OBJECTIVE ASSESSMENT OF CONCERT HALL ACOUSTICS

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1 INTRODUCTION

With the introduction of objective measures relating to subjective characteristics for listening to classical music in ISO 3382[1], most new auditoria are now tested in some sort of model, either computer simulation model or scale model. An alternative is to test by auralisation, an approach more valued by some than others! 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 a 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 offers a technique for assessing acoustic behaviour which complements approaches that are already in use. The following discusses the rationale behind and the use of 'temporal energy analysis' for assessing concert spaces.

2 SUBJECTIVE CONSIDERATIONS

Though the acoustic character of a concert hall is often discussed as an overall characteristic, 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[2], and apparent in this author's subjective study of British halls[3]. At least three groups have been identified: those that like reverberance (sense of reverberation), those that like acoustic intimacy and those that above all prize high clarity.

If one wishes to buy a good bottle of red wine, does one ask advice from someone who always drinks white wine? Fortunately this metaphor does not appear to entirely apply to concert hall listening. For the trained ear it seems that all important subjective characteristics can be appreciated and assessed, even though individual preference varies. But one does need to question how suitable it is for one consultant/listener to impose their own preferences on a concert hall design?

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 inappropriate. Reverberation time is the exception here since it usually 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]. It is important never to lose sight of the fact that current objective measures are not perfect; they are not perfectly 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[4]; for modest RT changes they are all probably equivalent.

Effects of an orchestra on stage are also significant; 'musicians' should be included in models. This and other issues associated with objective measurement are discussed in[4].

3.2 Optimum values for objective measures

A full objective analysis of a concert auditorium should involve measurements over at least five octaves (125 to 2000 Hz) and over a reasonable number of seat positions, between 10 and 20 positions for a large auditorium. With five objective measures (reverberation time, EDT, C_{80}, lateral fraction, LF, and total sound level, G) a lot of data is generated. 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 (corrected for RT if appropriate) is to compare measured values with ranges of acceptability, as shown in Table 1.

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

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

In the case of total sound level, a more sophisticated criterion related to loudness assessment has been proposed[5]. Other methods of assessment for individual measures are given in[4], such as considering the ratio of mean EDT to RT.

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[6], also summarised in reference 7.

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, while the reflected sound is assumed to be constant throughout the space. Barron and

Lee[6] proposed that the reflected component is also a function of source-receiver distance. They proposed the model that the direct sound is as previously and that the decay is linear with a slope according to the reverberation time. However the reverberant decay can only begin when the direct sound arrives. Figure 1 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.

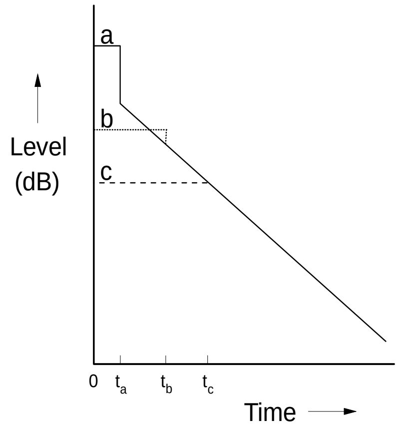

Figure 1. Integrated impulse curves at three receiver distances from a source in a room according to revised theory. Here, t = 0 is the time when the sound was emitted from the source, t_a is the direct sound arrival time at position A close to the source. Positions B and C are progressively further from the source.

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. Barron and Lee[6] 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 an acoustically diffuse space[8].

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. The temporal division between early and late for music spaces 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 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 in music auditoria with an omni-directional source are assumed.

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

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

With two equations and two unknowns, the early level (10 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 is concert hall spaces can often be gained. In this paper, mid-frequency behaviour is considered only, using mean values for the octaves 500, 100 and 2000 Hz.

The advantage of considering the early and late sound independently is that they are physically 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. The case of balcony overhangs illustrates this well, as discussed below.

5 TEMPORAL ENERGY ANALYSIS

5.1 Analysis procedure

The proposal is that sound behaviour within an auditorium can be clarified by presenting 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, Figure 2. Revised theory has two parameters determining predictions: the hall volume and reverberation time. (Where the EDT differs significantly from the RT, the mean EDT for seats not overhung should be used instead of the RT.) All figures have the decibel scale with the same range of 8 dB.

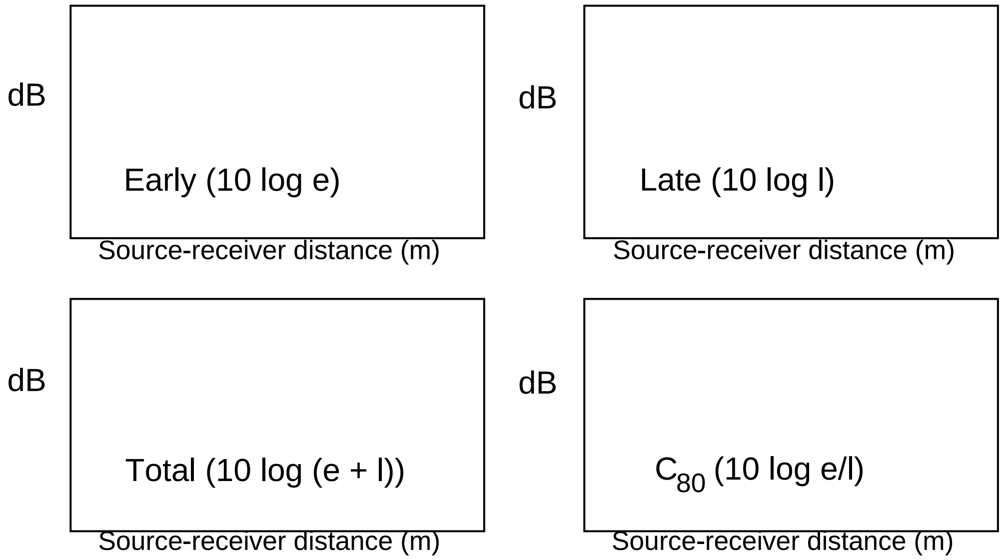

Figure 2. Proposed graphs for temporal energy analysis.

The upper part of the diagram is concerned with the interplay between hall design and acoustic consequences. 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. The next section considers results for an actual concert hall before discussion of behaviour at seats under balcony overhangs. The three halls considered below are reviewed in reference 7.

5.2 Royal Festival Hall, London (1982)

Figure 3 shows the temporal energy analysis of the Royal Festival Hall measured in 1982. The hall has since undergone major refurbishment reopening in 2007. What Figure 3 demonstrates is that at the time of measurement, the early sound levels were close to revised theory expectations. The situation is similar for the late sound except for the two positions measured under the balcony overhang (open circles in Figure 3), where lower late levels are found. Agreement with revised theory is also good for the total level and C_{80} but the overhung seats have a low total level and high objective clarity is observed at the most overhung seat.

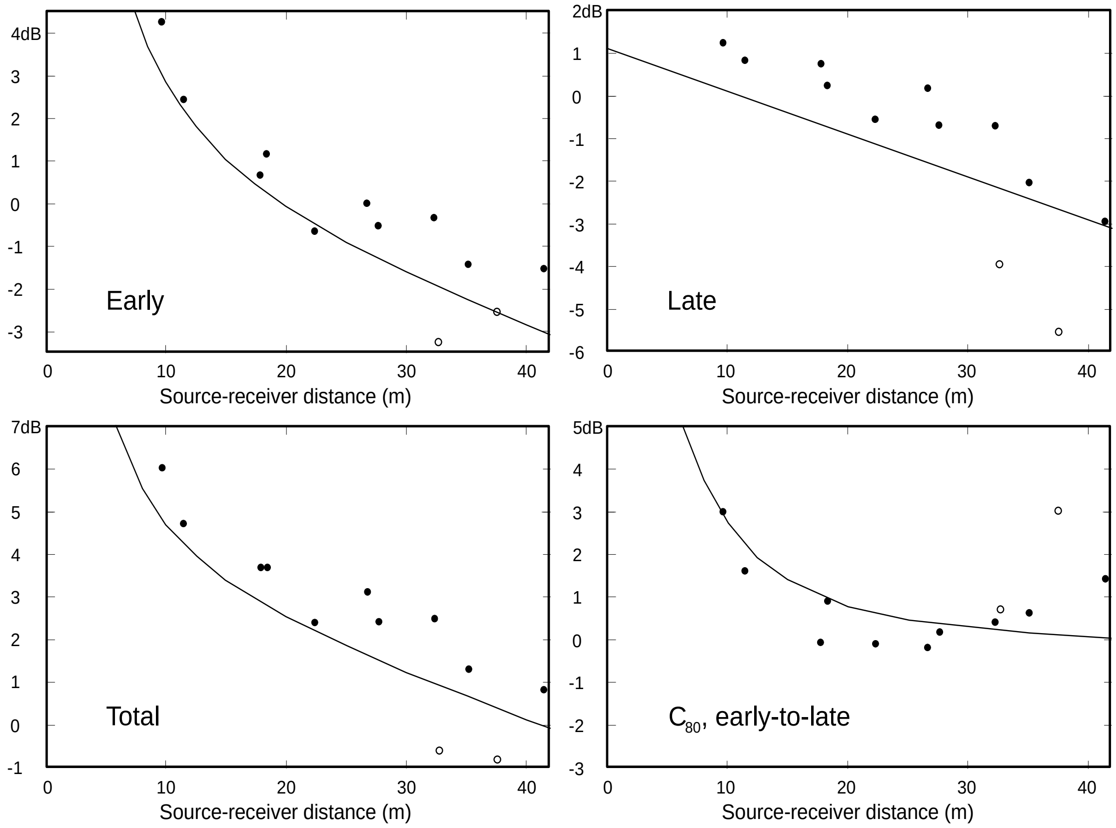

Figure 3. Values of early, late, total and C_{80} levels in the unoccupied Royal Festival Hall, London, measured in 1982. Lines represent values according to revised theory. Open circles (o) represent measured values at seats below the balcony.

5.3 Sound level behaviour under balcony overhangs

A study of behaviour under balcony overhangs[9] indicated that behaviour of the early sound relative to revised theory is haphazard, whereas the behaviour of late sound was consistent in that levels were reduced under overhangs. The measurements in the Royal Festival Hall are characteristic in this respect.

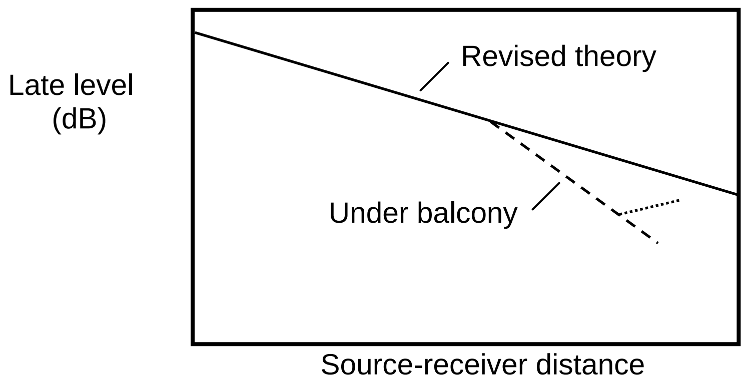

Figure 4. Simple model for behaviour of late sound under a balcony overhang (dashed line). The dotted line shows possible behaviour towards the rear of the overhung seats.

Idealised behaviour for late sound under a balcony overhang (dashed line) is shown in Figure 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.

Figure 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 late sound reaches the listener. For acceptable balcony overhangs, Barron has proposed[9] a minimum value for the angle of view of 40°. Beranek[10] proposed that the ratio of depth (D in Figure 5) to height (H) as a parameter; D/H should not be more than 1.0. The values for the two positions in the Royal Festival Hall are θ = 25° and 18° and for the overhang itself D/H = 3.1.

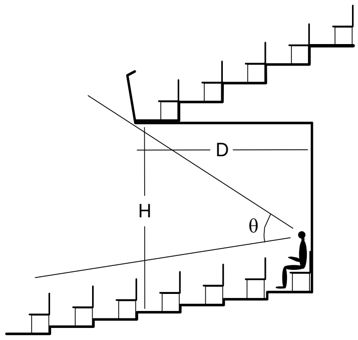

Figure 5. Section through a balcony overhang with relevant geometrical quantities.

5.4 Analysis of two further concert halls

5.4.1 Colston Hall, Bristol

The Colston Hall was completed in the same year 1951 as the Royal Festival Hall in London and in both cases the pressure to keep audience numbers up led to excessive balcony overhangs (both have single balconies). In Figure 6, behaviour of the early sound is close to revised theory, but for the late sound the points divide into two groups: a set starting with the position at 10 m from the source which 'follows' a steep line and a set which follows revised theory. The first set contains all the positions in the stalls, the second set is seats in the balcony. In late energy terms we have a subdivided acoustic space. The feature which distinguishes the Bristol from the London hall is that in Bristol 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 a low sense of reverberation would be perceived here.

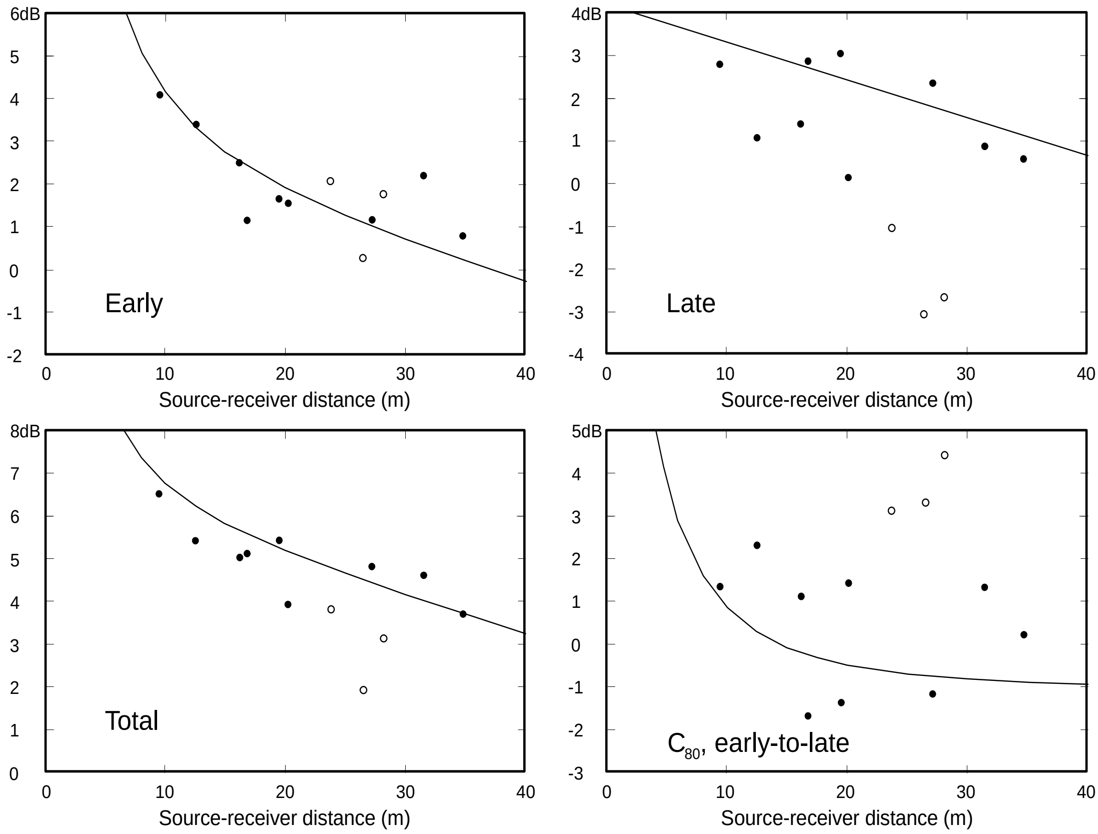

Figure 6. Temporal energy analysis of the unoccupied Colston Hall, Bristol, measured in 1982. Open circles (o) represent measured values at seats below the balcony.

5.4.2 Barbican Concert Hall, London

Measurements in the Barbican Concert Hall were made in 1984, well before renovations which were completed in 2001.

Whereas in the Colston Hall the late sound behaviour is somewhat extreme, in the case of the Barbican Concert Hall it is the early sound behaviour which is extreme. In Figure 7, the slope of the regression line through measured early sound levels would be much steeper than revised theory, whereas the late sound behaviour is much as expected. The causes for this are likely to be the substantial width of 43 m and the pairs of 3.7 m deep beams supporting the ceiling, which run across and along the hall[7]. The subjective consequences are poor loudness and low clarity at the rear of the hall.

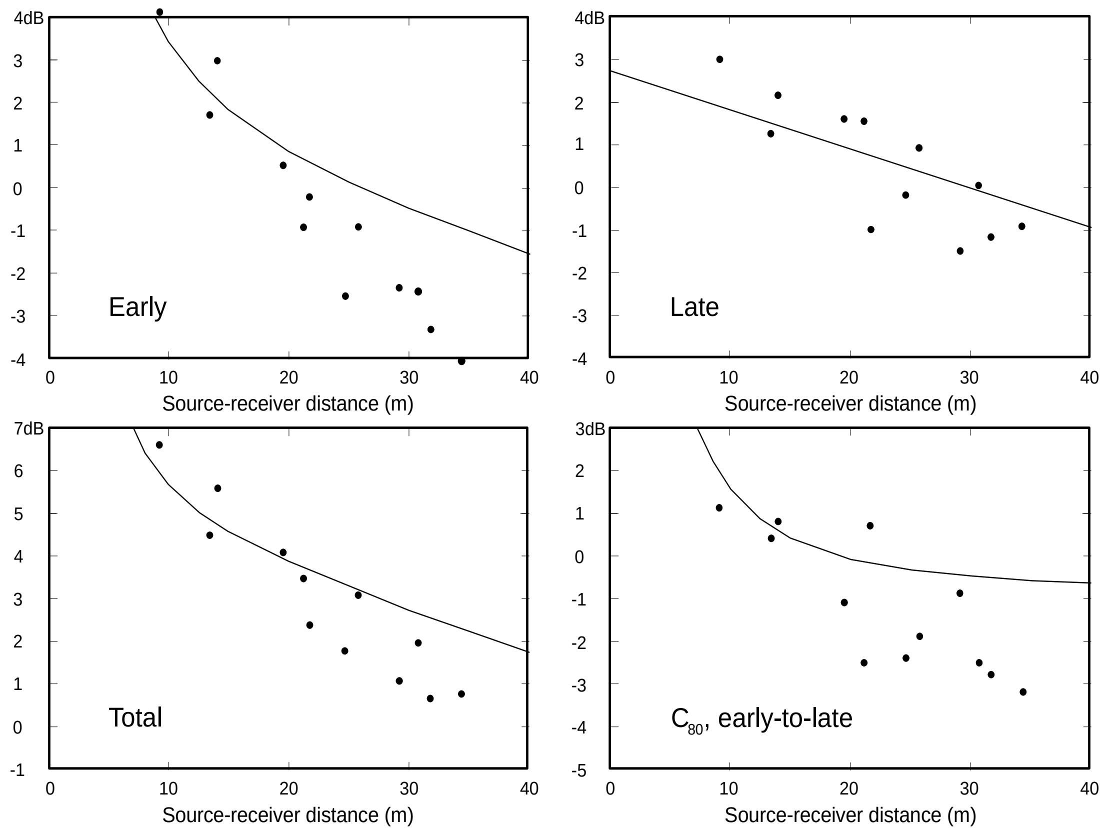

Figure 7. Temporal energy analysis of the unoccupied Barbican Concert Hall, London, measured in 1984.

6 CONCLUSIONS

In the author's experience, examination of objective behaviour in terms of the early, late and total levels and the early-to-late sound index (C_{80}) provides valuable insights into the interplay between geometrical design of concert halls and the acoustic consequences. For design development using either computer or scale models, temporal energy analysis can highlight seating areas where acoustic quality may be different. The fact that at a measured position there is agreement with revised theory or not does not necessarily indicate good or poor acoustic quality, but the proposed analysis at least serves to highlight seat positions where careful decisions may be needed.

Temporal energy analysis can offer insights into the following:

- Overall geometrical design
- Balcony design
- Causes of low (total) sound levels and excess or inadequate objective clarity
- Uniformity of response throughout the auditorium
- Comparison with average behaviour for the volume and RT of the hall
- Areas of enhanced sound level (a possibility near the stage)

Temporal energy analysis says nothing about spatial acoustic effects (such as source broadening) and little about the state of sound diffusion. It only assesses mid-frequency behaviour though there are lessons to be learnt by similar analysis at low frequencies. And temporal energy analysis is simply one possible analysis tool among several.

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