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Theory and measurement of early, late and total sound levels in concert spaces

by Mike Barron

ABSTRACT

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Theory and measurement of early, late and total sound levels in concert spaces

Mike Barron[a)]
Fleming and Barron, Combe Royal Cottage, Bathwick Hill, Bath BA2 6EQ, England

A revised theory of sound level distribution in rooms was proposed in 1988, which responded to the observation that reflected sound level decreases as one moves away from the source. This behavior is ubiquitous in concert spaces and has been shown also to occur in an acoustically diffuse space. This paper presents a more general theoretical derivation and compares measured levels of the early, late, and total sound, as well as the early-to-late index, with theoretical predictions. The scatter of measured sound levels in concert spaces about a linear relationship with source-receiver distance was also compared with a theoretical prediction. Two modifications to the basic theory were investigated, though the original formulation proves best for the general concert space. The revised theory matches average behavior well and represents predicted behavior in a diffuse sound field with the same reverberation time and auditorium volume. Consistent deviations within concert halls were matched with design details.

I. INTRODUCTION

The revised theory of sound level behavior in rooms derives from the observation in concert spaces that the reflected component is not constant throughout the room but decreases as one moves away from the sound source. While the nature of sound in rooms had been comprehensively studied earlier, this had mainly been in reverberation chamber-type spaces in which the revised theory effect is barely measurable. In 1985 at a meeting in Cambridge, England, a paper by Gade[1] and a paper by this author[2] both reported recent but independent measurements and both noted that the reflected level decreases within a concert space as one moves away from the source, with the result that average levels in halls were less than traditional theory. Gade's results[3] had in fact already appeared in the previous year.

In this author's paper of 1988,[4] data from measurements in 17 music spaces was used for various comparisons with traditional diffuse field theory. A revised theory for sound level in rooms was proposed, including relationships for early and late sound. In addition to evidence that the theory predicts well on average, physical attributes in individual halls were listed where there are significant deviations from theory. Whereas the title of reference[4] included "I" for Part I, the second and third parts were published with more direct titles: "Bass sound in concert auditoria" (Ref. 5) and "Balcony overhangs in concert auditoria" (Ref. 6). Bass compared with mid-frequency sound was found to be principally influenced by the reverberation time (RT) frequency characteristic and the seat dip effect; because of the latter, halls with weak ceiling reflections tend to have poor bass at the rear. Under balcony overhangs, the late sound suffers leading to deficient reverberance; a key parameter, the vertical angle of view, was proposed with a minimum acceptable angle of 40°, Fig. 1.

Revised theory has proved to be very useful for related issues, such as "Interpretation of early decay times (EDTs) in concert auditoria" (Ref. 7) and "Loudness in concert halls" (Ref. 8). Concert auditoria are not obviously diffuse spaces since absorption is concentrated on the floor. A scale model exercise with specially designed test chambers was undertaken to demonstrate that revised theory was also appropriate in a diffuse sound field;[9] for the effect to be easily measurable, a mean absorption coefficient of greater than about 0.2 is required. Observations in real spaces that subjective loudness is reasonably constant in auditoria, known as "loudness constancy," led to a revised criterion for minimum total sound level or Strength, G dB, which is a function of source-receiver distance; higher sound levels are required close to the stage.[10] Since revised theory predictions represent average behavior, comparison in a hall of measured and theoretical values of early, late, and total sound level and the early-to-late index, C_{80} dB, by plotting them against source-receiver distance tends to offer valuable insights into sound behavior within the hall,[11,12] a procedure called "Temporal Energy Analysis" (see Sec. VI below).

Several other authors have referred to the revised theory of sound level behavior in rooms; the following is a selection (presented roughly chronologically). Bradley,[13] in a discussion of the acoustics of the three most famous 19th century classical halls, found reasonable agreement between measured values of Strength, G, with revised theory. Similar comparisons by Bradley were given for 13 North American concert halls with good agreement in half of the halls.[14] Bradley, by plotting measured levels against source-receiver distance and comparing with revised theory, also demonstrated its value for diagnostic purposes in actual halls.[15] Polack[16] found a good match between revised theory and predictions based on a billiard theory of sound in rooms.

[a)]Electronic mail: m.barron@flemingbarron.co.uk

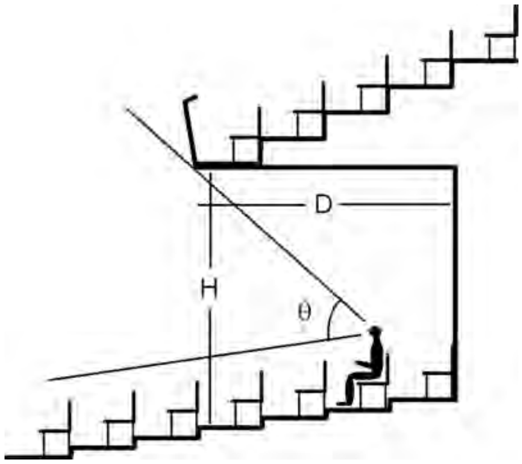

FIG. 1. Basic balcony overhang dimensions, showing the vertical angle of view, θ.

Valuable comments on revised theory have come from Vorländer,[17] who proposed that integration of reflected energy should begin at the arrival time of the first reflection, rather than the arrival time of the direct sound. This will be discussed further in Sec. V A below. Svensson[18] used revised theory as the basis of his theory for predicting behavior in a room with electro-acoustic assistance. Nijs *et al.*[19] found revised theory valuable for predicting sound levels in rooms which required noise reduction.

Some authors have looked at sound behavior in churches, using revised theory as their starting point for comparisons with measured levels. Galindo *et al.*[20] looked at Mudejar-Gothic churches in southern Spain, while Cirillo and Martellotta[21] have investigated a group of Italian churches. More recently Berardi *et al.*[22] reviewed the history of these investigations and the modifications made to revised theory to achieve better agreements with measured results. Revised theory is based on diffuse sound theory, whereas churches are unlikely to have diffuse sound fields because of subdivided spaces etc.

Finally Aretz and Orlowski[23] have studied a group of small concert halls and found evidence of lower levels than predicted by revised theory (see Sec. VI).

This paper presents a review of aspects that are related to revised theory in concert spaces since 1988. First a theoretical derivation of the revised theory equations is presented based on the two most common relationships in room acoustics. Measured sound levels in an experimental diffuse space are then considered, as a prelude to looking at results from 21 concert spaces. Comparison is made with theoretical predictions of the scatter of sound levels spatially in both a diffuse space and concert auditoria. Two basic possible modifications to revised theory are considered. The review ends by looking at design features which consistently result in deviations from revised theory within individual concert halls.

The words "diffuse" and "scattering" appear frequently in this paper, a diffuse sound field is fundamental to revised theory. To avoid confusion, the words diffuse and diffusion will be used to describe a sound field, whereas scattering refers to a surface which scatters sound on reflection. The expression "diffuse reflection" will not employed, for instance.

II. THEORY

The revised theory as presented in Ref. 4 employed a relationship for integrated energy derived from a simple geometrical model in a rectangular space.[24] In fact, the first evidence of possible revised theory behavior was reported in that paper from 1973. The following treats the situation with the assumption of a diffuse sound field, using the two most common relations in room acoustics. The revised theory model is most simply presented as in Fig. 2; this shows three integrated impulse decays superimposed with a common time scale, where $t=0$ represents the moment when the pulse is emitted by the source.

The following assumptions are made:

(1) That during the decay the sound level is uniform throughout the space.
(2) That significant reflected energy arrives from the moment after the direct sound arrives.
(3) That the decay of sound level is linear from the moment after the direct sound arrives.

Discussion of the significance of each of these assumptions is included below.

The RT equation for a space with a room volume, V, and total acoustic absorption, A, where c the speed of sound, is

$$\text{Reverberation time,}\quad T=\frac{4\cdot 60}{c\,.\,10\log(e)}\,.\,\frac{V}{A}=0.161\,\frac{V}{A}. \tag{1}$$

This represents either the Sabine or Eyring equation, with A different in each case. Equation (1) will be used later. With RT, T, and t representing time,

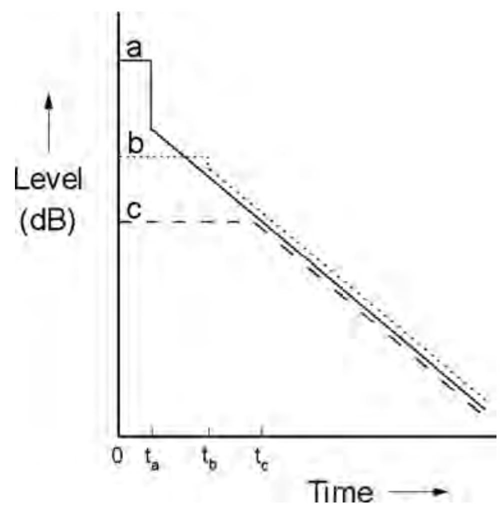

FIG. 2. Theoretical integrated impulse curves at three receiver distances from the source in a room. Curve "a" represents the position closest to the source, with travel time t_a for the direct sound. The time origin at $t=0$ is the time when the sound is emitted from the source. According to assumption (1), the diagonal lines are superimposed but have been separated here for clarity.

$$\text{time history of decay} = \text{Constant}-\frac{60t}{T}\ \text{dB}. \quad (2)$$

Converting out of decibels to give integrated energy

$$\begin{aligned} y(t) &= \text{Constant} \times 10^{-(60t/10T)} \\ &= \text{Constant} \times e^{-(6\ln(10).t/T)} \\ &= \text{Constant} \times e^{-(13.82t/T)}. \end{aligned} \quad (3)$$

However the decay in Fig. 2 is derived by integrating the impulse response in reverse time: so $y(t) = \int_t^\infty p^2(t).dt$. $y(t)$ therefore represents the energy from time t to infinity. If t is set at t_0, the arrival time of the direct sound, then the total sound level is

$$y(t_0) = \text{Constant} \times e^{-(13.82t_0/T)} = \text{Constant} \times e^{-(0.04r/T)}. \quad (4)$$

In the exponent, t_0 is replaced by r/c, where r is the source-receiver distance; its use here derives from the third assumption above.

The exponential term in Eq. (4) is the revised theory component. The constant in the equation represents the total reflected energy. In revised theory the level is position specific, whereas in the literature sound levels in rooms are often represented in terms of the average within the space.

In a diffuse sound field the spatial average of the energy density, w, is quoted as $w = 4W/cA$, where W is the sound power of the source.[25] This relation leads to the value for the averaged pressure squared (with ρ the density of air) given by

$$\frac{\overline{p^2}}{\rho c} = \frac{4W}{A}. \quad (5)$$

[The total reflected level from Eq. (5) is SWL + 10.log(4/A) dB, where SWL is the source sound power level.] If the total is split into a direct and a reflected component, it has been frequently argued that the reflected sound has all experienced a single reflection, hence an additional term $(1-\bar{\alpha})$ should be added, with $\bar{\alpha}$ as the mean absorption coefficient,

$$\frac{\overline{p^2_{\text{refl'd}}}}{\rho c} = \frac{4W}{A}(1-\bar{\alpha}). \quad (6)$$

The introduction of the extra term has also been used for modification of the room constant.[26] Vorländer[17] has proposed two modifications for the sound level version of Eq. (5), as follows (with S, the total surface area of the space and λ, the wavelength):

$$\text{Mean SPL} = \text{SWL} + 10\log\left(\frac{4}{A}\right) - 4.34\frac{A}{S} - 10\log\left(1+\frac{S\lambda}{8V}\right)\ \text{dB}. \quad (7)$$

The term $4.34A/S$ is directly related to the $(1-\bar{\alpha})$ term in Eq. (6), while the last term is the Waterhouse correction, which can be ignored in large spaces. The effect of the $4.34A/S$ term is to reduce the classical sound pressure level; revised theory can be seen as an alternative level reduction term. (Though the magnitudes of the corrections are similar, revised theory employs the source-receiver distance, which its equivalent $4.34A/S$ does not.) Vorländer's modifications are included in the relevant standard relating to sound power measurement in reverberation chambers.[27]

The analysis using a simple geometrical model[24] gave Eq. (5) as the appropriate expression for the constant in Eq. (4); this was found to work in practice.[4] For the particular case of a reverberation chamber being used for sound power measurement, the sound level variation throughout the chamber is very small and the $(1-\bar{\alpha})$ correction and revised theory component are negligible, leading again to Eq. (5) for the constant for Eq. (4). Further supportive evidence is included below. Thus the constant in Eqs. (3) and (4) should be $4W/A$.

The corresponding direct sound term is $\overline{p^2_{\text{direct}}}/\rho c = W/4\pi r^2$. It is standard practice in room acoustics to refer sound levels to the direct sound level at 10 m, $\overline{p_0^2}/\rho c = W/400\pi$.

Combining these terms with Eq. (3), the energy from t to ∞ (relative to the direct sound at 10 m) becomes

$$y'(t) = \frac{1600\pi}{A}\ e^{-(13.82t/T)} = \frac{31200\,T}{V}\ e^{-(13.82t/T)}. \quad (8)$$

Equation (1) is used to modify the first term of the first version of the above.

Including the direct sound ($d = 100/r^2$), we get for total integrated energy:

$$\begin{aligned} y'(t_0) &= \frac{100}{r^2} + \frac{31200\,T}{V}\ e^{-(13.82t_0/T)} \\ &= \frac{100}{r^2} + \frac{31200\,T}{V}\ e^{-(0.04\,r/T)}. \end{aligned} \quad (9)$$

Note that this expression has variables V, T, and r only and avoids the issue of whether the Sabine or Eyring equation should be used.

If the term "t" in the exponent in Eq. (8) is set to t_0 plus a delay of 80 ms, etc., the early reflected (e_r) and late (l) sound energies can be derived

$$\begin{aligned} e_r &= \frac{31200\,T}{V}\ e^{-(0.04r/T)}.\left(1-e^{-(1.11/T)}\right) \text{ and} \\ l &= \frac{31200\,T}{V}\ e^{-(0.04r/T)}\ e^{-(1.11/T)}. \end{aligned} \quad (10)$$

Hence, the early-to-late index, $C_{80} = 10\log[(d+e_r)/l]$ and Strength, $G = 10\log(d+e_r+l)$ dB,

$$\text{The total reflected level} = 10\log(31200T/V) - 0.174r/T\ \text{dB}. \quad (11)$$

Nijs and Rychtárikova[28] have proposed an illuminating alternative to Eq. (9) for the total reflected energy, which involves introducing the mean free path (mfp). In diffuse spaces, mfp $= 4V/S$. Starting with the Eyring formula for RT,

$$T = \frac{-0.16\,V}{S\ln(1-\bar{\alpha})} = \frac{-0.04\,\mathrm{mfp}}{\ln(1-\bar{\alpha})}. \qquad (12)$$

Substituting this expression for T in the exponential term of Eq. (9),

$$y'(t_0) = \frac{100}{r^2} + \frac{31\,200\,T}{V}\,(1-\bar{\alpha})^{r/\mathrm{mfp}}. \qquad (13)$$

If the source-receiver distance equals the mfp, the reflected component is identical to that found in Eq. (6). When r is closer to the source, the reflected sound level is higher than the mean level in Eq. (6) and vice versa. Equation (13) thus establishes a close link between revised theory and the traditional expression for the mean reflected sound level, Eq. (6). It also reinforces the choice of $4W/A$ (or $31\,200T/V$) in Eq. (8), etc., for revised theory; according to revised theory $31\,200T/V$ is the reflected energy at the source ($r=0$).

The magnitude of the revised theory effect can be shown to be determined by the mean absorption coefficient and to a lesser extent the relative proportions of the space. The maximum effect from Eq. (11) is a function of r_{max}/T. If we start with a cube, side length z, the length of the diagonal is $\sqrt{3}\,z$ then r_{max} will be about 75% of this, namely, $0.75\sqrt{3}\,z$. Employing the Sabine equation, $T = 0.161\,V/S\,\bar{\alpha} = 0.161\,z^3/6\,z^2\,\bar{\alpha}$, giving the maximum revised theory effect as $8.4\,\bar{\alpha}$ dB. The equivalent effect for a double cube is $10\,\bar{\alpha}$ dB. Many rectangular concert halls approximate a double cube and a typical value of $\bar{\alpha}$ in a concert hall is 0.3 leading to a revised theory effect of around 3 dB. The magnitude of the $(1-\bar{\alpha})$ correction in Eq. (6) corresponds to a 1.5 dB average level reduction for $\bar{\alpha}=0.3$. These values are thus compatible and the level reduction is in each case a function of $\bar{\alpha}$.

On the other hand, in a reverberation chamber, $\bar{\alpha}=0.034$ at 1 kHz, giving a revised theory effect of only 0.3 dB (as in ISO354, $V=200$ m^3 and $A=7$ m^2, cubic shape assumed).

To comment on the assumptions at the beginning of this section, assumptions (1) and (3) are consequences of a diffuse sound field. Thus a diffuse sound field is also a condition for revised theory to be accurate. Assumptions (2) and (3) that there will be reflected energy and a linear decay immediately after the direct sound occur only rarely, the reality for decays can be seen in Fig. 3. But for quantities related to slightly longer initial periods such as the early level within 80 ms, the assumptions appear realistic. For instance, this is apparent in the agreement between measurement and theory for early sound level in Fig. 4.

III. MEASURED COMPARED WITH PREDICTED BEHAVIOUR

A. Behavior in a diffuse space

The validity of revised theory in purpose-built scale model diffuse spaces has been reported by Chiles and Barron.[9] The second model tested, which was the more diffuse, consisted of a rectangular space with scattering treatment using hemi-cylinders interspersed with strips of absorbing material on *all* room surfaces. With a scale factor of 1:25, the full-size equivalent dimensions of the model were $16.7\times 26.2\times 21.7$ m (volume 9450 m^3); the average RT was 1.28 s, and mean absorption coefficient 0.43. Measurements were made in two octaves, 250 and 500 Hz (full size); the low frequency limit was determined by the need for adequate signal-to-noise ratio with the spark source used, while the upper frequency was chosen to ensure an omni-directional receiver. Source and receiver locations were remote from the enclosure boundaries. Figure 5 gives an example of the measured reflected sound in this model. The reflected level clearly decreases as a function of source-receiver distance as opposed to traditional diffuse field theory which predicts that it is constant throughout the space. The agreement between the mean measured and revised theory prediction is also good in Fig. 5.

That we get revised theory behavior in this space should come as no surprise given assumptions (1) and (3) behind the theory above, which are those of a diffuse space. Assumption (2) concerning the start time of integration also appears well substantiated, as there is minimal offset between mean measured and mean theory.

B. Behavior in concert auditoria

Concert auditoria are not fundamentally diffuse spaces, since absorbing material in the form of the audience is concentrated on one of the six principal surfaces (assuming a rectangular space). Yet in most cases, sound behavior

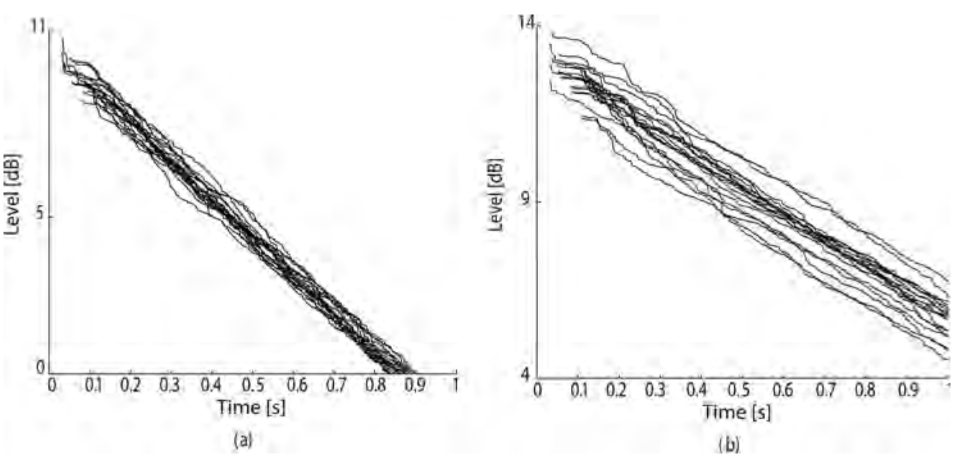

FIG. 3. Integrated impulse decays measured at different locations in a room, plotted with the true onset time relative to the impulse leaving the source. (a) In a diffuse space and (b) in a less diffuse space [after Green (Ref. 30)].

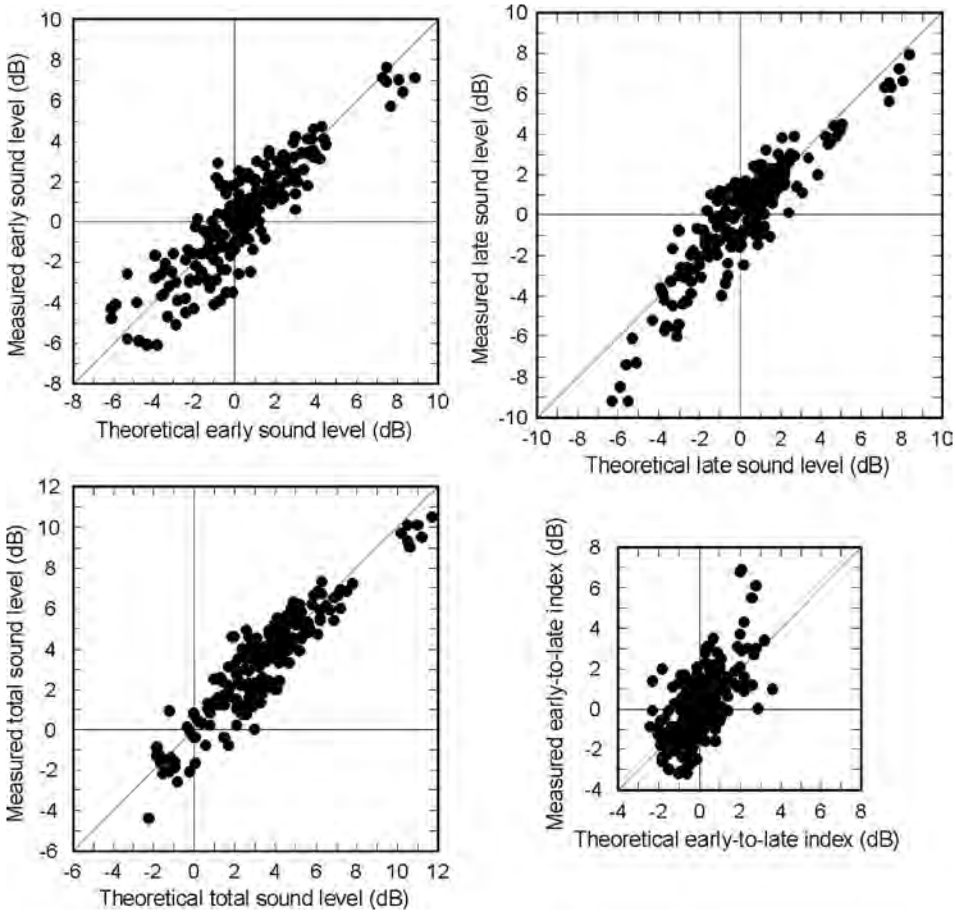

FIG. 4. Measured early, late, and total levels plus early-to-late indices plotted against revised theoretical values for 212 results from 19 concert spaces. Values are the means of the 500, 1000, and 2000 Hz octaves. Diagonal lines represent identity.

conforms to expectations according to diffuse field theory, most obviously in providing linear decays. The following considers measured level behavior in 19 concert spaces and how it compares with revised theory, which represents diffuse sound field behavior.

The measured data set has a total of 231 data points from 21 unoccupied concert spaces, as listed in Table I. All these halls are described and illustrated in Barron.[29] In nearly all cases, the omni-directional source was placed on the center line at 3 m from the stage front; the logic behind this choice is to avoid a stage floor reflection, which is generally not relevant when the stage is full of performers. The minimum source-receiver distance was 9.2 m. Measurements at overhung seats have been excluded. All measured data from full-size concert spaces presented in this paper use the means of octaves 500, 1000, and 2000 Hz, except in Secs. IV B and IV C where it is the 1 kHz octave only.

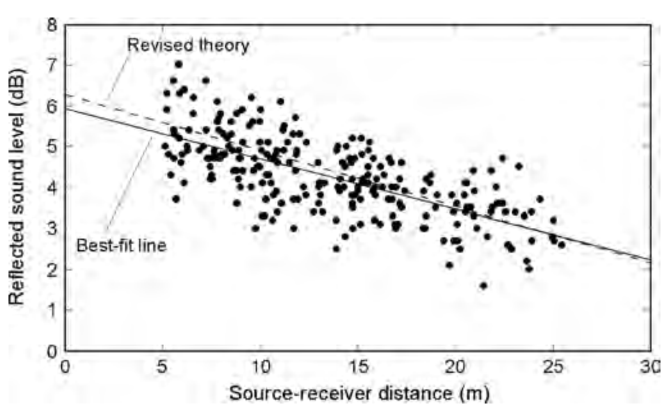

FIG. 5. Measured reflected sound levels in the 500 Hz octave in a model diffuse space, as a function of source-receiver distance [after Chiles and Barron (Ref. 9)].

To assess agreement between measured and theory, it is appropriate to remove data from two halls which have some absorbing material in the stage area (Queen Elizabeth Hall, London and Cambridge Music School auditorium). Absorbing material in the stage area has a clear effect on both early and late sound, discussed further in Sec. VI below. The remaining data set has 212 results from 19 halls. Figure 4 presents comparisons between measured and revised theory for early, late and total levels, as well as the early-to-late sound index. Table II presents the overall agreement quantitatively. The mean error is never more than 0.3 dB. The root-mean-square (rms) error is a measure of the accuracy of the prediction by revised theory; for this data set the largest rms error is less than 1.4 dB. The regression coefficient relates to the regression lines, which have not been plotted, but the coefficient provides a useful approximate measure of fit; the regression lines do not have slopes of exactly 1.0.

Agreement in Fig. 4 for the early-to-late sound index looks inferior to the other measures, which is reflected in the regression coefficient. Yet the errors for this index in Table II are not exceptional; many of the 212 points sit on each other in the early-to-late plot.

TABLE I. Basic data of the 21 halls measured. Seat numbers in halls with choir seating are shown as "auditorium + choir." RTs are the means of the 500, 1000, and 2000 Hz octaves.

No.	Label	Hall	Date	Seats	Auditorium volume (m^3)	Unoccupied reverb. time (s)
1	A	Royal Albert Hall, London.	1871	5090	86 650	2.99
2	G	Wigmore Hall, London	1901	544	2900	1.63
3	E	Usher Hall, Edinburgh.	1914	2217 + 333	16 000	2.01
4	L	Philharmonic Hall, Liverpool	1939	1767 + 184	13 560	1.73
5	W	Watford Colosseum	1940	1586	11 600	1.57
6	F	Royal Festival Hall, London	1951	2645 + 256	21 950	1.73
7	B	Colston Hall, Bristol	1951	1940 + 182	13 450	1.98
8	M	Free Trade Hall, Manchester ([a])	1951	2529	15 430	1.73
9	C	Fairfield Hall, Croydon	1962	1539 + 250	15 400	1.90
10	Q	Queen Elizabeth Hall, London	1967	1106	9600	2.07
11	Y	Wembley Conference Centre	1976	2511	24 000	1.34
12	S	Cambridge Music School Auditorium	1977	496	4100	2.00
13	P	Lighthouse Concert Hall, Poole	1978	1473 + 120	12 430	1.61
14	K	Butterworth Hall, University of Warwick	1981	1152 + 177	12 100	2.38
15	R	Barbican Concert Hall, London	1982	2026	17 750	1.91
16	D	St David's Hall, Cardiff	1982	1687 + 270	22 000	2.11
17	N	Royal Concert Hall, Nottingham	1982	2315 + 186	17 510	1.94
18	Z	Glasgow Royal Concert Hall	1990	2195 + 263	28 700	1.86
19	H	Symphony Hall, Birmingham	1991	1990 + 221	25 000	2.20
20	T	Bridgewater Hall, Manchester	1996	2127 + 276	25 050	2.41
21	I	Waterfront Hall, Belfast	1997	2039 + 195	30 800	2.00

[a]The Free Trade Hall was demolished in 1996.

The final row in Table II gives equivalent figures for the reflected level in the diffuse scale model discussed in the previous Sec. III A for the 500 Hz octave. Not surprisingly in a fully diffuse space the rms error is substantially less than for the 19 concert spaces (and predictably the rms error in Table II is virtually equal to the standard error (SE) of estimate for the data in Table III).

The most obvious outliers in Fig. 4 are low measured values for the late sound level and high measured values of the early-to-late index. Both of these were measured in the Wembley Conference Centre, which has an extreme fan-shape plan, namely, semi-circular. This case was considered in some detail in Ref. 4.

The theoretical reflected level consists of two terms, as in Eq. (11), the first is a function of A, the total acoustic absorption,

$$\text{Total reflected level} = f(A) – 0.174r/T \text{ dB}. \tag{14}$$

To eliminate the influence of this first term it may be normalized to a single value of A_0, leaving the variation of normalized total level just as a function of the revised theory effect. Starting with measured total level, the level is converted into energy, the theoretical direct sound energy is subtracted, the normalization of the absorption is performed, the direct sound energy is added back, and the whole converted back to a level. The comparison of normalized measured with normalized theoretical values of the total sound level is shown in Fig. 6. One notices that the range of levels is significantly reduced compared with the total sound level graph in Fig. 4; this has the effect of reducing the regression coefficient. However, agreement between measurement and theory in Table IV is basically identical for the normalized and non-normalized data. This provides further evidence for the validity of revised theory.

While the above looks at the average comparison between measurement and theory, a major value of revised theory is examination of deviations from theory in individual concert spaces, to be considered in Sec. VI.

TABLE II. Mean and rms errors in decibels between measured levels and revised theory values in 19 concert spaces (212 results).

Measure	Mean error (meas-th)	rms error	Regression coeff. (r)
Early	−0.1	1.29	0.88
Late	−0.3	1.19	0.91
Total	−0.1	1.02	0.92
Early-to-late index	0.1	1.36	0.62
Diffuse model, reflected level	−0.1	0.72	0.68

IV. DEVIATIONS IN PRACTICE FROM THE THEORETICAL MODEL FOR REVISED THEORY

Revised theory is based on a simple model of sound decays in rooms, as presented in Fig. 2. The equivalent to this figure as measured in real rooms is shown in Fig. 3.[30] The figure shows decays measured at different positions

TABLE III. Theoretical and measured scatter in a diffuse field scale model.

	Octave center frequency	
	250 Hz (dB)	500 Hz (dB)
Theoretical standard deviation, Eq. (15)	0.74	0.54
SE for reflected sound	0.99	0.70
Average st. deviation of instantaneous levels	0.74	0.57
SE of late levels after 200 ms	0.79	0.54

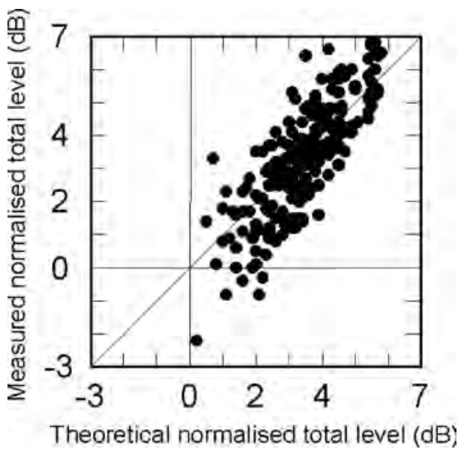

FIG. 6. Measured normalized total levels plotted against revised theoretical values for 212 results from 19 concert spaces. Values are the means of the 500, 1000, and 2000 Hz octaves. The diagonal line represents identity.

within a space, all with the time of the impulse leaving the source at $t = 0$ (as is the case in Fig. 2); the direct sound onset times clearly vary. However the obvious difference between reality and measurement is the scatter of instantaneous levels during the decay. This contravenes the first assumption listed in Sec. II above. It is well established that wave effects are one of the issues here caused by interference between reflections. Wave effects are the cause of unavoidable sound level scatter discussed in Sec. IV A, as measured by the standard deviation of the reflected sound level.

A second influence on the combined decays is the state of diffusion in the room. The traces in Fig. 3 come from a 1:25 scale model of a generic rectangular concert hall with no balcony. The model dimensions were 45 m length, 22 m width, and 18 m height full-size equivalent, with 1370 seats (with correct acoustic absorption) on a raked stalls floor. The walls and ceiling of the model contained openings into which alternative panels could be inserted. The condition for Fig. 3(a) was with all panels scattering, whereas for Fig. 3(b) all panels were plane. Discrete early reflections cause steps in the integrated decay, these steps are more evident in the space when it had all plane walls and ceiling, Fig. 3(b). The decays settle down earlier to becoming mainly linear in the diffuse case, Fig. 3(a). The steps in the early decays contradict assumption (3) in Sec. II; however when measured early levels within 80 ms are compared with theory no consistent disagreement emerges.

Few quantities are constant in room acoustics, in particular, RT and sound level in a space are statistical. The standard deviation of RT has been shown by Davy *et al.*[31] to have

TABLE IV. Mean and rms errors between measured total sound levels and revised theory values in 19 concert spaces (212 results). "Total" values (as in Table II) compared to normalized total sound level.

Measure	Mean error (meas-th in dB)	rms error (dB)	Regression coeff. (r)
Total	−0.1	1.02	0.92
Normalized total	−0.1	1.03	0.80

a minimum value which occurs in a diffuse sound field. The equivalent deviation for sound level is considered below.

A. Standard deviation of reflected sound level in diffuse spaces

Investigations into behavior in reverberation chambers during the 1950s and 1960s established that, even in a fully diffuse sound field, the sound level for a single source fluctuated between microphone positions. An expression for the minimum scatter as represented by the standard deviation was derived by Lubman[32] and Schroeder.[33] For a noise source, the standard deviation, σ, of the sound pressure level of the reflected component within a room, L, is a function of bandwidth, B, and RT, T,

$$\sigma(L) = \frac{4.34}{\sqrt{\left(1 + \left(\frac{BT}{6.9}\right)\right)}}\ \text{dB}. \tag{15}$$

This spatial deviation was compared by Lubman with measured values in several chambers; measured values were often slightly larger than the theoretical values from Eq. (15). In the case of the standard reverberation chamber mentioned at the end of Sec. II above ($V = 200$ m^3, $A = 7$ m^2, 1 kHz octave), the theoretical spatial standard deviation is 0.20 dB. With the maximum predicted variation of level according to revised theory of 0.3 dB in such a space (Sec. II), it is not surprising that the revised theory effect was not observed in reverberation chambers.

The standard deviation of sound pressure level in rooms is not very meaningful when the reflected level is a function of distance from the source, as will occur in spaces with a significant mean absorption coefficient. The relevant scatter will then be about the line-of-best fit, rather than a mean level. It is interesting to compare the former, known as the SE of estimate, with values from Eq. (15) in spaces with a significant revised theory effect. The relevant results from the diffuse field scale model referred to in Sec. III A (Ref. 9) are instructive. This diffuse field model differs from a reverberation chamber because the mean absorption coefficient is much larger.

The comparison for measured values in Table III is with the values from Eq. (15). The SE at 500 Hz is taken from the regression shown in Fig. 5; these errors exceed the theoretical standard deviation at both frequencies, probably due to discrete early reflections. However, for the average standard deviation of instantaneous levels and the SE of late levels, agreement with Eq. (15) is good. This is a reassuring result. The average standard deviation of instantaneous levels is taken from graphs like Fig. 3. The SE of late levels involves integrated levels from 200 ms delay to "infinity"; the choice of 200 ms came from inspection of the relevant superimposed decays (as in Fig. 3). From Table III, for linear decays we can expect values of the average standard deviation of instantaneous levels to be similar to the SE of late levels.

B. SEs for reflected sound level in concert spaces

From the experience of a diffuse space, in the 21 concert spaces the most suitable data for comparison with theoretical

TABLE V. The range and mean theoretical and measured scatter for the 1 kHz octave in 21 concert spaces. All figures are in decibels.

	Minimum	Mean	Maximum
Theoretical standard deviation, Eq. (15)	0.25	0.31	0.37
SE of late levels after 80 ms	0.35	0.82	1.33

scatter considered in Sec. III B is the SE of best-fit lines to late levels as a function of source-receiver distance. In the case of the concert space data, only the late level beyond 80 ms after the direct sound was available. The comparison is made for the 1 kHz octave, with the ranges in Table V and extreme values in Table VI. Measured data excludes seat positions under balcony overhangs.

Although there is a small overlap in Table V between the theoretical and measured scatter, in no case is the measured value equal to or less than the theoretical value. The theoretical values are, in fact, solely a function of RT. While the lowest measured SEs in halls are comparable with the theoretical standard deviations, the largest measured SEs are substantially greater than theory. The wave effects, which are the cause of the theoretical scatter, may be significant for the lowest group, but there must be something else which causes the high measured errors. One's first thought is the state of diffusion in the space.

In the case of the three halls with low measured SEs, they all have highly scattering ceilings,[29] which in each case include structure within the acoustic space to support the roof of the auditorium. This feature is likely to contribute to the state of diffusion. The measured SE may in these cases be a useful measure of this state of diffusion. Turning to the halls with high measured SEs, these all have (or had) unfortunate geometries. The Usher Hall has a horseshoe plan with a large concave rear wall, the Albert Hall is basically elliptical in plan, and the Free Trade Hall was subdivided by oversize balconies. In these cases, this comparison with theory is virtually meaningless; the behavior is better illustrated by plotting late sound against source-receiver distance as proposed in Sec. VI. These latter halls are unlikely to be diffuse.

C. Relationship between the scatter of early reflected and late sound

The impulse response is often divided into an early and late portion. As in Sec. VI, the division is valuable and the acoustic character of each is different. The early reflected part is determined by the surfaces near the source and receiver that provide reflections within the early 80 ms time period. The late sound, on the other hand, contains a high number of reflections as part of the overall decay; the late level is generally linked to the gross geometry and the state of diffusion. The direct and early sound, of course, establish the conditions for later sound. The nature of this link is certainly intriguing.

An interesting question is whether the scatter of results for the early reflected sound links to scatter of the late sound, or are they independent? The SE for linear regression between the late sound and source-receiver distance was considered in Sec. IV B. The SE for early reflected sound (early sound without the direct sound) has also been calculated for the 21 concert spaces. (Note that revised theory predicts linear relationships with distance for both early reflected and late sound.) Figure 7 gives a comparison of the two SEs, the letters refer to the hall labels listed in Table I.

One notes that the SE values are generally larger for the early reflected sound as opposed to the late sound. Average values of the SEs are 1.42 dB for the early reflected and 0.82 dB for the late sound. This is to be expected since the late sound consists of many more reflections and is much more diffuse than the early reflections. There is however no correlation between the two SEs ($r = 0.10$). One might say, that the trend is for a small early reflected SE to correspond to a small late sound SE, and large with large, but halls exist with small early and large late SE as well as large early and small late SEs. These "exceptions" are of particular interest, note however that positions under balconies were not included.

Starting with the cases of modest early reflected SE and large late sound SE, the Free Trade Hall, Manchester (label M), though it had a scattering ceiling, had poor geometry for a diffuse sound field with two major balconies partially subdividing the space contributing to a large SE for the late sound. However regarding the early sound, for many seats there were nearby surfaces potentially able to provide early reflections, hence a small SE for early reflected sound. The acoustic design of this space was not brilliant by modern standards, but the opposing SEs are a surprising result. Similarly in the Usher Hall, Edinburgh (E) and the Colston

TABLE VI. Extreme values of the SE of late levels for the 1 kHz octave in 21 concert spaces, compared with the theoretical standard deviation from Eq. (15). All figures are in decibels.

Concert hall	Theoretical St. Dev.	Measured SE
Cambridge Music School Auditorium	0.30	0.35
St. David's Hall, Cardiff	0.29	0.41
Butterworth Hall, Univ. of Warwick	0.28	0.43
—	—	—
Usher Hall, Edinburgh	0.30	1.23
Royal Albert Hall, London	0.25	1.29
Free Trade Hall, Manchester	0.33	1.33

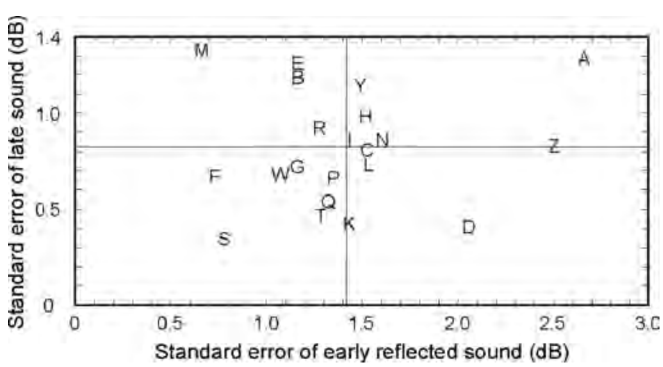

FIG. 7. The SEs for 21 individual halls for early reflected sound plotted against late sound for the 1 kHz octave. The errors in each case are the result of correlation for each hall with source-receiver distance. The hall letters are listed in Table I. The vertical and horizontal lines represent the mean values of the relevant SE.

Hall, Bristol (B) both have extensive balconies which may contribute to poor diffusion, whereas most seat positions are not far from reflective surfaces. Turning to the opposite extreme, St. David's Hall, Cardiff (D) is the major example of a high early reflected SE and low late SE. In this hall the early sound levels at distant seats are significantly lower than expected; this is a terraced-style hall but the dividing surfaces between individual terraces are mostly radial and thus not able to provide useful first reflections. Finally the Royal Albert Hall, London, deserves mention with large errors for both early and late sound; its design was not influenced by acoustic concerns! In general, anomalies such as these are likely to be picked up using Temporal Energy Analysis, Sec. VI below.

Uniform acoustics are often considered to be a virtue. The distance of the points from the origin in Fig. 7 is a possible measure of uniformity, though an appropriate weighting of the two SEs might be considered. The scatter (SE) of early sound is influenced by the "large concert hall problem" (Ref. 29): a large auditorium volume is required for a suitably long RT, which tends to push out room surfaces, delaying and thereby weakening early reflections. Several of the halls in the sample however have shorter RTs than optimum caused by inadequate hall volumes, which can offer a possible benefit for early reflections, at the expense of the effects of a short RT.

V. POSSIBLE MODIFICATIONS TO REVISED THEORY

A. Start time for integration of energy

As already mentioned, Vorländer[17] considered the accuracy of sound level measurements in rooms, with particular reference to reverberation chambers. He proposed that, contrary to revised theory, integration of reflected energy should not start with the arrival time of the direct sound, but rather the arrival time of the first reflection. He demonstrated that the average delay of the first reflection (relative to emission from the source) is $4V/cS$, based on the mfp ($4V/S$). This then leads to the frequently quoted expression for the mean reflected squared pressure in a space, Eq. (6). His paper proceeds to discuss ways in which the accuracy of test measurements can be improved.

It is of interest to see how changing the time limit for the start of integration affects agreement between measurement and revised theory for concert halls. The delay of the first reflection relative to the direct sound is often called the initial-time-delay-gap (itdg), a label first coined by Beranek.[34] Itdg data was available for 18 of the 21 halls (not the last three in Table I) but as in Sec. III B the results for the Queen Elizabeth Hall, London and Cambridge Music School auditorium have been omitted. The following is derived from 170 results in 16 halls. The mean itdg is 20 ms for this data set.

Table VII compares the mean and rms errors for comparisons of measured and theoretical results, derived first using the direct sound and second using the arrival time of the first reflection as the start time for integration of the reflected sound. (For the errors with the direct sound start time, one can observe minor differences with Table II, which are due to the slightly different data sets.) In all but one case the errors are smaller using the revised theory scheme based on the direct sound start time. The effect of using the first reflection start time is on average to reduce the theoretical early sound by 1.1 dB and the total sound level by 0.5 dB. In the case of the early-to-late index, the rms error is slightly less with the first reflection start time.

TABLE VII. The mean and rms differences between measured and revised theory predictions for the early and total sound levels, plus the early-to-late sound index for two different start times for early reflected sound. All figures are in decibels. Values in bold type are lower than their equivalent. Values are the means of the 500, 1000, and 2000 Hz octaves.

	Theory using direct sound		Theory using first reflection arrival	
Measure	Mean error	rms error	Mean error	rms error
Early	**−0.2**	**1.30**	0.9	1.61
Total	**−0.2**	**1.02**	0.3	1.11
Early-to-late index	**0.1**	1.41	1.3	**1.28**

This exercise with concert hall data supports the revised theory scheme based on the direct sound, as does the exercise in the diffuse space (Sec. III A and Table II). As regards the process of integration, early reflections are discrete events responsible for stepped integrated impulse decays just after the direct sound, so that the integration limit should assume the smearing of discrete reflection energy. The source and receiver positions may also affect results; for these measurements in concert halls the source position was 2–3 m from the stage front on the center line in order to avoid a stage reflection, while the receiver positions are close to a sound-absorbing boundary (the seating).

B. RT or EDT

In the revised theory expressions, one could justifiably propose that the EDT might be more appropriate in the formulas than the RT. Earlier sound within a time period contributes more to energy; for a 2 s RT, the EDT relates to the first 330 ms. Using the EDT in the theory was investigated for the data set used in Sec. III B, 212 results from 19 concert halls. As before, results for seats below overhangs were omitted.

A useful parameter when discussing EDT values is the ratio EDT/RT. For hall mean values in the 19 halls, the EDT/RT ratio takes values between 0.80 and 1.06, with a mean of 0.95. Thus EDTs shorter than the corresponding RT are the norm.[7] Three different ways of introducing the EDT were used: method (1) used the individual position EDT values, method (2) used hall mean EDT values, whereas method (3) employed the RT for the first term in Eq. (9) and the EDT for the second term, the direct sound is unaffected. The logic behind method (3) was that the total acoustic absorption is principally linked to the RT, whereas revised theory effects are linked to the earlier part of the impulse response.

Table VIII lists differences between theory and measurement for the whole data set, using either the RT or the EDT; the method giving the best match when using the EDT is given in the final column. In fact, differences between the

TABLE VIII. The mean and rms differences between measured and revised theory predictions for the early, late, and total sound levels, plus the early-to-late sound index. The comparison of revised theory is made using either the RT or EDT. Three methods of introducing the EDT were used as defined in the text above; results below are for the best method in each case with the optimum method listed in brackets in the final column. Values in bold type are lower than their equivalent.

19 halls	Theory using RT		Theory using EDTs	
Measure	Mean error (dB)	rms error (dB)	Mean error (dB)	rms error (dB)
Early	**−0.1**	**1.29**	**0.1**	1.31 (3)
Late	−0.3	**1.19**	**0.2**	1.34 (3)
Total	−0.1	**1.02**	**0.0**	1.17 (2)
Early-to-late index	**0.1**	1.36	−0.3	**1.13** (3)

three methods are small. The results in the table suggest that there is no particular advantage in replacing the RT in general.

Replacing the RT by the EDT is likely to be appropriate when the EDT and RT are most different. To examine this, an investigation was made into the situation for the 10 halls with the smallest values for the mean EDT/RT, which for this data set corresponds to a ratio of less than 0.95. Table IX lists the number halls in which using the EDT (method 2) offers advantages. Small differences are however of little consequence, the second row of Table IX lists the number of halls in which the differences are significant (categorized as changing the mean error by at least 0.5 dB). This shows that there is little benefit in using the EDT for the early and total sound. However in 3/10 halls, prediction of the late sound is more accurate with the EDT rather than the RT. For the early-to-late ratio, there is a benefit in using the EDT, as opposed to the RT, in half the halls in this sub-group.

Two halls are known (to this author) where there is a clear advantage in using the EDT: these are the Christchurch Town Hall and Michael Fowler Centre, Wellington, both in New Zealand.[29] The figures for the first of these are presented in Table X using method (2), showing that in all cases use of the EDT provides better agreement with theory; the mid-frequency EDT/RT ratio in this hall is 0.82. One feature of these halls is that their measured RTs are longer than the calculated.[35]

VI. BEHAVIOR WITHIN CONCERT SPACES

Comparing measured data graphically with revised theory predictions offers valuable insights into sound

TABLE IX. Number of halls with the EDT giving better revised theory predictions for halls with mean EDT/RT ratios <0.95.

Halls with EDT/RT ratios <0.95	Early	Late	Total (G)	E/L
No. of halls with EDT preferred (/10)	6	4	2	6
No. of halls with significant improvement with EDT (/10)	0	3	0	5

TABLE X. The mean and rms differences between measured and revised theory predictions for the early, late, and total sound levels, plus the early-to-late sound index, in the Christchurch Town Hall, New Zealand, when using either the RT or EDT in the theory. Values in bold type are lower than their equivalent.

Christchurch, NZ	Theory using RT		Theory using hall average EDT	
Measure	Mean error (dB)	rms error (dB)	Mean error (dB)	rms error (dB)
Early	−0.4	0.56	**−0.1**	**0.39**
Late	−2.8	2.96	**−1.1**	**1.50**
Total	−1.6	1.64	**−0.5**	**0.69**
Early-to-late index	2.4	2.61	**1.0**	**1.51**

behavior in a concert space. Sound levels and the early-to-late index can be plotted against source-receiver distance. Considering the early and late levels independently is particularly valuable since design features influence them differently. The early sound is determined by the direct sound and discrete early reflections. The late sound is dependent on more gross features such as the overall geometrical form of the space. The total sound level and the early-to-late index are the sum and difference of the early and late levels and are considered to be measures of subjective loudness and clarity.

Plotting the early, late, and total levels plus the early-to-late index against source-receiver distance has been called Temporal Energy Analysis and is proposed as a valuable aid for assessing sound in an auditorium,[12] as in Fig. 8.

Consistent deviations from revised theory are particularly interesting, where they can be linked to design details; many were highlighted in the original paper on revised theory.[4] The first considered here is the effect of sound absorbing material close to the stage area, which was the situation in 2 of the 21 British halls. Because of this, the Queen Elizabeth Hall, London and the Cambridge Music School Auditorium were omitted from analysis in Secs. III B, V A, and V B in global comparisons. Agreement between measured and theory for these two halls is illustrated in Table XI.

Due to its location, sound absorbing material in the stage region has an influence beyond simply reducing the RT, because it subtends a significant solid angle at the source.[36] In the two cases in Table XI, there is a roughly uniform effect on both early and late sound levels. In a small to medium size hall, reducing sound levels in this way may be acceptable, particularly for large orchestral forces where it may in fact be necessary to limit subjective overload. Variable absorption in these smaller halls is often desirable.

The presence of upholstered seating for the performers and the musicians themselves in an orchestra on stage also influence the sound level for the listeners. A measurement in Birmingham Symphony Hall was made on a bare stage and with 50 chairs on stage; the mean level for listeners dropped 1.0 dB at mid-frequencies with the chairs in place.[37] Similar level changes have been observed in scale models.

There is some evidence that the measured total level in small halls is less than predicted by revised theory, in Ref. 21, for example. This occurs in the Wigmore Hall, London, which does not have absorbing treatment in the stage area.

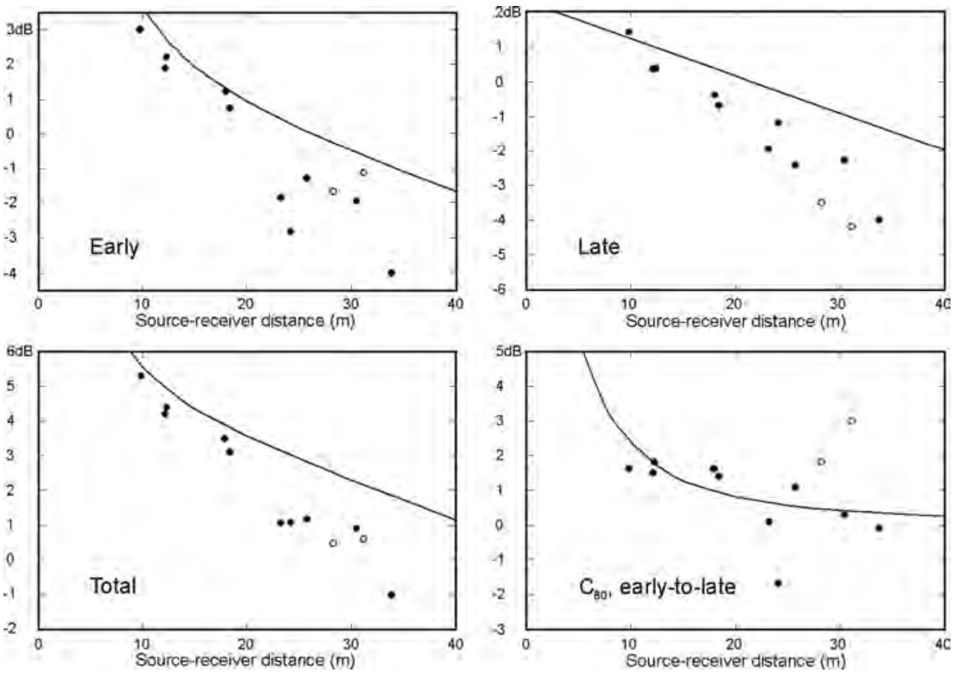

FIG. 8. Plots of measured values in the Fairfield Hall, Croydon, for the early, late, and total sound levels, plus the early-to-late index. All figures have the source-receiver distance on the x axis. Solid lines/curves represent revised theory predictions. Positions under the balcony overhang are represented by open circles. The measured greater decrease with distance of both the early and late sound in this hall are attributed to fins which rise from the boxes on the side walls up to the ceiling, as well as downstand beams in the ceiling (Ref. 29).

The seven points in the top right corner for early, late, and total sound in Fig. 4 are from the Wigmore Hall and for the early, late, and total sound the mean difference between revised and measured is -1.1 dB in each case. Aretz and Orlowski[23] found similar behavior is one of their halls, when no absorbing material was present. Two obvious possibilities exist to explain these observations: that lower measured levels are a characteristic of smaller halls or that a limited state of diffusion is involved.

High rates of decrease with distance of early sound tend to be associated with highly scattering ceilings (as in the case of the Barbican Concert Hall, London).[4] One can argue that, with highly scattering walls and/or ceiling, the surfaces closer to the stage receive more incident energy but with Lambert scattering most sound is reflected normal to the surface irrespective of the angle of incidence. The result of this is that less sound reaches the back of the hall than would occur for plane walls and ceiling.

As already mentioned, the late sound decreases under balcony overhangs. A similar excess rate of decrease of late sound occurs in fan-shaped plan halls, particularly in a semicircular plan hall like Wembley Conference Centre.[4] The opposite plan shape to the fan is known as the reverse-splay. The reverse-splay can result in increased early and late levels; the example of Segerstrom Hall, California[6] is particularly interesting in this respect.

Finally, the introduction of suspended reflectors above the stage can increase early sound levels. This has been observed in the following halls: the Royal Albert and Royal Festival Halls, London, and the Royal Concert Hall, Nottingham.

TABLE XI. Mean level differences between measured and revised theory predictions for the early, late, and total sound levels, plus the early-to-late index, in two halls with absorbing treatment in the stage area.

Concert hall	Early	Late	Total (G)	E/L
Queen Elizabeth Hall, London	−1.7	−1.7	−1.7	0.0
Cambridge Music School Auditorium	−1.6	−1.1	−1.3	−0.5

VII. CONCLUSIONS

The revised theory of sound level behavior in rooms has been referenced by quite a few authors. It has proved very useful for research purposes and has the potential to provide valuable comparison values for measured sound levels in concert spaces, including total, early and late levels.

The derivation of the theoretical relationships highlights the fact that revised theory relates to a space with a diffuse sound field. Concert spaces have their absorption concentrated on only one of the six principal surfaces, so they are inherently not fully diffuse spaces. However the RT equations are also based on the assumption of a diffuse space and are generally quite accurate in concert spaces. Concert spaces can behave in several respects as if they were diffuse, particularly if they contain surfaces that scatter sound. The 19th century rectangular halls fall into this category. But do we want a concert space to behave like a diffuse one? Our hearing system cannot detect diffuseness very well, as long as there is no strong directional bias. It is probably reasonable to say that behavior of sound level similar to that in a diffuse space is safe for good listening conditions, but adherence to diffuse behavior is not necessary for the best acoustics. In the latter situation, revised theory provides a reference and deviations from diffuse behavior can be knowingly assessed.

In a scale model diffuse space[9] measurements indicate that average sound level behavior behaves according to revised theory. However as with many acoustic phenomena there was scatter associated with measured sound levels. This scatter, in the case of the late sound, was found to agree with the theory proposed by Lubman[32] and Schroeder.[33] Comparison between revised theory values and measurements in concert spaces shows that revised theory predicts well on average, with an rms error of not more than 1.4 dB for the early, late, and total sound level, plus the early-to-late sound levels. The scatter of measured levels in concert spaces was always found to be greater than the Lubman/Schroeder theory.

Two modifications of revised theory were investigated: changing the onset time for reflected sound from the arrival of the direct sound to that of the first reflection and replacing the RT in the formulas by the EDT. In neither case was there evidence that changing the theory was warranted in general.

Temporal Energy Analysis was proposed as a valuable method to analyze sound level behavior in individual halls. The analysis is good at highlighting trends in deviations from revised theory, as well as illustrating, or not, acoustic uniformity throughout a hall. It does however require measurements with an omni-directional source and receiver. Comparing measured and predicted, a simple technique is to highlight differences of greater than 1 dB to alert one to possible significant situations.

To conclude, revised theory has been found to represent average behavior well. It has the potential to highlight the sound level effects of certain design details and provides valuable reference values for sound levels in a diffuse space with the same RT and auditorium volume. From the analyses shown here, there is little evidence that modification of the formulas is worthwhile in the general case. Coupled spaces represent another possible sound field condition in concert halls, which will have their own behavior.[38]

It is however important to stress that revised theory predictions are based on the measured or predicted RT. The theory provides expected sound levels for those particular RT and volume values. For instance, with a short RT due to inadequate volume, the total level and early-to-late index become higher, but the subjective issues associated with a short RT remain. Agreement with revised theory is not a substitute for other analysis techniques.

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