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Using the standard on objective measures for concert auditoria, ISO 3382, to give reliable results

Mike Barron*

Department of Architecture and Civil Engineering, University of Bath, BATH BA2 7AY, UK

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Abstract: The current version of the standard ISO 3382 has now been in existence for seven years, yet for many the contents of Annexes A and B on newer measures remain confusing. A major issue is the use to which these measures are put. Where the 'new' measures for auditoria differ from other acoustic parameters is that they refer to a range of subjective effects, which are perceived simultaneously. Using the newer measures requires a good understanding of the multi-dimensional nature of music perception. Measurement data requires interpretation. When measurements are made in unoccupied auditoria, the data requires correction to the situation with full audience. Another issue is how to condense data measured across audience areas. The simplest approach is to present mean values of the different quantities, but this ignores the fact that many quantities vary significantly with location; the disappointment of sitting in a poor seat in an auditorium is no less for the knowledge that the overall mean is good. Several of these issues are discussed here with the aim of promoting more uniformity in the way the objective measures proposed in the Standard are applied by different research groups and companies.

Keywords: Auditorium acoustics, Concert halls, Reverberation time

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1. INTRODUCTION

The 1997 revision of ISO 3382 was titled "Measurement of the reverberation time of rooms with reference to other acoustic parameters" [1]. The previous version from 1975 concerned itself exclusively with reverberation time. The 1997 version is currently being revised into a Part 1 (the 1997 standard intended principally for performance spaces) and Part 2 for reverberation time measurements in ordinary rooms. The principle applied to Part 2 is that the accuracy of measurement in ordinary rooms can be less than in auditoria (mainly allowing for fewer source and receiver positions).

The following measures are defined in the 1997 standard:

reverberation time (*RT*) — main body of standard
sound strength (*G*) — Annex A
early decay time (*EDT*) — Annex A
balance between early and late arriving energy (C_{80} and others) — Annex A
early lateral energy measures (*LF* and *LFC*) — Annex A
inter-aural cross correlation coefficient (*IACC*) — Annex B

This paper will restrict itself to concert hall measurements and will be concerned principally with the newer measures from Annex A.

2. SUBJECTIVE CRITERIA

There are many verbal expressions used for subjective response to live music performance. It is certain that further subtleties remain to be resolved. At least eight subjective qualities are currently mentioned regularly, as listed in Table 1 together with recommended objective measures. Listeners with some experience of completing questionnaires can usually comment on each of these subjective qualities. There is substantial evidence however that listeners vary in their preferences, so that they select different criteria when making an overall judgement. Subjective studies to date conclude that listeners subdivide into at least three groups: those that prefer either clarity or reverberance or intimacy above other concerns [2, p. 188]. It is clear that a simplistic interpretation of the significance of the measures found in ISO 3382 is unwise.

As shown in Table 1, what was often called spatial impression is now understood to comprise two separate

*e-mail: m.barron@bath.ac.uk

Table 1 Subjective qualities in concert halls and their possible objective correlates.

Subjective quality	Objective measure
Clarity	Clarity Index (C_{80})
Reverberance	Early decay time (*EDT*)
Intimacy	Total relative sound level (*G*)
Source broadening	Early lateral energy fraction and sound level
Listener envelopment	Late lateral level
Loudness	Total sound level and source-receiver distance
Brilliance	?
Warmth	Bass level balance?

subjective effects: source broadening and listener envelopment. Bradley and Soulodre [3] have proposed the late lateral level as a measure of envelopment. This is not included in the 1997 version of the standard but is under discussion for its revision. Some of this author's views on spatial issues are found in [4]. Total relative sound level is often referred to as 'Strength.'

An understanding of the significance of each of these proposed objective measures is enhanced by knowledge of their history [5]. The history is important because subjective experiments relating to concert hall listening are not straightforward and have generally been conducted by individuals working in different labs around the world on their own initiative (there being little economic imperative in this area). The measures listed in the Standard are the best currently available but could in most cases be improved. One major difficulty with the proposed objective measures is their interdependence. For instance, reverberation time influences C_{80}, *EDT* and *G*.

A mystery at present in concert hall acoustics concerns the subjective effects of substantial diffusing surfaces on the walls and ceiling of halls. There is some evidence that listeners prefer diffuse conditions [6] but this is not conclusive. The state of diffusion remains to be satisfactorily quantified and no suggestions have been offered for how we perceive diffusion.

3. OBJECTIVE MEASUREMENT PROCEDURES

3.1. Calibration

For two of the objective measures (*LF* and *G*), calibration is important for accurate results. For the measurement of the early lateral energy fraction (*LF*), measurement of the lateral portion is made with a figure-of-eight microphone, with the lateral energy being compared with that measured with an omni-directional microphone. The maximum sensitivity of the figure-of-eight microphone at the measuring frequencies should be measured relative to that of the omni-directional microphone: an anechoic chamber is likely to be the best location for this. Measured values should be corrected for these sensitivity differences.

Measurement of the total relative sound level (*G*) depends on knowing the source sound power, or the magnitude of the direct sound component. This should be checked regularly, preferably on site before auditorium measurements using a technique which enables the direct sound to be isolated.

3.2. Audience Occupancy

In several respects, the usual measurement conditions in halls differ from the performance situation. A frequent difference concerns occupancy, both in the audience seating and on the stage. The ideal is either to make occupied measurements or to include absorbers which simulate people, such as that proposed by Hidaka, Nishihara and Beranek [7].

In the case of measurements without audience, most concert halls fortunately have well-upholstered seating which, though never as absorbent as occupied seating, is almost as absorbent. It is likely that in most concert halls the correction of objective measures for the change of reverberation time is sufficiently accurate. Corrections should be applied to all measures except the spatial ones, as outlined in Sect. 6.1.

Typical magnitudes of corrections are four difference limen for *RT* and *EDT* and one and a half difference limen for C_{80} and *G*. These have been derived as follows from reverberation time data and difference limen for the various objective measures, as in Table 2. Occupied and unoccupied reverberation times of 17 concert halls are given by Hidaka *et al.* [7], Table 2. If the Vienna Musikvereinssaal data is omitted because some of its seating is hard, then the mean unoccupied and occupied *RT*s are 2.32 and 1.85 s, with a ratio of 0.80. With a difference limen of 5% for *RT*, this corresponds to four difference limen. A similar number of difference limen will apply to *EDT*; though the ratio of *EDT* to *RT* varies slightly [8], the ratio is independent of actual *RT* value. The author's revised theory for sound level in rooms (Sect. 7 below) allows typical values of C_{80} and *G* to be predicted: for the reverberation time change mentioned, the maximum change of C_{80} is 1.5 dB (for a source-receiver distance of 10 m) and for *G* is 1.6 dB (for a

Table 2 Possible frequency ranges for octave band measurements in concert halls and subjective difference limen after Bork [23].

Measure	Frequency range (Hz)	Difference limen
Reverberation time	125–4,000	5%
Early decay time	125–2,000	5%
Clarity Index (C_{80})	500–2,000	1 dB
Early lateral energy fraction, *LF*	125–1,000	0.05
Total relative sound level, *G*	125–2,000	1 dB

source receiver distance of 40 m). In both cases, this corresponds to changes between one and two difference limen.

3.3. Stage Occupancy

When one goes to make a measurement in a hall, one can either find the stage empty or occupied with chairs and music stands. Of these, the latter is definitely to be preferred. Ideally to match conditions with an orchestra, chairs on stage would be occupied; however unoccupied chairs and stands will partly obscure stage floor reflections, which are the exception rather than the rule for symphony orchestra performance. Measurement on an empty stage, with in many cases floor reflections, will of course be relevant to performances with small numbers of musicians.

The presence of chairs on stage also influences the measured sound strength in the auditorium and may easily reduce the sound level by a decibel or more; this is an example of the effect of absorption close to the source [9]. This has been observed in more than one location, most recently in a large concert hall that was measured on different days, on one occasion with 50 chairs on stage and the other with a bare stage (the source position was the same for both measurements, namely 2 m from the stage front). The average auditorium level difference was 1.0 dB [10]; that is about one difference limen. The ISO standard rightly specifies that the stage conditions should be carefully recorded.

3.4. Source Locations

The possible influence of stage floor reflections should also be taken into account when choosing sound source locations. For this author's measurements, the tendency has been to use a single source position on the hall centre line 3 m from the stage front. This location was chosen to minimise the chance of stage floor reflections to the audience occurring. With a full orchestra on stage, these reflections will be obscured for most musicians. A stage reflection can be expected to increase level by more than a dB; that is in excess of one difference limen.

Using just a single source position can of course be criticised since conditions are likely to vary with source position on the platform. However this seems a lesser risk than the inclusion of floor reflections for some source positions and not others. In other words, in the absence of chairs on stage, a single forward source position seems the best compromise, when one wants to measure conditions appropriate to an orchestra performing on stage.

3.5. Source Directivity

A much less manageable difficulty with objective measurements concerns the source. An orchestra occupies around 200 m^2 of stage with instruments which each have a complex directivity, which also changes depending on the note being played. The standard measurement technique is to use a single omni-directional source, usually a dodecahedron loudspeaker. To appreciate the artificiality of a single source, one needs to listen to anechoically recorded music played through an omni-directional source on a concert hall stage; it is a lifeless listening experience. No research into the significance of this issue appears to have been done.

3.6. Receiver Positions

The ISO standard is specific about the minimum number of microphone positions, depending on auditorium size. These should be distributed uniformly about the seating area. When measuring a symmetrical hall, if the decision has been made to measure with a source (or sources) only on the centre line, then microphone positions only in one half of the hall may be used. In this case microphone positions should not be within 1 m of the line of symmetry to avoid degenerate situations.

For audience conditions, there is no merit in measuring too close to the source where the direct sound dominates. In large concert halls a minimum source-receiver distance of around 10 m seems appropriate; this dimension is perhaps best expressed in terms of the reverberation radius (where the direct and reflected sound components are equal in level). The reverberation radius is a function of the total acoustic absorption; for concert halls with 10 m^3/seat and an RT of 2 s, the reverberation radius varies between 4 and 7 m for 1,000 to 3,000 seats. The suggested minimum source-receiver distance is thus between 2.5 and 1.4 times the reverberation radius and therefore in the region dominated by reflected sound.

4. MEASUREMENT FREQUENCIES

The ISO standard avoids being prescriptive about the appropriate frequencies for measurement. Nor does the standard say how results should be averaged to establish the overall clarity, or whatever, in a concert hall. It is recommended that measurements be taken in the six octave bands from 125–4,000 Hz. The standard suggests quoting results by averaging over pairs of octaves to give low, mid- and high frequency values. Bradley [11] uses this approach for timbre-related parameters.

There are however two complications that occur at the 4,000 Hz octave. Firstly the reverberation time etc. are sensitive to air absorption, determined by temperature and relative humidity. The main part of the standard states that temperature and humidity should be measured, which allows for correction of the reverberation time if measured with non-standard temperatures or relative humidities. The second difficulty at 4,000 Hz is that a typical dodecahedron loudspeaker (with a diameter in the order of 400 mm) becomes directional at this frequency. One can compensate for this difficulty by making several measurements with different orientations of the loudspeaker, but this is time-consuming. Behler and Müller [12] have solved this problem by using a separate 100 mm diameter dodecahedron for high frequency measurements.

The author [9,13,14] has tended to measure over five octaves 125–2,000 Hz and divide results into a bass region, 125–250 Hz, and a mid-frequency region, 500–2,000 Hz. The major differences between the bass and mid-frequency are different amounts and type of absorption (usually panel vs. porous absorption) and that the bass frequencies are affected by the seat-dip effect [2, pp. 19–21], for which the frequency of maximum absorption lies within the two octaves 125 and 250 Hz. Since individual octave measurements are influenced by interference, either constructive or destructive, except in the case of reverberation time it is preferable to use averages of several octaves where appropriate, as elaborated below.

This last point, about averaging octave results to reduce interference effects, does not apply in the case of most computer simulation programmes, since they usually ignore phase. To gain a result equivalent say to the average of 500–2,000 Hz, a computation at only 1,000 Hz may be suitable, as long as absorption coefficients etc. for 1,000 Hz are the average of those for the frequency range in question.

Some recommended frequency ranges for the different measures are included in Table 2 [15]. In the case of C_{80}, the literature is limited, though Beranek and Schultz [16] suggest that low frequencies do not contribute to clarity. Since low-frequency early sound levels are strongly influenced by the seat-dip effect, whose magnitude varies depending on seat location [13], whereas clarity is affected by other concerns, measuring C_{80} over the range 500–2,000 Hz looks appropriate. On the other hand, for the early lateral fraction there is significant evidence that low frequencies are important whereas high frequencies are less so [17–20].

Regarding quoting measured values, individual mean octave values can be used for *RT* and *EDT*. Individual *EDT* values at different positions can be quoted as mid-frequency and bass frequency values. For C_{80} the three-octave mean of 500–2,000 Hz can be used, while for *LF* the four-octave mean of 125–1,000 Hz is appropriate. Whether *G* should be calculated as a full-frequency average or split between bass and mid-frequencies depends on the situation in hand.

5. AVERAGING OF RESULTS OF DIFFERENT MEASUREMENT POSITIONS

The standard specifies that for halls with more than 2,000 seats at least 10 seat positions should be measured. With five or more measures at five or six octaves, a lot of data is generated. To make sense of this plethora of numbers, some averaging is appropriate.

5.1. Measurement Scatter

One issue relevant to measurement accuracy is the variation of objective quantities for small movements of the microphone [21]. To our knowledge, theoretical values of scatter only exist for reverberation time and total sound level (G). The measured scatter of reflected sound level in a model diffuse space is illustrated in Fig. 1. This topic is discussed in [22], which quotes the approximate theoretical standard deviation proposed by Lubman and Schroeder:

$$s_{G_r} = \frac{4.34}{\sqrt{\left(1 + \left(\frac{B \cdot T}{6.9}\right)\right)}} \text{ dB} \qquad (1)$$

where B is the bandwidth and T the reverberation time. This relationship provides a justification for averaging objective measures over several octaves, as mentioned above.

To experience subjective changes within concert halls it is usually necessary to move to a seat position several metres away, whereas objective data often changes between one seat and its neighbour. The relevant comparison is with subjective difference limen; limen listed by Bork [23] were included in Table 2. It is thus tempting to average over a few or many measurement positions. Averaging over blocks of audience seating has its place,

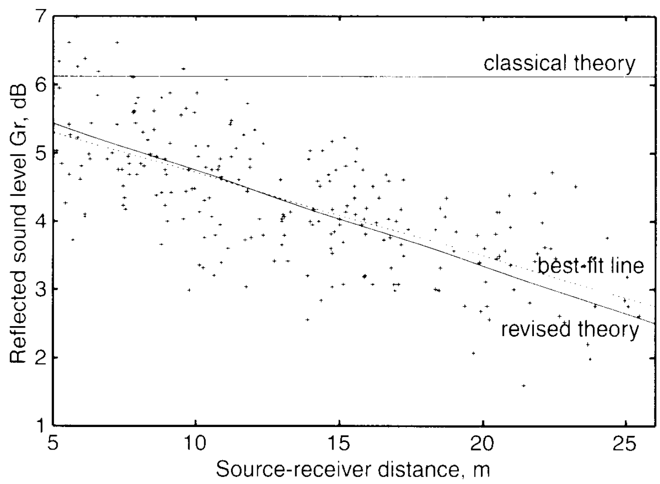

Fig. 1 Measured values of reflected sound level for 240 source-receiver pairs in a scale model diffuse space. Reflected sound level values are relative to the direct sound level at 10 m from the source. The notional model scale factor is 1:25; source-receiver distances are full-size equivalents as is the 500 Hz octave at which the measurements were made. Included on the figure are predicted values according to classical and revised theory [9].

but the extreme of presenting hall average values needs careful assessment.

5.2. Whole-Hall Averages

Beranek in his extensive survey of world concert halls [24] presents mean values for objective quantities and uses these to establish guidelines for concert hall design. While this limits the quantity of data one has to process, it tends to make extracting significant results difficult because the means do not differ much. For example, a comparison of two British halls, one much liked and the other with disappointing acoustics, is barely predicted by their mean objective behaviour [5].

When an objective quantity varies only little throughout a hall (or more precisely little more than the subjective difference limen), then it is appropriate to talk about the value of the quantity for the hall and work with the mean of the objective quantity. This is generally the case with reverberation time. If however the quantity varies significantly throughout the hall (relative to the difference limen), then the mean value is only representative of a small number of audience locations. The mean value says nothing about the spread of values, nothing about the best and worst seats. Most of the newer measures vary significantly within halls and there is usually a lot of overlap between measured values of quantities such as C_{80} between two halls. A satisfactory mean value only indicates a tendency for the quantity/quality to be satisfactory.

To give a simple example, the total relative sound level (G) typically varies about 4.0 dB between seats 10 and 40 m from the source in a large concert hall. This corresponds to about four difference limen. The mean value may apply to seat locations towards the rear of the Stalls but says little about the level in the highest balcony. It says little about the acoustic designer's ability to provide good acoustics throughout the auditorium. Including in presented data the variation within halls is more difficult but it indicates the full variety to be experienced within individual concert halls.

One way of deriving a single figure of merit for halls for a quantity such as C_{80} is to quote the fraction of values measured at different positions in a hall which fall within the preferred range for that quantity.

Where mean values are used for EDT and C_{80}, they are probably best calculated without including seats under overhangs (Sect. 6.8). Mean values of LF need not exclude these seats.

6. INTERPRETATION OF OBJECTIVE MEASURES

6.1. Correction for Reverberation Time Change

For tests in full-size halls, measurements of the newer measures are usually conducted with the hall unoccupied, whereas we are generally interested in concert conditions with a full audience. A measurement of occupied reverberation time is generally made soon after a hall opens. It is therefore appropriate to make corrections to other objective measures for the change in reverberation time between the unoccupied and occupied state. In the case of measurements in scale models, the model reverberation time is often slightly different to that expected in the real hall, probably because of small inaccuracies in the absorption coefficients of model materials. Again corrections are appropriate for RT change. The measures affected are EDT, C_{80} and relative level. Spatial measures such as LF and $IACC$ are little affected by RT change.

The following authors have suggested techniques for correcting for reverberation time: Hidaka *et al.* [7], Bradley [11] and Barron [2, p. 419]. Though the methods have different origins, they are likely to give similar results. The accuracy of the correction will decrease for larger reverberation time differences. When seating is well-upholstered, the RT change is modest and corrections are likely to be reasonably accurate. The discussion of criteria below will relate to figures following a reverberation time correction.

6.2. Simple Range Criteria

Many authors have provided recommended ranges for objective measures for concert hall listening. This author's recommendations based on objective and subjective surveys of concert halls are given in Table 3 [2, p. 61].

Under balcony overhangs, measured values tend to be lower (for EDT and G) and higher (for C_{80}), as discussed in Sect. 6.8 below. It may be argued that slightly less stringent criteria are applied for EDT and C_{80} in these locations. When objective data for a hall is displayed, there is a strong case for treating values from overhung seats separately. For the same reason, mean values are probably better taken omitting these locations — though the value of whole hall mean objective measures has been questioned in Sect. 5.2 above.

The following discusses more elaborate ways in which objective data can be analysed. In all cases apart from reverberation time, values vary throughout auditoria. By

Table 3 Recommended ranges for objective measures for concert halls.

Measure	Acceptable range
Reverberation time (RT)	$1.8 \leq RT \leq 2.2$ s
Early decay time (EDT)	$1.8 \leq EDT \leq 2.2$ s
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 (see text)

just assessing average values, a lot of detailed understanding is lost. Where frequency is not mentioned below, it should be assumed that mid-frequency values averaged over the three octaves 500–2,000 Hz are being considered.

6.3. Reverberation Time

Reverberation time varies little throughout a well-designed concert auditorium and usually the mean value can be assessed alone. Davy [25] has published expected standard deviations in reverberation time measurements, which can be used as an indicator of the diffuseness of individual halls. These relationships for expected deviation will be included in revisions of ISO 3382.

If a hall includes excessively deep or low overhangs, *RT* values will be less than in exposed seats. This should be seen as evidence of poor overhang design.

6.4. Early Decay Time

This measure is now thought to correspond more accurately with perceived reverberance than the tradition reverberation time. Though the reverberation time is very convenient, not least because it tends to be constant throughout halls, its subjective significance is now considered less important. Thus deviation from the *EDT* criterion should be seen as more serious than deviation from optimum reverberation time values outside the suggested range of 1.8 to 2.2 seconds. In particular, *RT*s in excess of 2.2 seconds are probably acceptable if *EDT* values are within the range 1.8–2.2 s.

Two global measures of *EDT* are worth calculating: the ratio of the mean *EDT* (omitting overhung seats) to the mean *RT* and the relative standard deviation of the *EDT* (standard deviation/mean *EDT*) [8]. The mean *EDT/RT* ratio takes values between about 0.8 and 1.1; it can be seen as a measure of the directedness of a design. If surfaces direct early reflections onto audience seating, this reduces the early decay time, giving a low value to the ratio. This is acceptable if the reverberation time is long, giving an *EDT* within the recommended range. On the other hand, there seems little virtue in having ratios which much exceed 1.0.

The relative standard deviation is a measure of uniformity and should have a value between about 0.08 and 0.12 [8].

In a well-designed hall with a diffuse field, there should be few observable trends in terms of variation of *EDT* with position. Performing a linear regression between measured *EDT* and source-receiver distance is worthwhile, with the preference being that there is no correlation. *EDT* values close to the source will be less because of the relatively strong direct sound; however for source-receiver distances in excess of 10 m, this effect is very small. The design features which cause serious deviations between the *EDT* and the mean *RT* are also discussed in [8].

6.5. Early-to-Late Sound Index (C_{80})

The first issue regarding C_{80} is the appropriate criterion. An early suggestion was made by Reichardt *et al.* [26] who provided criteria for two different musical types: classical music $-1.6 < C_{80} < +1.6$ dB and romantic music $-4.6 < C_{80} < -1.4$ dB. There are many halls which have no positions with C_{80} values below -1 dB, but it seems unlikely that they have excessive clarity. One might in fact argue that clarity cannot be excessive as long as it is not at the expense of other aspects, in particular reverberance.

The early-to-late index tends to be well-correlated (negatively) with *EDT*: a high C_{80} corresponds with a low *EDT* and *vice versa* [8]. In subjective terms, high clarity is often associated with low reverberance, as occurs for instance with a short reverberation time. (Interestingly though, in subjective surveys one tends not to find a strong inverse correlation, as in [15] and the Berlin study of Wilkens and Lehmann summarised in Cremer and Müller p. 589 [27].) C_{80} tends to be more sensitive to different early reflection sequences than does *EDT* and has higher values close to the source.

A frequent criticism of the early-to-late sound index is that it involves a sharp temporal division, which the ear does not itself make. However from experience of many measurements, this is rarely a problem in practice. The temporal division does however offer a very real advantage for analysis, in that it is then possible to investigate early and late sound levels independently. Often design details influence one component but not the other [9].

6.6. Early Lateral Energy Fraction (*LF*)

Applying the simple range of acceptability in Table 3 works better for this measure than for some others. No corrections are required for reverberation time change with *LF*. Smaller values tend to occur close to the source but there is in general no consistent dependence of *LF* on distance from the source [28].

The magnitude of the subjective effect, source broadening, depends not only on the fraction of early sound coming from the side but also on the music level. Music level depends on both the sound power of the combined musicians, the varying dynamic of the music and the 'gain' of the hall, or relative sound level. From work by Morimoto and Iida [29], the following was derived [30]:

$$\text{Degree of source broadening } (DSB) = LF + (\text{Early level})/60 \qquad (2)$$

Further confirmation of this relationship would be welcome. It is appropriate to apply an acceptable range for *DSB*. Tentatively, a minimum value for *DSB* of 0.1 can be proposed. The *DSB* determines the dynamic level of the orchestra (e.g. *piano* or *mf*) at which source broadening becomes perceptible [30,31].

6.7. Total Relative Sound Level/Strength (G)

Since sound level decreases significantly with source-receiver distance, the criterion of $G > 0$ dB may be too simplistic. Interestingly this criterion is compatible with two maximum values frequently quoted for concert halls: that the largest acceptable seat capacity is 3,000 and that the furthest seat should be not more than 40 m from the stage. On the basis of revised theory (Sect. 7), a hall with this size audience and a 2 s reverberation time would have a sound level of 0.7 dB at 40 m from the source [9].

The quietest seats tend to be those at the rear of the auditorium. If the level at these seats just fails the criterion, will loudness judgements be satisfactory at other positions in the hall with higher G values? There is interesting evidence about subjective judgements of loudness that suggests we relate judgements of loudness to distance from the source [32]. Perceived loudness was found to be positively correlated with source-receiver distance, whereas measured sound levels in halls are negatively correlated with source-receiver distance. The implication is that loudness is judged by listeners relative to expectations. A hall would therefore be judged quiet if the sound level was low for the source-receiver distance concerned. The total relative sound level may be above 0 dB but, because of the seat position concerned, it may still be judged too quiet.

The above argument suggests that a criterion for G should also depend on source-receiver distance. Revised theory matches average behaviour, so this is an appropriate basis for such a criterion. A hall with a volume of 30,000 m^3 and reverberation time of 2 s has a predicted level of 0 dB at 40 m according to revised theory. Levels as a function of distance for this hall are given in Fig. 2, which can be proposed as a more sophisticated minimum criterion than the simple $G > 0$ dB. (The equation of the line is $L = 10\log(100/r^2 + 2.08e^{-0.02r})$, where r is the source-receiver distance.)

6.8. Behaviour under Balcony Overhangs

Analysis of objective behaviour under overhangs [14] showed that the major effect was a reduction in late sound energy. This results in a reduction of *EDT*, an increase in C_{80} and a slight reduction in total level under overhangs. The major perceived change is likely to be a reduced sense of reverberation under overhangs. (A reduced sense of listener envelopment is a further likely effect.)

One approach to presentation of measured results for a hall is to divide measurement locations into exposed and overhung. The relationship of the overhung to the exposed is a measure of the suitability of the balcony design.

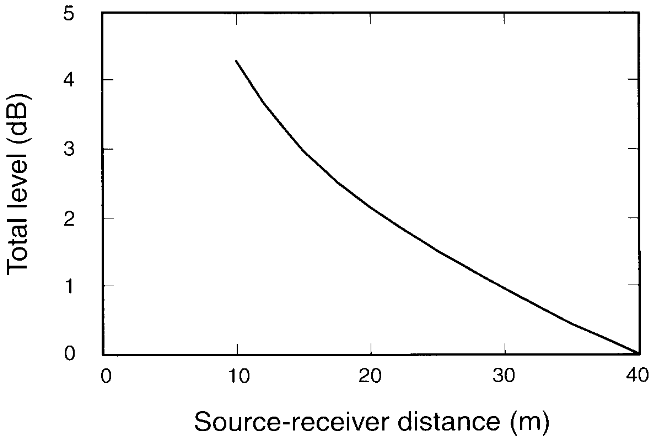

Fig. 2 Proposed minimum total sound level (re. direct sound at 10 m) in concert halls as a function of distance.

7. REVISED THEORY

An analysis of measurements of total sound level in concert auditoria [9] showed that traditional theory was inaccurate, in particular that the reflected sound level is not constant with position throughout a hall. Recent work [22] has shown that this behaviour also extends to diffuse proportionate spaces that do not have absorption concentrated on floor surfaces. A revised theory was proposed [9], which is based on an expression derived from a simple image model of a rectangular space. Revised theory uses the reverberation time, hall volume and source-receiver distance as parameters. This revised theory matches average behaviour well; for instance in the case of total sound level with an r.m.s error of around 1.0 dB.

Revised theory also allows the early and late level to be predicted. Comparison of measured with predicted values of the early and late sound components proves to be a valuable method for analysing acoustic behaviour in rooms, used for example by Bradley [33].

8. CONCLUSIONS

The objective measures included within ISO 3382 have the potential to significantly increase the quality of acoustic design but several pitfalls await the ignorant. To undertake measurements, the need for careful calibration and careful choice of source location were raised. Most measurements are made in halls unoccupied by audience, in which case correction for reverberation time change is appropriate. Stage occupancy also influences measured values with regard to the influence of a floor reflection and with regard to measured audience sound levels.

Averaging results over frequency bands is appropriate but averaging over all measurement positions to gain a hall mean value seems generally unhelpful, except in the case of reverberation time. Criteria for the various measures were discussed. In the case of the early lateral energy fraction (*LF*), looking at a combined measure including sound level looks valuable. For the total relative sound level (or Strength), a criterion which is a function of source/receiver distance has been proposed.

Using objective measures to assess acoustic design is fairly straightforward. To use objective measures for design development, it is important to understand the way design details influence each of the measures.

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Mike Barron graduated in 1967 from Cambridge University and moved to the Institute of Sound and Vibration Research in Southampton to start his acoustics training and begin post-graduate research. His research topic was the subjective effects of early lateral reflections in concert halls. The significance of early lateral reflections had been suggested by Harold Marshall and between 1971 and '73 Mike Barron worked with Harold Marshall at the University of Western Australia. After two years working as an acoustic consultant with Sandy Brown Associates in London, Mike Barron was invited in 1975 by Peter Parkin to set up an acoustic scale modelling laboratory at Cambridge University. Work was initially with large models at a scale of 1:8 but techniques were developed for testing at scales down to 1:50. Experience with models suggested that full-size auditoria might provide the opportunity to understand links between geometrical factors and acoustic performance of auditoria. From 1981–84 he undertook an acoustic survey of British auditoria involving both objective and subjective tests in concert halls, drama theatres, opera houses and multi-purpose spaces. This survey provided the basis for his book "Auditorium acoustics and architectural design" published in 1993. Since 1987, Mike Barron has been a partner of Fleming & Barron, acoustic consultants, which now has offices in London and Bath. For the last 15 years he has also held the post of lecturer in acoustics at the Department of Architecture and Civil Engineering at the University of Bath, England.