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Objective assessment of concert hall acoustics using Temporal Energy Analysis

by Mike Barron

ABSTRACT

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See also:

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Objective assessment of concert hall acoustics using Temporal Energy Analysis

Mike Barron *

Fleming & Barron, Combe Royal Cottage, Bathwick Hill, Bath BA2 6EQ, United Kingdom

a b s t r a c t

While for concert halls there are preferred ranges of values for the objective measures described in ISO3382-1, a method for comparing measured sound levels with theoretically expected values is pro-posed here. The theoretical values are based on the revised theory of sound level, with both measured and theoretical values plotted against source-receiver distance. The discussion concentrates on mid-fre-quency behaviour. The comparison can be made for early sound (less than 80 ms delay), late sound (greater than 80 ms delay), total sound level (G, strength) and the early-to-late sound index, C_{80}. A com-posite of four graphs, one for each quantity, is suggested. The early and late levels can be considered from an objective standpoint as determined by the auditorium design, while the total level and early-to-late index relate to subjective response. Four case studies are presented which illustrate both typical behav-iour and divergences from revised theory due to design features in the halls themselves. This Temporal Energy Analysis is proposed as an additional method for assessing acoustic behaviour with the advantage of illustrating behaviour at different locations within the auditorium.

1. Introduction

With the introduction of objective measures relating to subjective characteristics for listening to classical music in ISO 3382-1 [1], most new auditoria are now modelled using either a computer simulation model or an acoustic scale model. An alternative is to test by auralisation, an approach more valued by some more than others! (auralisation is never perfect but assessing the influence of inaccuracies on aural presentations is very difficult and as yet unpublished. Even the question of the manner and location of reproduction is problematic) For work using objective measures, criteria are needed to assess the numerical values, the most common of which is to compare measured or predicted values with an optimum range. If the value of an objective measure falls outside the optimum range it can often not be obvious why this has occurred, what aspect of the geometrical design is responsible?

The revised theory of sound level in rooms [2] offers a technique for assessing acoustic behaviour which complements approaches already in use. The following discusses the rationale behind and the use of 'Temporal Energy Analysis' for assessing concert spaces.

* *E-mail address:* m.barron@flemingbarron.co.uk

An earlier version of this paper was presented at the Institute of Acoustics meeting in Oslo "Auditorium Acoustics 2008" [3].

2. Subjective considerations

Though the acoustic character of a concert hall is often discussed as an overall characteristic (such as "the hall has good acoustics"), this is to ignore the fact that listeners differ in their preferences. This was first demonstrated in a study conducted in Berlin in the 1970s, reviewed by Cremer and Müller [4], and was also apparent from this author's subjective study of British halls [5]. At least three groups of listeners have been identified: those that like reverberance (sense of reverberation), those that like acoustic intimacy and those that above all prize high clarity. Nevertheless, for the trained ear it seems that most important subjective characteristics can be appreciated and assessed, even though individual preference varies. Hence the validity of criteria for objective measures applicable to the majority of listeners.

In addition, though the subjective acoustic character of a hall as a whole is often considered, there will generally be significant subjective variations between different seating areas. When interpreting the results of objective measurements, just working with average values of quantities which vary throughout the auditorium is not appropriate. Reverberation time is usually the exception here since it generally varies little throughout the space and single hall values are acceptable.

3. Objective measures

3.1. General considerations

A set of objective measures are now recommended and generally accepted for use in music auditoria [1]. However it is important never to lose sight of the fact that current objective measures are not perfect; they are not fully correlated with the subjective impressions to which they are linked. Nor do current objective measures cover all subjective aspects of sound in halls.

In the case of measurements in full-size halls, objective measurements are generally conducted without an audience present. The most obvious change between no audience and with audience is that the reverberation time falls. The corresponding changes for other objective measures are that early decay time (EDT) decreases, the early-to-late sound index C_{80} increases and total sound level, G, decreases. For valid comparisons between halls, correction for the effect of audience is essential. Several correction techniques for reverberation time (RT) have been proposed [6]; for modest RT changes they are all probably equivalent. This author's technique is included in the Appendix.

Effects of an orchestra on stage are also significant for sound level behaviour. An example of a 1.0 dB reduction of level G (strength) for the audience is recorded [6] when 50 moderately upholstered chairs were added on stage in a concert hall with 2210 seats. 'Musicians' should therefore be included in models. This and other issues associated with objective measurement are discussed in [6].

3.2. Optimum values for objective measures

A full objective analysis of a concert auditorium should involve measurements with an omni-directional source over at least five octaves (125–2000 Hz) and over a reasonable number of seat positions, between 10 and 20 positions for a large auditorium. ISO 3382 [1] proposes measurements in six octaves up to the 4000 Hz octave, in spite of the fact that standard omni-directional dodecahedron loudspeakers become highly directional at this frequency. This problem can be overcome by making a series of measurements for each source-receiver combination with the source rotated through a sequence of orientations. This has the penalty of considerably increasing measurement time and has not been used for the results presented here. The additional information gained by including data in the 4000 Hz octave is not thought to be great.

A minimum source-receiver distance of around 10 m seems reasonable in large concert halls given the physical extent of the orchestra. With five objective measures (reverberation time, EDT, C_{80}, lateral fraction, LF, and total sound level, G) a lot of data is generated. (For spatial impression, some people prefer to work with the IACC, interaural cross-correlation coefficient, also included in ISO3382.) Data reduction is appropriate but, as already mentioned, only in the case of reverberation time is it appropriate to work with a hall mean. Data reduction for energy measures (C_{80}, LF and G) into two frequency bands appears suitable: the mean of 125 and 250 Hz (bass) and the mean of 500, 1000 and 2000 Hz for mid-frequency.

The most obvious assessment method for objective data is to compare measured values with ranges of acceptability for occupied concert hall use [7], as shown in Table 1.

The criterion for G was proposed in Ref. [7] on the basis of measurements by the author and others; it appears not to have been subsequently challenged. A more sophisticated criterion has since been proposed responding to the evidence for loudness constancy in rooms [8]. The revised criterion for the minimum acceptable total level is a function of source-receiver distance, d: $G = 10\cdot\log(100/d^2 + 2.08\cdot e^{-0.02d})$; this takes the value of $G = 0$ dB at a distance of 40 m. Regarding the significance of this revision for the halls considered in Section 6, total sound level values measured in the Barbican Concert Hall in 1984 are shown in Fig. 1 with the two criteria. This suggests that loudness in this hall may have been too quiet at five as opposed to two positions when the simple $G > 0$ dB criterion is applied. For the other halls considered in Section 6, none of the positions are below the revised criterion in the Wessex Hall, but in the Royal Albert Hall the sound level at even the closest position (10 m, 2.8 dB) becomes too quiet. In the Colston Hall, one position in the rear stalls below the overhang turns out to be too quiet.

Other assessment methods for individual measures are given in [6], such as considering the ratio of mean EDT to RT [9].

This paper considers a new assessment approach which complements the acceptability range method. It is based on the author's revised theory for sound level behaviour in rooms [2,7]. One considerable merit of this approach is that it can reveal variations within individual concert halls. Similar plots of sound levels against distance have also been presented by Bradley [10] among others.

Table 1
Recommended ranges for objective measures at mid-frequencies for concert halls.

Measure	Acceptable range
Reverberation time (RT)	$1.8 \leqslant \text{RT} \leqslant 2.2$ s
Early decay time (EDT)	$1.8 \leqslant \text{EDT} \leqslant 2.2$ s
Early-to-late sound index (C_{80})	$-2 \leqslant C_{80} \leqslant +2$ dB
Early lateral energy fraction (LF)	$0.1 \leqslant \text{LF} \leqslant 0.35$
Total relative sound level (G)	$G > 0$ dB

4. Revised theory for sound level in rooms

4.1. The basic theory

Traditional theory for sound level in a room with an omni-directional point source considers a direct sound component and a reflected sound component. The direct sound follows simple inverse square law behaviour, while the reflected sound is assumed to be constant throughout the space. Barron and Lee [2] proposed that the reflected component is also a function of source-receiver distance. In this model the direct sound is as previously and the decay is assumed to be linear with a slope according to the reverberation time. However the reverberant decay can only

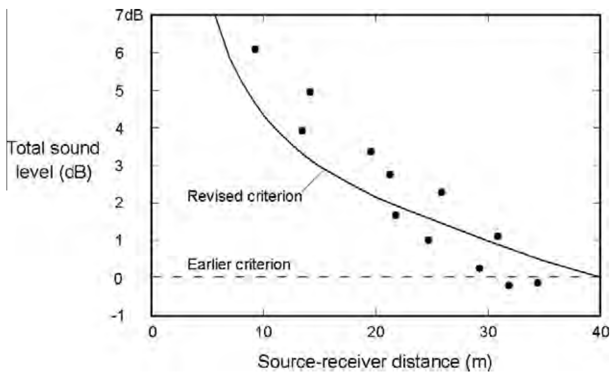

Fig. 1. Values of the total sound level in the occupied Barbican Concert Hall, London, as in Fig. 10, with the earlier and revised criteria for adequate loudness, as explained in Section 3.2.

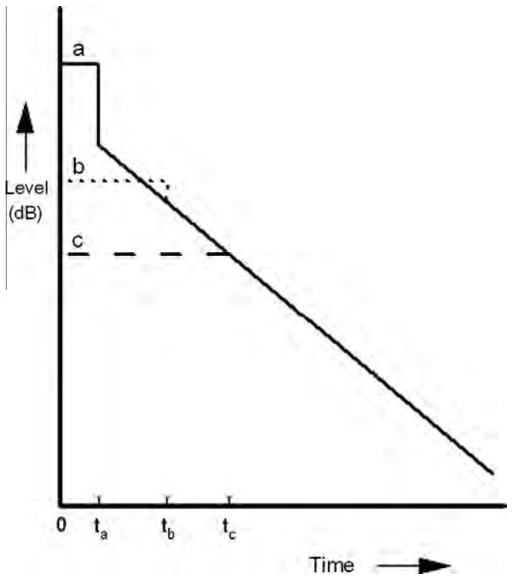

Fig. 2. Integrated impulse curves at three receiver distances from a source in a room according to revised theory. Here $t = 0$ is the time when the sound was emitted from the source; t_a is the direct sound arrival time at position A close to the source etc. Positions B and C are progressively further from the source.

begin when the direct sound arrives. Fig. 2 shows three superimposed decays, or more precisely impulse responses integrated in reverse time, as would be used for measuring the reverberation time according to the Schroeder method. At a late time, the sound level is assumed to be the same throughout the room, so the three decays are the same. The decay can only begin when the direct sound arrives, thus the duration of the decay is longer for positions close to the source, and hence the magnitude of the reflected sound is greater closer to the source.

The sight (and sound) lines for direct sound are assumed to be good so that the traditional inverse square expression is legitimate. This tends to be valid at mid-frequencies. At bass frequencies, the seat-dip effect will influence direct sound levels at most seats except in the front rows of balconies [7].

Analytical expressions can be derived from this model not only for the total reflected sound but also for temporal segments, such as the early sound within 80 ms of the direct sound (see Appendix). Barron and Lee [2] demonstrated that average behaviour measured in a group of concert auditoria corresponded with predictions according to revised theory. In several cases, divergences from revised theory could be ascribed to specific design features. Revised theory behaviour has also been observed in a purpose-built acoustically diffuse space [11]. This evidence contradicts the usual assumption that the reflected sound is constant throughout the space. The magnitude of the 'revised theory effect' is determined by the mean absorption coefficient [11]. In a standard reverberation chamber, the mean absorption coefficient is small and the revised theory effect is likewise small. The effect is significant in concert halls where the mean absorption coefficient tends to be around 0.3.

4.2. Early and late sound

Two measures recommended in ISO 3382 for measurements in auditoria can be used to extract the early and late energy. For classical music, the temporal division between early and late is generally taken as 80 ms, with the early-to-late sound index known as C_{80} dB. 'Early' here includes the direct sound and reflections that arrive before 80 ms after the direct sound. C_{80} can be called 'objective clarity'. Total sound level, G dB, also known as strength, is the total level relative to the direct sound level at 10 m from the source. Measurements with an omni-directional source are assumed in music auditoria.

If 'e' is the early energy (relative to direct sound energy at 10 m) and 'l' is the late energy then:

$$G = 10 \cdot \log(e + l) \text{ and } C_{80} = 10 \cdot \log(e/l)$$

With two equations and two unknowns, the early level $(10 \cdot \log e)$ and late level can be calculated. By analysing the behaviour of the early and late levels as a function of distance from the source, an understanding of sound behaviour in concert hall spaces can be gained. In this paper, mid-frequency behaviour is considered only, using mean values for the octaves 500, 1000 and 2000 Hz.

The advantage of considering the early and late sound independently is that their physical origins are different. The early sound is made up of the direct sound and individual reflections whose paths can usually be traced. The late sound on the other hand is dominated by reverberant sound, which in many cases is reasonably diffuse, at least in the main body of the auditorium. Disproportionate and non-unified rooms have poorer degrees of diffusion, which may influence late sound level behaviour. The case of balcony overhangs illustrates this well, as discussed in Section 5.2.

5. Temporal Energy Analysis

5.1. Analysis procedure

The proposal is that sound behaviour within an auditorium can be clarified by presenting graphically the early and late levels, the total level, G, and the early-to-late sound index, C_{80} dB, all plotted on a single diagram as a function of source-receiver distance together with the revised theory prediction, Fig. 3. Revised theory has two parameters determining predictions: the hall volume and reverberation time. All figures have the decibel scale with the same range of 8 dB.

The upper part of the diagram is concerned with the interplay between hall design and objective acoustic consequences, hence the label "Objective". The lower part presents the measures relevant to subjective response, basically loudness and subjective clarity. The individual values of early and late level determine, of course, the total level and objective clarity, C_{80}: a low early sound level will result in a low total level and a low objective clarity etc. One can consider the upper part of the diagram as the objective cause and the lower part as the subjectively relevant effects.

The next three sections consider situations were behaviour differs from basic revised theory.

5.2. Sound level behaviour under balcony overhangs

A study of behaviour under balcony overhangs [12] indicated that behaviour of the early sound relative to revised theory for overhung seats is haphazard, whereas the behaviour of late sound was consistent in that levels were reduced under overhangs. The measurements in the Royal Festival Hall [3] are characteristic in this respect.

Idealised behaviour for late sound under a balcony overhang (dashed line) is shown in Fig. 4. (The dotted line shows possible behaviour towards the rear of a balcony overhang; the probable cause of this is additional reflections from the wall etc. behind the overhung seating.)

Fig. 5 illustrates the likely reason for the late sound decreasing under overhangs. The angle θ is the vertical angle of view. One assumes that the sound field in the body of the auditorium is diffuse; as one moves to seats more overhung, the angle decreases and less

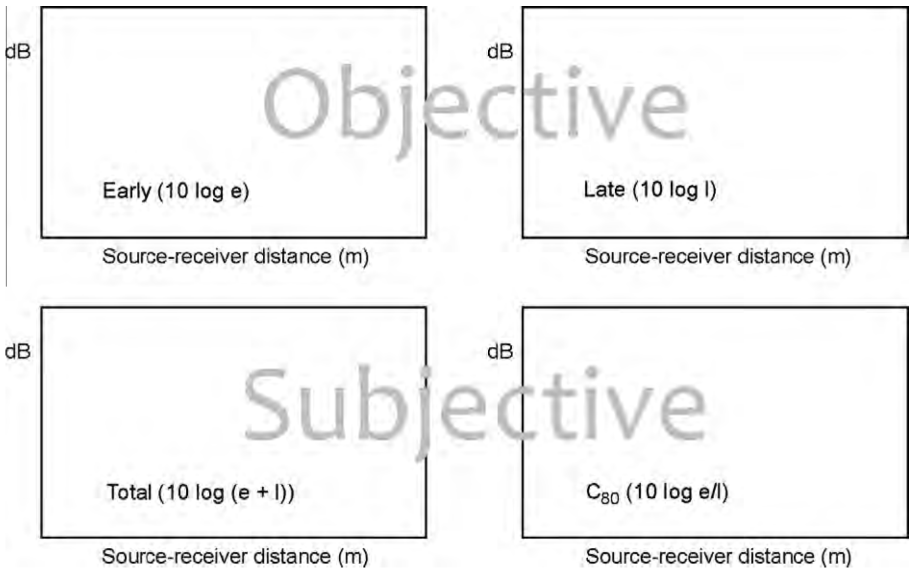

Fig. 3. Proposed graphs for Temporal Energy Analysis.

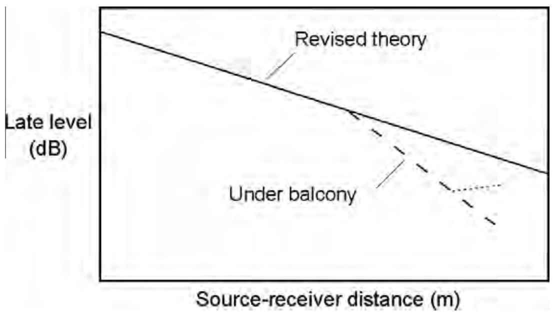

Fig. 4. Simple model for behaviour of late sound under a balcony overhang (dashed line). The dotted line shows possible behaviour towards the rear of the overhung seats, due to reflection from the rear wall.

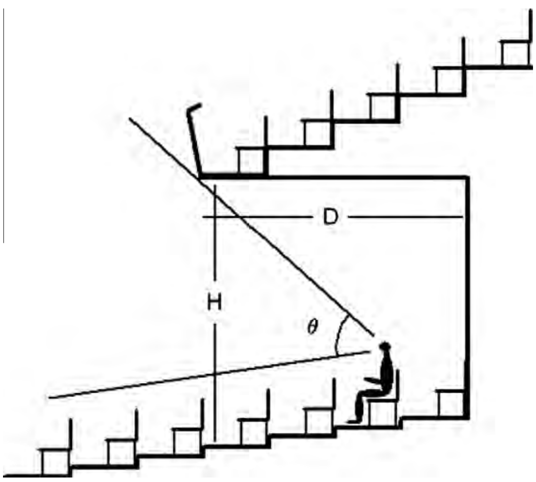

Fig. 5. Section through a balcony overhang with relevant geometrical quantities.

late sound reaches the listener. For acceptable balcony overhangs and minimal effect on sound levels, Barron has proposed [12] a minimum value for the angle of view of 40°. Beranek [13] proposed that the ratio of depth (D in Fig. 5) to height (H) as a parameter; D/H should not be more than 1.0.

5.3. Early decay time shorter than reverberation time

In a few concert halls, the early decay time (EDT) is significantly less than the reverberation time. The cause of this behaviour in these halls is generally that room surfaces have been angled to direct strong early reflections onto audience, what may be called directed reflection sequence halls [7,14]. Examples of such halls are the Christchurch Town Hall, New Zealand and the Michael Fowler Centre, Wellington, New Zealand [7]. The EDT is measured over the first 10 dB of a decay, which corresponds to the first 330 ms for a reverberation time of 2.0 s. It is not surprising that in these cases, agreement between measurement and revised theory is better if the mean EDT in seats not overhung is substituted for the reverberation time (RT) in the theoretical formulae. This is illustrated in Fig. 6 for the case of the total sound level in the Michael Fowler Centre, Wellington, New Zealand, where the ratio of EDT/RT is 0.83. One observes better agreement in Fig. 6 between measurement and theory when the EDT is used in the theoretical formulae. (This consideration does not apply to the four cases reported in the next section.)

One might ask, why is the reverberation time used in the revised theory formulae rather than EDT? This is basically because

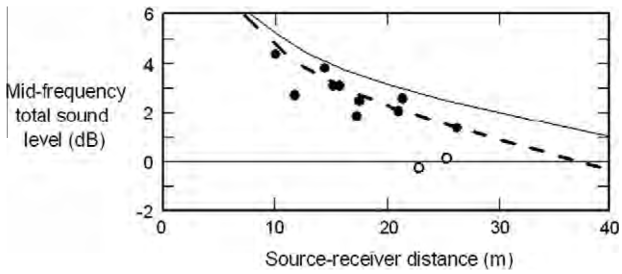

Fig. 6. Total sound level in the Michael Fowler Centre, Wellington, New Zealand. The solid line is the revised theory prediction using the reverberation time, while the dashed line uses the mean EDT instead of the RT. Open dots (o) refer to overhung seats.

often the EDT is not known, whereas reverberation time is more commonly predicted or measured.

5.4. Absorbing material in the stage area

It has already been mentioned in Section 3.1 that sound levels for the audience are reduced by the presence of (absorbing) seating or performers on stage. When absorbing material is added near the source position, it results in a small reduction in reverberation time as would any added absorbing material but this does not influence assessment compared with revised theory. However due to the large solid angle it subtends at the source, absorbing material in the stage region also results in reduced levels (both early and late) relative to revised theory in the audience area [2]. Adding absorbing material to a large concert hall being used for classical concerts is generally not recommended; it is more commonly encountered in smaller halls. Additional absorbing material in the stage area has not been added in any of the four halls discussed below.

6. Analysis of four concert halls

Four case studies of English concert halls are considered here using the analysis scheme proposed above. In each case, the measurements were made in the unoccupied halls. As presented in Figs. 7–10, the results have been corrected for the RT change which occurs with an audience present. All objective measurements were made between 1982 and 1984; in three out of four halls, modifications which are acoustically significant have since been made. For this comparison, results in Ref. [2] can be consulted, which relate deviations from revised theory to physical features of the halls concerned. Each of the halls below is illustrated with plans and photos in Ref. [7].

6.1. Wessex Hall, Poole

The Wessex Hall has 1590 seats and was opened in 1978. In plan it is parallel-sided and in long section the Stalls are raked; there is a single balcony with minimal overhang. A distinguishing feature is the treatment of the side walls above the level of the balcony soffit; these follow a wavy profile in plan and are built of bricks that have been laid to produce a scattering surface. Most of the side walls are treated in this way and one can expect that they contribute to good diffusion.

In Fig. 7, one finds reasonable agreement between measured values and revised theory for all quantities. In the case of the early sound, measured sound levels at the rear are a little low. This may be a consequence of the scattering side walls and mildly scattering ceiling [2]. Good agreement is observed for the late sound, though levels at the rear are also a little low. These low levels at the rear inevitably reappear for the total sound; all total levels are however above the subjective criterion of 0 dB. If during the design phase, one had observed these low levels at the rear, it would have warranted investigation. Behaviour of the early-to-late sound index (C_{80} dB) appears more haphazard, but measured values lie within the recommended range of ±2 dB.

Revised theory predictions are based on three parameters: reverberation time, auditorium volume and source-receiver distance. Agreement with theory as presented in Figs. 7–10 here is therefore independent of the actual reverberation time (RT). In the Wessex Hall at the time of measurement the mid-frequency reverberation time was 1.55 s, which is certainly short. Subsequently, the RT has been raised by reducing absorption by both the wavy walls and the seats. At the time of these renovations (2001/2), the name of the hall was changed to the Lighthouse Concert Hall.

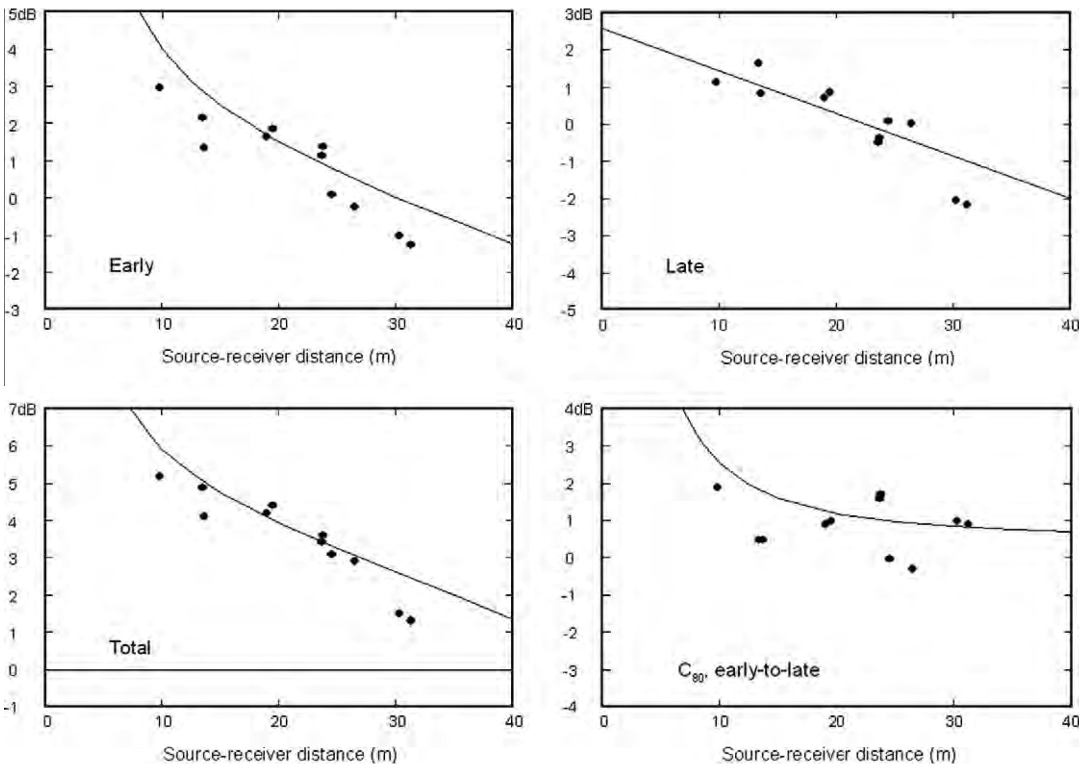

Fig. 7. Values of the early, late, total and C_{80} levels in the occupied Wessex Hall, Poole, measured in 1982. Lines represent values according to revised theory.

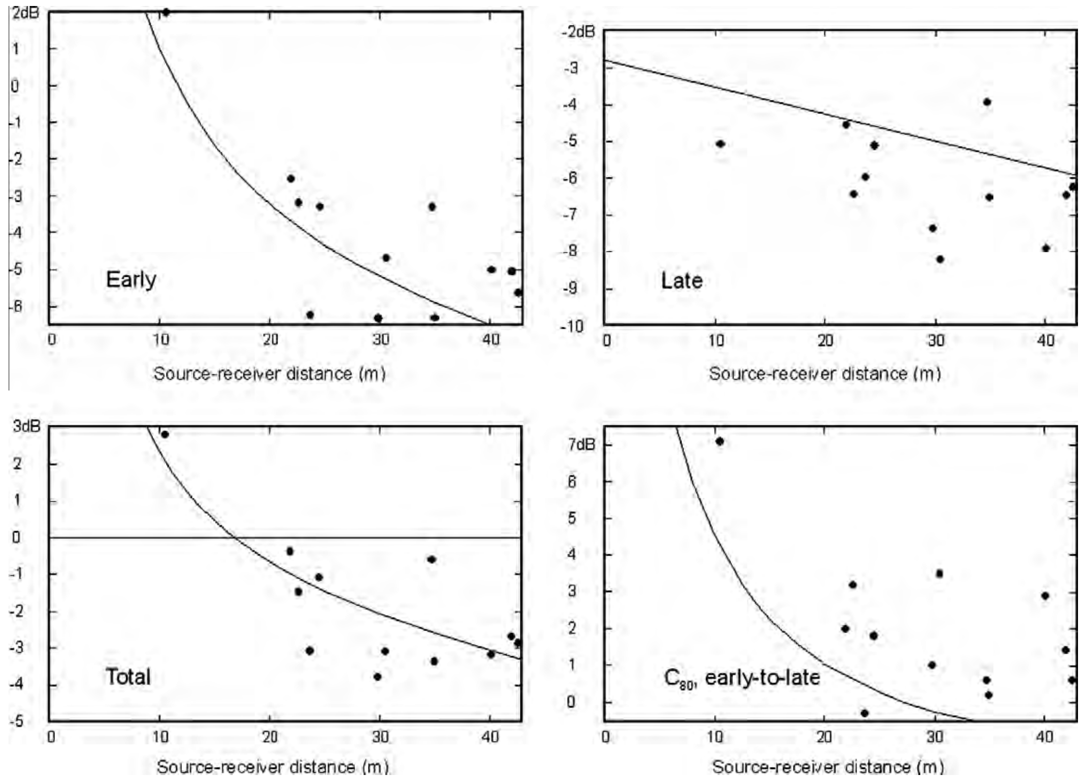

Fig. 8. Values of the early, late, total and C_{80} levels in the occupied Royal Albert Hall, London, measured in 1982. Lines represent values according to revised theory.

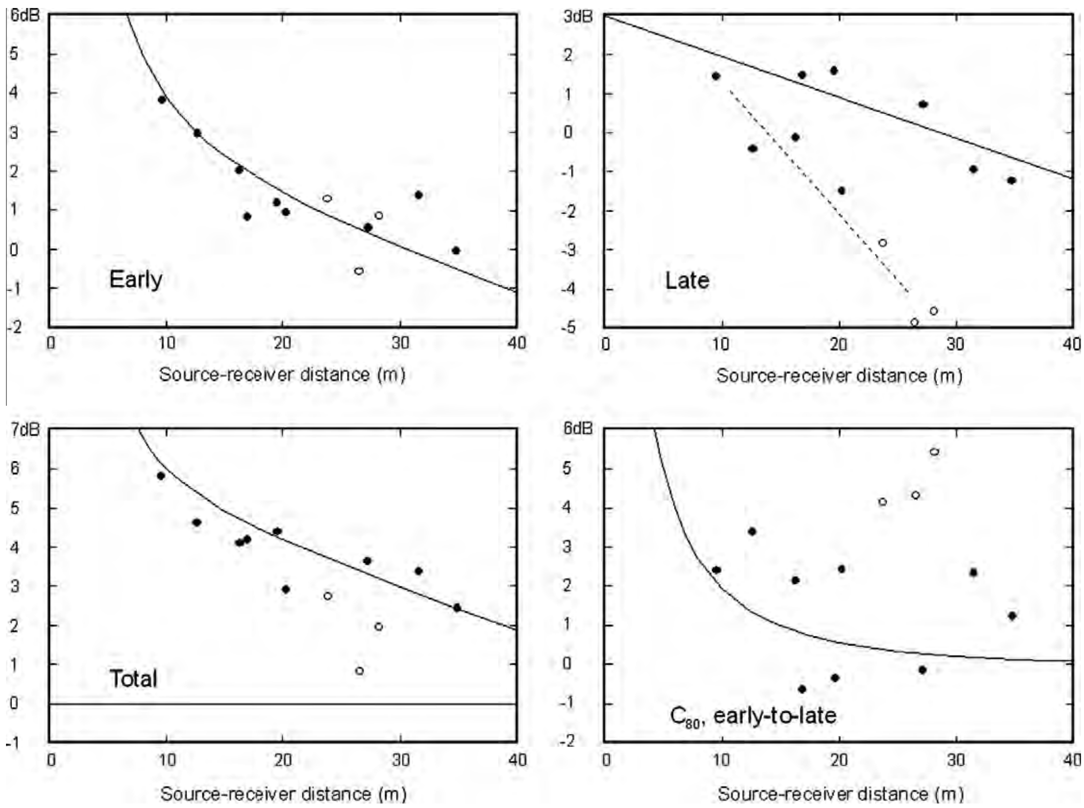

Fig. 9. Values of the early, late, total and C_{80} levels in the occupied Colston Hall, Bristol, measured in 1982. Lines represent values according to revised theory. Open circles (o) correspond to seat positions below the balcony overhang. The dashed line in the late sound graph illustrates how levels for positions in the Stalls have a roughly linear trend.

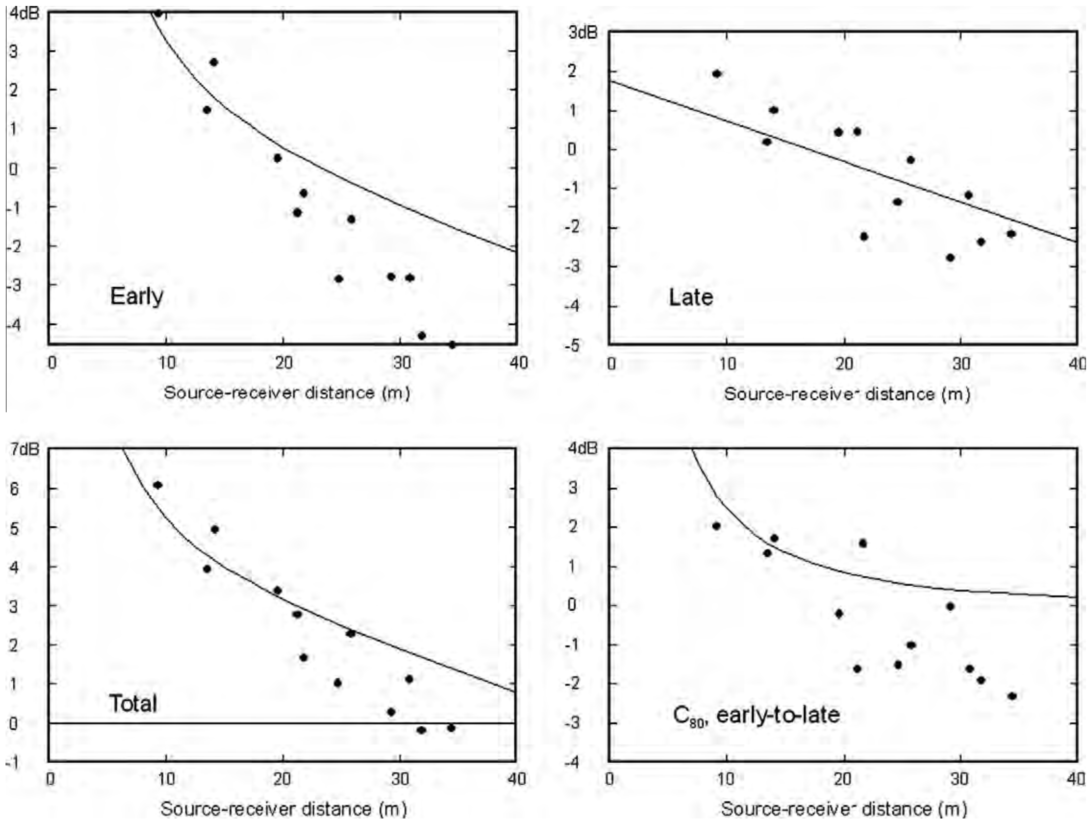

Fig. 10. Values of the early, late, total and C_{80} levels in the occupied Barbican Concert Hall, London, measured in 1984. Lines represent values according to revised theory.

6.2. Royal Albert Hall, London

Completed in 1871, the Royal Albert Hall was not specifically designed for music performance, indeed the contemporary Engineer magazine considered it "wrong for anything but gladiatorial combat"! The elliptical plan form has the potential for focussing and the large concave dome created a massive echo delayed about 170 ms. Focussing by the dome has been mostly suppressed by the combination of absorbing treatment and 134 suspended reflecting saucers. Overall the biggest acoustic issue now is the sheer size of the hall and seat capacity of over 5000. The measurements displayed here were taken in 1982; the hall underwent major refurbishment between 1996 and 2003.

Fig. 8 shows that levels in this hall are highly scattered, which is perhaps not surprising given the inappropriate acoustic design. The early sound is on average 0.8 dB greater than equivalent theoretical values, whereas the late sound is on average 1.0 dB less than equivalent theoretical values. For the total sound, one observes that measured results for all positions beyond a source-receiver distance of 20 m are below the criterion of 0 dB. This figure however shows that theory predicts this behaviour beyond 17 m. The low sound levels are therefore a consequence of the total acoustic absorption of the hall, which is primarily due to the excessive audience capacity and thus excessive total absorption.

Turning to the early-to-late index (C_{80}), at all but one measured location the measured values are larger than theory. This is inevitable given the high early energy and low late energy. Values at several positions are above +2 dB, indicating high clarity at the expense of reverberance. These are surprising observations given the long occupied mid-frequency reverberation time of 2.4 s. Not enough sound is contributing to the reverberant field and reaching the audience, though providing a rational explanation of this behaviour would be far from easy in this space.

6.3. Colston Hall, Bristol

The Colston Hall of 1951 is contemporary with the Royal Festival Hall in London and its acoustics were due to some of the same consultants. In both halls the side walls are parallel and there is a single balcony. But whereas the Festival Hall was a wholly new construction, the Bristol hall was built within its predecessor's shell, resulting in a modest 24 m width but required to seat 2120. This was 'handled' by having an excessive balcony overhang as in the Festival Hall. In the London hall the balcony front is straight facing the stage, whereas in the Colston Hall, the balcony extends down the side walls rather like a series of large boxes. Its occupied reverberation time is 1.7 s.

In Fig. 9, behaviour of the early sound is close to revised theory, though around 30 m there is one loud position in the balcony and a quiet position under the balcony overhang. The late sound however shows striking behaviour: points divide into two groups. One set starting with the position at 10 m from the source 'follows' a steep line (dashed in Fig. 9) and another set follows revised theory. The first set contains all the positions in the Stalls, the second set is seats in the balcony. In this hall there is an extreme example of the behaviour under balcony overhangs; note that the early sound is not influenced in a similar way.

In late energy terms we have a subdivided acoustic space. The feature which distinguishes the Bristol hall is that the balcony steps down the side walls in a series of 'open boxes' extending up to the front of the stage. This literally creates a subdivision of the majority of the auditorium in long section. Though a sensible approach in architectural terms, it has serious acoustic disadvantages.

For total sound level, the levels under the balcony become low, particularly towards but not quite at the back of the overhung seating. At these seats, high values of objective clarity are observed and one would expect a low sense of reverberation to be perceived here. This behaviour contributes to large variations of objective clarity in this hall.

6.4. Barbican Concert Hall, London

The Barbican Concert Hall in the City of London opened in 1982 with a seat capacity of 2026. Seating is subdivided into three levels one behind the other with no balcony overhangs. In overall dimensions it has a modest maximum height of 18 m and large maximum width of 43 m. The unusual feature of the hall is related to structural support of the ceiling. Several halls exist worldwide where the structural support is included within the acoustic volume but open steel trusses are usually used which have minor acoustic implications. In the Barbican Hall two pairs of solid concrete beams 3.7 m deep run along and across the ceiling. The hall's occupied reverberation time was 1.6 s. The objective data used here dates from 1984; remedial measures were undertaken in the hall between 1994 and 2001 to improve the acoustics.

Examination of the behaviour of early sound indicates an unusual trend: the early level decreases at a much faster rate as a function of source-receiver distance than expected, with a roughly linear relationship. This results in a particularly wide overall variation in early level. The late level on the other hand behaves as expected but with two particularly low values 22 and 29 m. The effect of this on the total sound is to produce several low values, below the 0 dB criterion in two cases. Again for the total sound there is a roughly linear relationship with distance at a greater slope than revised theory. The lack of early energy has the effect of leaving several positions towards the rear of the hall with low levels of objective clarity.

It seems very likely that the cause of the early sound behaviour in this hall is a lack of reflections from the ceiling. Spaces between the ceiling beams are relatively scattering in this hall but this is not sufficient to overcome the shadows created by the beams themselves.

7. Conclusions

Revised theory has been shown at mid-frequencies to match average behaviour of total sound level in concert halls [7]. It was also shown to match the levels of the early (0–80 ms after the direct sound) and late (>80 ms) sound [2]. The proposal presented here is that there is merit in inspecting the behaviour of the early, late and total sound levels plus the early-to-late index as a function of source-receiver distance and comparing this behaviour with expectations from revised theory. This procedure may be called a Temporal Energy Analysis.

The physical determinants of the early and late sounds are rather different: the early is predominantly determined by the direct sound and individual early reflections, whereas the late sound is influenced by the diffusion of the reverberant sound field. The behaviour of the early and late sound can thus frequently be related to the physical design of a concert hall. The early and late sound govern the total sound level (sum) and early-to-late index (difference), which are related to subjective loudness and clarity respectively.

The four case studies presented indicate the variety of behaviour found in actual concert halls, with the following examples: close agreement with revised theory, highly variable levels with position, divergence of late sound compared with theory and divergence of early sound compared with theory. The range of behaviour in concert halls is far from limited to these four; Temporal Energy Analysis shows that most concert halls 'have a story to tell'.

In practice, a simple analysis procedure is to highlight measurement positions where the difference between measured and predicted is more than 1 dB. If possible, the cause of the deviation should then be related to the hall design. This raises the question of whether deviations are subjectively significant beyond meeting the criteria for sound level and objective clarity. One issue not covered by analysis of sound level is the degree of diffusion.

Is behaviour according to revised theory optimum? The answer to that may be that revised theory behaviour is unlikely to be criticised subjectively. But strict agreement with revised theory predictions may not guarantee the best acoustics. In several halls here, deviations from revised theory have been associated with subjective shortcomings. However there are possible situations where deviations might be subjectively desirable, for instance a raised early sound might enhance clarity and intimacy, particularly valuable if the EDT is longer than usual.

Revised theory involves just three parameters: source receiver distance, auditorium volume and reverberation time. Agreement between theory and measurement is sometimes better if the early decay time (EDT) is substituted for the reverberation time.

Appendix A

For revised theory, the impulse response is divided into three components: the direct sound, the early reflected sound with a delay of less than 80 ms and the late sound after 80 ms. The reference level, L_0, is the direct sound level at a distance of 10 m from the omni-directional sound source. The direct sound energy, d, is determined by the source-receiver distance, r, as in the traditional relationship, whereas the early reflected energy, e_r, and late energy, l, are also functions of reverberation time, T, and auditorium volume, V:

$$d = 100/r^2$$

$$e_r = (31,200T/V)e^{-0.04r/T} \cdot (1 - e^{-1.11/T})$$

$$l = (31,200T/V)e^{-0.04r/T} \cdot e^{-1.11/T}$$

The term $31{,}200T/V$ is a function of 1/(total acoustic absorption) modified by using the Sabine equation.

The total sound level, $L - L_0$ (=G, strength), and early-to-late index, C_{80}, are then:

$$L - L_o = G = 10 \cdot \log(d + e_r + l)dB$$

$$C_{80} = 10 \cdot \log[(d + e_r)/l)]dB$$

The following presents a procedure for correcting values of C_{80} and G for the change in reverberation time from unoccupied to occupied conditions. The correction procedure relies on revised theory.

If the superscript "th" is used for the theoretical value according to revised theory above, while the subscript "o" is for occupied and "u" is for unoccupied conditions, then the correction formula for objective clarity is:

$$C80_o = C80_u + C80_o^{th} - C80_u^{th}$$

To correct the total sound level, G, it is assumed that the direct sound level corresponds to theory. The correction procedure is to convert the total sound level to energy and subtract the theoretical direct sound energy to give the reflected energy. This is then multiplied by the ratio of theoretical reflected energies $(e_{ro}^{th} + l_o^{th})/(e_{ru}^{th} + l_u^{th})$ to correct for the reverberation time change. To give the corrected total sound level, the theoretical direct sound energy is added to this modified reflected energy and the sum is converted into level by taking logarithms. Because of the seat-dip effect, this procedure is not appropriate for low frequency total levels.

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