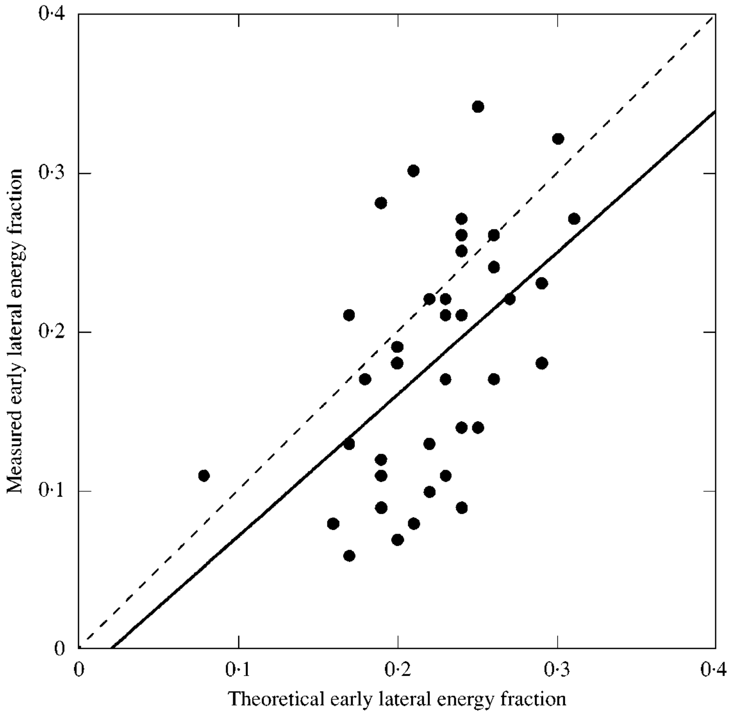

Figure 8. Measured early lateral energy fractions plotted against theoretical values for source–receiver distances between 9 and 15 m in British concert halls. Solid line is line of best fit; dashed line represents perfect agreement.

To test whether the direct sound is also significant for measured values of the early lateral fraction, measured values of the fraction in British halls have been compared with predictions based on a simple theoretical model of early sound energy. The theory (see the Appendix A) is based on the traditional expression for the direct sound and revised theory [17] for the early sound energy. To calculate the early lateral energy, the rather gross assumption is made that the directional distribution of the early reflections is similar to a diffuse distribution.

This theoretical model is of little use for larger source-receiver distances; design differences matter too much for these. However for positions close to the stage the simple theoretical model just described goes some way to explaining behaviour of the lateral fraction. Figure 8 compares measured and predicted early lateral energy fractions for measurements in all 17 British halls for source–receiver distances between 9 and 15 m. For the 40 results, the correlation coefficient is $r = 0{\cdot}53$.

A further comment should be made about the situation close to the source. In practice, when listening from a seat near the stage to a performance with a reasonable size orchestra, the physical size of the orchestra compensates for the small source broadening found at these positions.

Away from the source, the variation of *LF* is strongly influenced by auditorium form. In only one of the 17 British halls is source–receiver distance a significant determinant of *LF* within the hall: in the Barbican Concert Hall, London, the lateral fraction increases with distance from the source. Generalizing from behaviour in this unusual design is not warranted.

One general characteristic can be observed in Figure 5: that halls with larger mean values of *LF* tend to have a wider spread of values. This occurs because local design features within the halls enhance the lateral fraction only locally. The presence of a balcony above the measurement position normally has only a small influence on *LF*, since both ceiling and cornice reflections are blocked by the balcony overhang.

Regarding *LF* behaviour within halls, three plan forms deserve discussion: parallel-sided, fan-shape and reverse splay.

Of the seven British parallel-sided halls, there is in three of them a consistent increase in lateral fraction as one moves away from the central axis of symmetry. In general however away from the source in these halls, the *LF* is reasonably constant.

For the combined British and American data sets, the five lowest mean *LF*s are found in fan-shaped plan halls. This plan form is obviously unsuitable for good spatial impression. As far as variation of the lateral fraction within fan-shaped halls is concerned, there is a modest trend for smaller *LF* values to occur towards the rear of the hall. In just one fan-shaped hall (Akron, label: a) there is a significant progressive decrease of *LF* with distance from the source.

The reverse splay has the virtues which are vices for its design opposite, the fan-shape plan. Figure 9 shows the benefit for the reverse splay for a single reflection, but there are further contributions to lateral fractions due to interreflection between the walls; these multiple reflections also maintain sound level in a reverse splay situation.

But the reverse splay plan cannot be used for the whole of a concert hall because the width becomes too large at the platform end. Reverse splays can be included in halls where seating is subdivided, such as in terraced concert halls (e.g., the Philharmonie, Berlin). Three halls with reverse splay plans have been measured: the

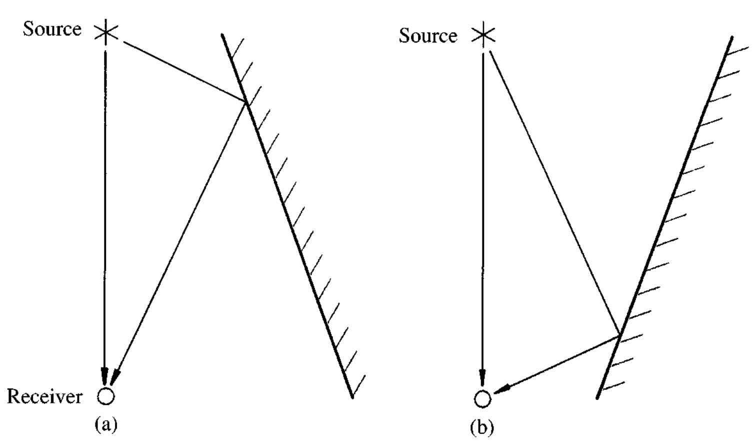

Figure 9. The lateral reflection path in (a) a fan-shape plan and (b) a reverse splay plan (after Marshall [19]).

Free Trade Hall, Manchester (label: M), the Royal Concert Hall, Glasgow [6] and Segerstrom Hall, Orange County Performing Arts Center, California [4, 6]. Each exhibits high values of the lateral fraction.

6. EARLY LATERAL FRACTIONS IN OPERA HOUSES

One of the major differences between opera and concert halls is that for opera there are two sound sources: the singers on stage and the orchestra in the pit. With their comparatively low sound power, it is questionable whether sound from singers produces audible source broadening. The discussion here is limited to the situation for the orchestral sound alone. Measurements have been made in four British houses of conventional design with audience capacities between 950 and 2350; the houses were all built prior to 1910.

Analysis of the measured results soon reveals that values measured in the Stalls are generally higher than elsewhere in the house. For this reason, results in Figure 10 are divided in each house between those measured in the Stalls and those measured at higher seating levels. The reason for the higher lateral fractions in the Stalls is simply that the direct sound from the pit to the audience in the Stalls is obscured by the pit rail. But though the pit rail is significant, balcony overhangs have no particular effect on lateral fractions.

One observes in Figure 10 that smaller volume auditoria have slightly higher mean values associated with them. One difference with concert halls is the large

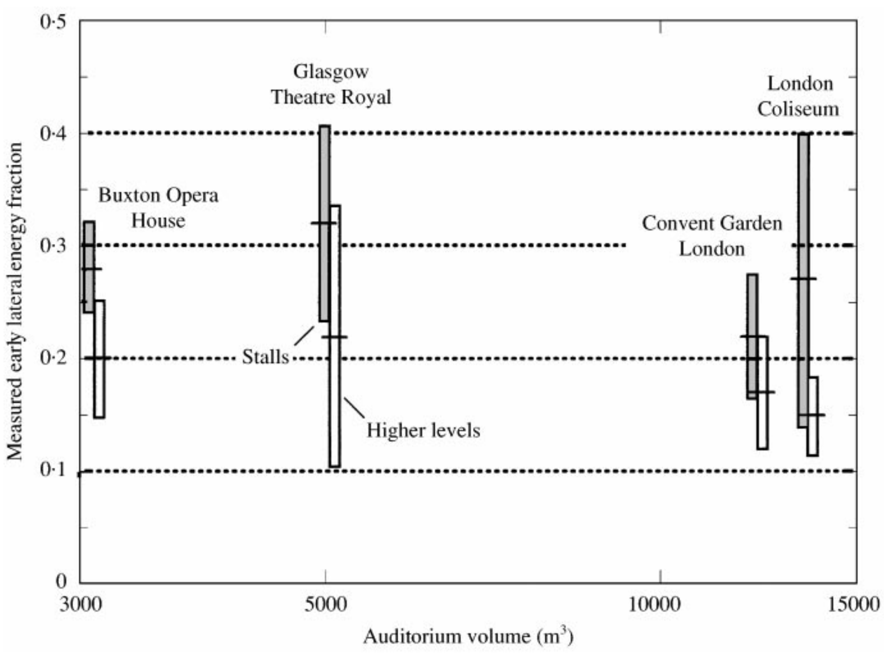

Figure 10. Mean and spread ($\pm$ one standard deviation) of measured early lateral energy fractions in four British opera houses plotted by auditorium volume.

spread of lateral fractions within some houses, which could no doubt be attributed to design details. The mean house values ranged between 0·18 and 0·25.

7. COMBINING LATERAL FRACTION WITH SOUND LEVEL

Ever since Keet [11] made the initial suggestion, sound level has been considered to contribute to spatial impression. Source broadening increases during loud passages of a performance and can disappear during quiet passages with few instruments playing. This leaves the question of how the lateral fraction and sound level should be combined.

The simplest technique, as used by Bradley [28], is to consider the early lateral sound level:

$$\text{Early lateral sound level} = \text{Early level} + 10\log(LF). \quad (4)$$

The non-logarithmic version, the early lateral energy, is an alternative:

$$\text{Early lateral energy} = \text{Early energy} \times LF. \quad (5)$$

Selection or rejection of either of these depends on whether they are linearly related to the subjective effect. The early lateral energy fraction was selected, as opposed to such measures as the ratio of lateral to non-lateral sound in decibels, because it was linearly related to the subjective effect. In Keet's simple experiment, the apparent source width was measured in degrees and found to be roughly linearly related to sound level.

This suggests the following means of combining the spatial measure with level:

$$\text{Degree of source broadening } (DSB) = LF + (\text{Early level})/\kappa, \quad (6)$$

where κ is a constant. Extrapolating from Keet's experiment and the experiments which led to the proposal for the early lateral energy fraction [3], a value for κ of 98 is derived (from equation (9) in reference [3], $\kappa = 14{\cdot}5 \times 4{\cdot}5 \times 1{\cdot}5$, the final 1·5 being due to the directivity of a figure-of-eight microphone). In this author's subjective questionnaire survey of British symphony concert halls [29], values of κ between 20 and 60 were tried in order to optimize the correlation with responses on a scale relating to spatial impression. It turned out that the sensitivity to different values was small but the value for κ which gave the best correlation was 30. Yet for the results of that subjective survey, the correlation was almost as good when the early lateral energy was used as the objective measure.

Recent work by Morimoto and Iida [30] using simulation apparatus reaffirmed Keet's result that the measured apparent source width is linearly related to level and by interpretation, ASW is also linearly related to LF. From this work a value for κ of 60 can be derived, though this is tentative at this stage. The value $\kappa = 60$ has been used below.

7.1. MEASURED DEGRESS OF SOURCE BROADENING

The early lateral energy fraction data based on the simple image model as used for Figure 7 was multiplied by the relevant values for the early energy to give a plot

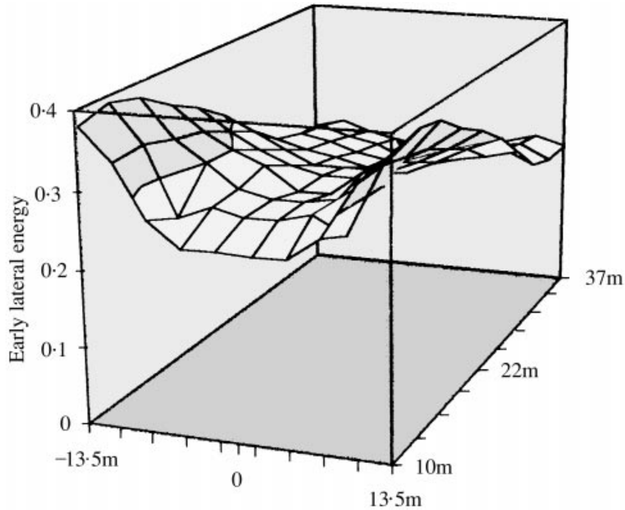

Figure 11. Computed early lateral energies in the seating area of a rectangular room according to a simple image model. Bottom scale is lateral distance from the axis of symmetry, right-hand scale is longitudinal distance from the source: □, 0·3–0·4; □, 0·2–0·3; ■, 0·1–0·2.

of the early lateral energy in a rectangular plan hall. This is plotted in Figure 11 which shows that the dip in the lateral fraction near the source is compensated by the higher sound levels close to the source. The greatest source broadening is to be expected near the side walls.

Sound level is more important to the early lateral energy than it is to the proposed degree of source broadening, equation (6) with $\kappa = 60$. The degree of source broadening according to equation (6) with $\kappa = 60$ has been calculated for the 189 positions in the British data set; the frequency mean values (125–1000 Hz) for *LF* and early level were used in the equation. The mean and spread of values by hall are presented in Figure 12.

Conveniently the mean value of the early level in British halls is numerically small at $-0{\cdot}2$ dB, so the overall mean values of *LF* and *DSB* are the same (for level, 0 dB is the level of the direct sound at 10 m). This allows direct comparison between Figures 4 and 12; if a hall has moved from its position in Figure 4 then the mean early level in the hall is greater or less than average. One observes that inclusion of level in the degree of source broadening increases the differences between halls.

In Figure 12, the two halls with the highest mean *DSB* values are small halls with seating capacities close to 500. These halls have high sound levels for a given source power because of their small total acoustic absorption. But is this a fair comparison? These two halls are basically recital halls and in the case of Wigmore Hall, London (label: G) the stage has an area of only 33 m^2, certainly too small for even a chamber orchestra. The size of the orchestral forces is a further determinant of the spatial effect, so comparisons of the degree of source broadening are only really valid between similar hall types.

To return to Figure 12, many of the halls with intermediate lateral fraction positions are unaffected by inclusion of sound level. But in the cases of

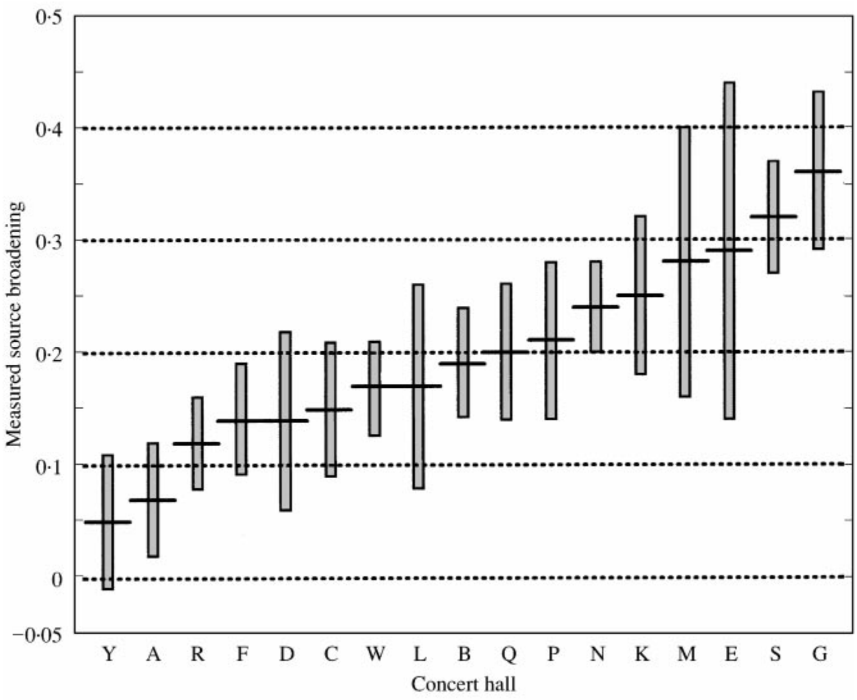

Figure 12. Means and spread ($\pm$ one standard deviation) of measured source broadening ($= LF +$ (Early level)/60) in 17 British concert halls. Hall labels according to Table 1.

the Royal Albert Hall, London (label: A) and Wembley Conference Centre (label: Y), inclusion of level pushes them to the extreme low values. The case of Wembley Conference Centre, a semi-circular hall, can be taken as an example of a fan-shape plan: both the poor lateral reflection situation and the low levels found in fan-shape halls combine to give low degrees of source broadening with this plan form.

8. CONCLUSIONS

The idea that early reflections were important in concert halls orginated 30 years ago. At the time the subjective effect was referred to by many as spatial impression. Recent developments suggest that at least two spatial effects are present: source broadening and envelopment, with the former linked to early reflections and the latter to later reverberant sound.

Concern for spatial impression or rather source broadening has had a major influence on design. From casual attitudes in the 1960s to appropriate concert hall form, we now have just a few design shapes that are considered acceptable. For some, only parallel-sided halls have good acoustics, though source broadening is not thought to be the only reason for the quality of their sound. At least two design forms owe their development to early lateral reflections: the lateral directed reflection sequence hall (such as the Town Hall, Christchurch, New Zealand) and halls with the upper side walls tilted down (such as Pikes Peak Center, Colorado Springs, USA). The vineyard terrace hall can with care be designed so that the surfaces, which divide seating blocks, supply lateral reflections.

In this paper, two sets of early lateral energy fraction (*LF*) data measured in British and American concern halls have been analyzed; they have mean values of 0·19 and 0·15, which is roughly half the value of a diffuse sound field. The difference between two means can probably as ascribed to design differences for the two sets of halls measured. When data for individual halls are compared, it is clear that there is considerable overlap between halls. There is however a significant correlation between hall mean *LF*s and hall width for all hall shapes, though a substantial change of 10 m in hall width corresponds to a change of only 0·03 in the mean lateral fraction. Parallel-sided halls have higher mean *LF*s because they are relatively narrow, whereas fan-shaped halls have low mean *LF*s due to their being relatively wide.

Within halls it is clear that the direct sound dominates the situation near the source and depresses *LF* values. In symphony concerts this may not matter because when one is sitting close to the stage the physical extent of the orchestral source will compensate. At positions away from the stage, behaviour varies with plan form. In parallel-sided halls the highest *LF* values are close to the side walls. In fan-shaped halls, *LF* values tend to decrease as one moves towards the rear of the hall. The reverse splay plan is the preferred form for good source broadening.

The significance of sound level has also been acknowledged for spatial impression since the start 30 years ago. How *LF* and level should be combined has not been agreed, but subjective experiments suggest adding *LF* to the early level divided by a constant. The degree of source broadening (*DSB*) was defined here as ($LF + E/60$), where E is the level of the early sound.

For many of the British halls, inclusion of level has little influence. Most obvious shifts in rank ordering occur for halls at the extremes: small halls tend to have a large *DSB*, large halls a small *DSB*. The fan-shaped hall performs badly both with regard to *LF* and level.

In practice, perceived source broadening is also influenced by the size of the musical forces. A symphony orchestra in a small hall is the optimum combination for high source broadening. Hall geometry and surface acoustic character alone determine the early lateral energy fraction. For this reason, it seems worth retaining *LF* as an important parameter for concert halls rather than always subsuming *LF* in a source broadening measure that includes level.

Modern concert hall designs are tending to become progressively more complex, for which simple descriptions of plan form are often no longer adequate. In such halls, provision of large source broadening can often be seen as a local problem for different seating areas in the hall. Source broadening throughout for all listeners depends on there being surfaces near enough to all areas of audience; it is not possible to provide high source broadening with large expanses of undivided audience seating. Cornice reflections involving side walls and soffits also deserve consideration. Perhaps we can look forward to more ingenuity in concert hall design to accommodate early lateral reflections for all audience members.

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APPENDIX A: THEORETICAL MODEL FOR THE EARLY LATERAL FRACTION NEAR THE SOURCE

Energies are expressed relative to the direct sound at 10 m from the omni-directional source. The expression for the direct sound energy, d, is the traditional one. That for the early reflected sound within 80 ms of the direct sound, e_r, is taken from revised theory for sound in auditoria [17]:

$$d = 100/r^2,\ e_r = (31200T/V)\mathrm{e}^{-0{\cdot}04r/T}\cdot(1-\mathrm{e}^{-1{\cdot}11/T}).$$

Here V is the auditorium volume, T the reverberation time and r the distance from the source. For a diffuse sound field, the lateral energy measured by a figure-of-eight microphone $= e_r/3$.

Hence, the theoretical early lateral energy fraction $(LF) = (e_r/3)/(d + e_r)$.