AUDITORIUM ACOUSTICS – A ROOM ACOUSTICIAN'S PERSPECTIVE

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1 INTRODUCTION

Auditorium acoustics is both a science and an art, both advance slowly due to the limited numbers of these buildings that are built. Design is a result of team work. Up to around 1975, the architect often dominated design development for auditoria. Partly due to the realisation that a hall with a poor acoustic reputation is likely to suffer financially, the role of the acoustician has been enhanced since around 1980. This has been accompanied by less experimentation in the form of auditoria.

Meanwhile, the requirements of acousticians and sound engineers have probably remained unreconciled! Particularly in large auditoria intended for unamplified sound, the designer generally takes the view that adding absorbing material is to be avoided, to limit the loss of acoustic energy. In many cases, the presence of strong discreet reflections is acceptable. These reflections tend to be more obvious (due to comb filtering, spatial effects or if late enough as echoes) for sound from loudspeakers. Where a sound engineer would like to apply sound absorbing treatment, the acoustic consultant may consider this totally unacceptable. Making a surface scattering may be a solution approved by both. Variable acoustics are another option but anything 'too clever' runs the risk of being used incorrectly.

Rather than discuss the conflicting requirements of acoustic consultants and sound system designers, this paper will present four separate topics to illustrate current issues in auditorium acoustics:

Speech intelligibility in drama theatres
Sound level behaviour in rooms
Using the standard ISO 3382 for objective measurements in auditoria
Development of concert hall form

2 SPEECH INTELLIGIBILITY IN DRAMA THEATRES

During the period 1982-5, objective and subjective studies were made of key British theatres. This has not received much publicity and holds some interesting results worth reiterating. The objective results in 12 drama theatres are summarised in Barron (1993) and the subjective results from three of these theatres are discussed in Barron (1986).

Very little has been published on acoustic conditions in drama theatres, yet listening problems do exist in some of them. Early studies indicated that the directivity of the human speaker is significant and thus for objective measurements at least two orientations for actors has to be used, as shown in Figure 1. The objective measurements included reverberation time, measures relating to speech intelligibility and sound level (G - strength). The subjective study used a questionnaire completed by experienced listeners at actual performances, Figure 2. An average of 5.8 listeners completed questionnaires at each audience location.

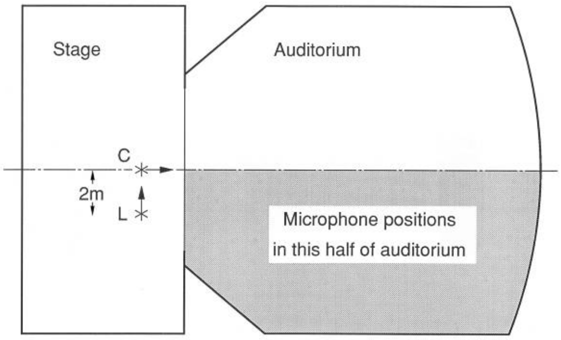
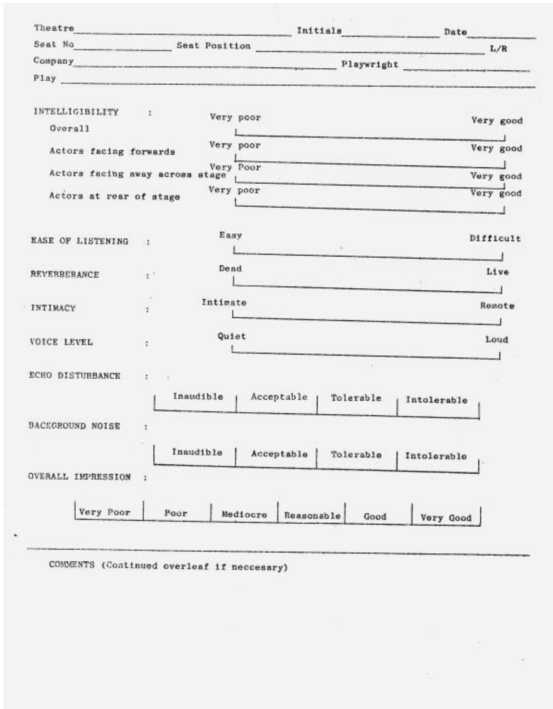


Figure 1. Source and receiver locations suitable for theatre measurements. C, central source; L, lateral source.



Theatre ______ Initials ______ Date ______
Seat No ______ Seat Position ______ L/R
Company ______ Playwright ______
Play ______

INTELLIGIBILITY :
Overall — Very poor ... Very good
Actors facing forwards — Very poor ... Very good
Actors facing away across stage — Very Poor ... Very good
Actors at rear of stage — Very poor ... Very good

EASE OF LISTENING : Easy ... Difficult

REVERBERANCE : Dead ... Live

INTIMACY : Intimate ... Remote

VOICE LEVEL : Quiet ... Loud

ECHO DISTURBANCE :

Inaudible	Acceptable	Tolerable	Intolerable

BACKGROUND NOISE :

Inaudible	Acceptable	Tolerable	Intolerable

OVERALL IMPRESSION :

Very Poor	Poor	Mediocre	Reasonable	Good	Very Good

COMMENTS (Continued overleaf if neccesary)

Figure 2. Questionnaire used in drama theatres at public performances.

The results of the questionnaire were subjected to factor analysis to determine which scales were significant. Three clearly independent dimensions emerge from this analysis:

Intelligibility/Ease of listening
Intimacy
Reverberance

To establish which of these are important for listeners, the correlations of individual scales with 'Overall impression' were investigated. Only the intelligibility dimension correlates well with a high correlation coefficient of $r = 0.85$. An important conclusion is that while listeners can judge acoustic intimacy and reverberance consistently, *they do not consider that they contribute to their overall judgement*.

Objective measurements had been made in the theatres of several quantities suggested for speech intelligibility. This objective data was compared with subjective responses from the questionnaire study. Figure 3 shows the correlation coefficients achieved for the measures: LB (Lochner and Burger), CT (Centre Time), MTF (Modulation Transfer Function = Speech Transmission Index), EEF (Early energy fraction, D_{50}) and MD (Modulation Depth, a crude MTF measurement).

The three columns in Figure 3 refer to different frequency ratings: a simple mean for the three octaves 500 – 2000 Hz, a weighting proposed for the Articulation Index and a weighting proposed for the Modulation Transfer Function. The last two weightings are listed numerically in Table 1.

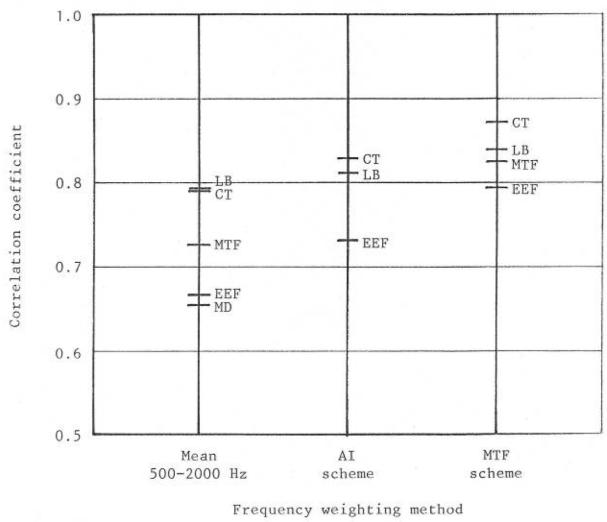


Figure 3. Correlation coefficients between subjective intelligibility and objective measures, as in text above, for three different weighting methods of objective signal frequency.

Octave frequency (Hz)	125	250	500	1k	2k	4k
AI weighting	0	.05	.15	.23	.32	.25
MTF weighting	.13	.14	.11	.15	.23	.24

Table 1. Frequency weightings used in Figure 3.

From Figure 3 it is clear that the MTF weighting gives the best correlations, a result which is surprising since it weights the low frequencies as significant. The objective measure, Centre Time, comes out as 'the best', another surprising result. What is also surprising is that the highest correlation has a coefficient of r = - 0.87, a remarkably high value when one considers that the subjective data is just based on marks on bipolar scales, Figure 4.

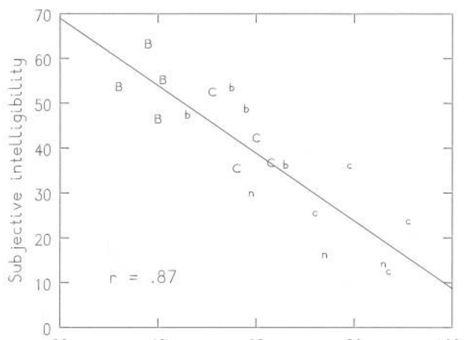


Figure 4. Correlation between subjective intelligibility and Centre Time weighted according to the MTF values in Table 1.

This exercise thus confirmed that traditional measures are valid in drama theatres. It was also apparent that signal-to-noise level was rarely a problem in drama theatres, except at a few seats in a few theatres where there was also a deficiency of early sound.

3 SOUND LEVEL BEHAVIOUR IN ROOMS

When designing a sound system, the criterion for sound level generated is presumably influenced by the need to sound natural, at least for good designers. There is evidence that listeners have expectations that are based on average behaviour in rooms. Yet average behaviour differs from traditional theories.

Theories of sound level generally divide the received sound into two components: the direct sound and reflected sound. If there is clear line-of-sight, the direct sound level is dominated by inverse square law behaviour. Traditional theory for the reflected sound level, which can be derived from a simple differential equation, says that the reflected level is constant, determined by the total acoustic absorption. Figure 5 shows measured values in a typical large concert hall of the total sound level, also known as Strength, G dB. The agreement with tradition theory is clearly not very good. From measurements in many concert halls an alternative theory was proposed, which is shown in Figure 5 as the solid line, a much better match for observed behaviour.

The basis of the revised theory is that the reflected level is not constant but a line with a slope of 0.174/T dB per m, where T is the reverberation time, Figure 6. The equations relating to the revised theory are to be found in Barron and Lee (1988) and Barron (1993). The agreement between measured values and revised theory in 17 concert halls is shown in Figure 7. Sound level behaviour according to revised theory is not only found in auditoria but also in a fully diffuse sound space, Chiles and Barron (2004).

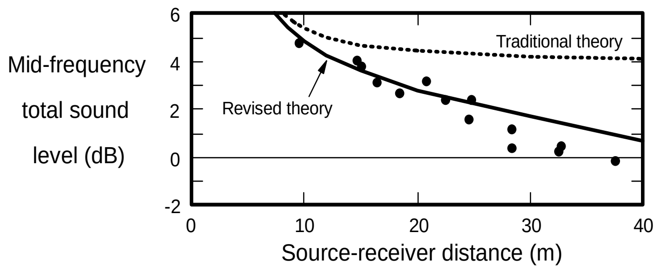


Figure 5. Measured values of sound strength in a recent large concert hall, compared with traditional and revised theoretical values.

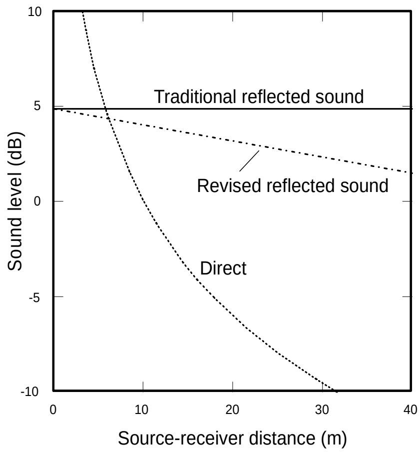


Figure 6. Behaviour of direct and reflected sound as a function of distance according to traditional and revised theory.

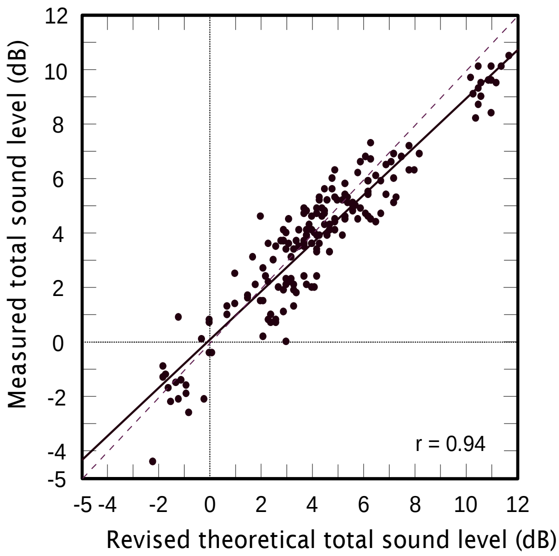


Figure 7. Measured vs. revised theoretical total sound level at mid-frequencies. 174 positions in 17 concert halls.

Does the finding that sound levels are lower than was previously thought in fact matter? In many ways, it does not but one consideration is the sensation of loudness which listeners perceive as a function of sound level. Subjective tests in concert halls, Barron (1988), have shown that loudness judgements are also influenced by source-receiver distance, and that there is good evidence to suggest that loudness is perceived as constant in a typical concert hall space. The objective and subjective conditions are sketched in Figure 8, Barron (2007). The implications of this are that sound levels much above expectations according to the revised theory will be judged as unnatural. The need to keep amplified sound level down in the interest of naturalness is well known, the objective behaviour for single sources indicates that reduced sound levels may be appropriate at the rear of an auditorium.

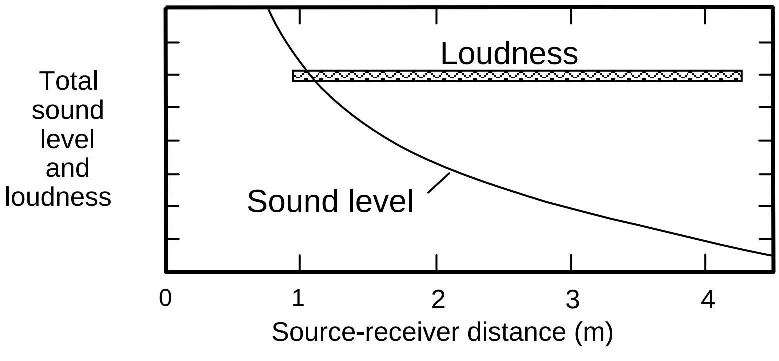


Figure 8. Behaviour of sound level and subjective loudness as a function of source-receiver distance.

4 USING THE STANDARD ISO 3382 FOR OBJECTIVE MEASUREMENTS IN AUDITORIA

ISO3382 formally introduces key objective measures currently used for assessing auditoria:

Reverberation time
Early decay time (EDT)
Balance between early and late arriving energy (C_{80} etc.)
Early lateral energy measures (lateral fraction, LF) or cross-correlation measures
Sound strength (G)

There is evidence that consultants can use these measures more out of duty than because they believe that they can usefully contribute to auditorium design! The measures are probably used most in earnest when designers use computer simulation software.

Reverberation time has been with us for over 100 years now and is usually a characteristic of a space as a whole. It is easy to measure and the criterion for concert halls of 1.8 – 2.2 seconds is easy to apply, as are criteria for the variation with frequency. The value of reverberation time must not however be exaggerated. Subjective evidence points to early decay time (EDT, which is measured over the first 10 dB of the decay) being better related to perceived reverberance. A major complication of the newer measures is that they vary with position, making interpretation difficult. This is a multi-dimensional world which can be challenging to make sense of.

For measurements in completed halls, as discussed in Barron (2005), there are serious calibration issues for the lateral fraction (LF) and sound strength (G). The choice of source location on stage may or may not involve a stage floor reflection, which will influence results of C_{80}, LF and G, in particular. Chairs on stage provide a more realistic situation compared with the performing condition, chairs do however reduce sound strength by about 1 dB. The ISO standard proposes a sensible number of different receiver positions, a minimum of 10 positions is recommended for halls with greater than 2000 seats.

Measurements in actual auditoria are nearly always made in unoccupied conditions. It is now clear that the change in total acoustic absorption between occupied and unoccupied seats depends on the nature of the seats themselves, Beranek and Hidaka (1998). The change in reverberation time with occupancy is well known, but this influences the EDT, C_{80} and G as well. Table 2 shows the typical changes with occupancy in terms of difference limen for the various measures, Barron (2005).

Measure	Typical change with occupancy	Difference limen	Number of limen change
Reverberation time	0.80	5%	4
Early decay time	0.80	5%	4
Early-to-late, C_{80}	1.5 dB	1 dB	1.5
Early lateral fraction, LF	Minimal	0.05	-
Sound strength, G	1.6 dB	1 dB	1.6

Table 2. Typical changes of objective measures between empty and occupied halls compared with difference limen. In the case of C_{80} and G, the typical change is the typical maximum change within a hall.

Given the magnitude of objective changes with occupancy, it is appropriate to correct measured results in unoccupied auditoria to those for the occupied hall. In the case of the reverberation time change, Hidaka *et al*. (2001) have valuable data. Bradley (1991), Barron (1993, p.419) and Hidaka *et al*. (2001) have each suggested techniques for correcting EDT, C_{80} and G for reverberation time

(RT) change. Though the suggested procedures are different in principle, they are likely to give similar results for modest RT changes.

A measurement programme in a large hall generates typically 250 numbers for each source position (5 measures, 5 octave frequencies and 10 receiver positions). Some averaging is needed to make meaningful judgements. Averaging over frequency is not contentious. Low frequencies suffer seat-dip attenuation which is minimal at mid-frequencies. A division into 125 – 250 Hz (two octaves) and 500 – 2000 Hz (three octaves) has much to recommend it.

There are different views on averaging over seat positions. As already mentioned, a reverberation time for the space as a whole is appropriate, but other measures vary with position. One approach used by Beranek (2004) is to calculate average values for the hall for EDT, C_{80}, LF and G. Particularly in the case of the last three, average hall values are to this author of questionable value. No seat in a hall has conditions given by all the average values and the overlap between measured values in comparable halls is large. Just using average values is a case of excessive data reduction.

One category of seats deserves to be treated separately: those under balcony overhangs where there are generally higher values of C_{80} and lower values of G. In the case of sound strength, G, there is a simple solution that is appropriate when a measure varies with source-receiver distance: this is to plot G values against source-receiver distance as in Figure 5. A similar approach may be suitable for C_{80} and LF, bearing in mind limiting values for each measure.

While there is much more to subjective response than is reflected in the objective measures in ISO3382, consistent treatment of the measures should offer valuable data for assessing key aspects of concert hall acoustic conditions.

5 DEVELOPMENT OF CONCERT HALL FORM

The way the form or shape of concert halls has developed over the past 150 years or so is a fascinating topic. Generally concert hall form is specified in terms of the plan shape; the ceiling height needs to be large to achieve an appropriate reverberation time. The most famous form is the rectangular or parallel-sided hall, which was inspired originally by ballrooms, such as the Redoutensaal of 1752 in Vienna. A tradition of using this form must have been linked to favourable experience. The Musikvereinssaal in Vienna (1870), the Concertgebouw in Amsterdam (1988) and Boston Symphony Hall (1900) are now frequently considered to have the best acoustics in the world, they follow shoebox proportions with balconies running along the sides and rear wall opposite the stage; see Bradley (1991) for a discussion of their objective characteristics. The 19th century versions of rectangular halls are also noted for the extensive plaster decoration on the walls and ceiling, which provide acoustic scattering.

Figure 9 shows the distribution by decade of different concert hall forms between 1850 and 2000. Four different forms have been selected: shoebox/rectangular, theatre form (as in 19th century drama theatres with balconies), fan-shaped plans and terraced concert halls. Other forms, such as oval, hexagonal, surround halls and music-in-the-round have been combined into an amorphous group ‘other’. Figure 9 includes 70 representative concert halls, listed in the appendix in Barron (2006), plus the Royal Albert Hall in London.

New auditoria during the second half of the 19th century were relatively infrequent. One surprise for the period up to 1940 is that as well as rectangular halls, several halls following theatre forms were built; the Usher Hall in Edinburgh is an example. The gradual realisation that the acoustics of these halls were disappointing must have spelt the eventual demise of this form for concert halls.

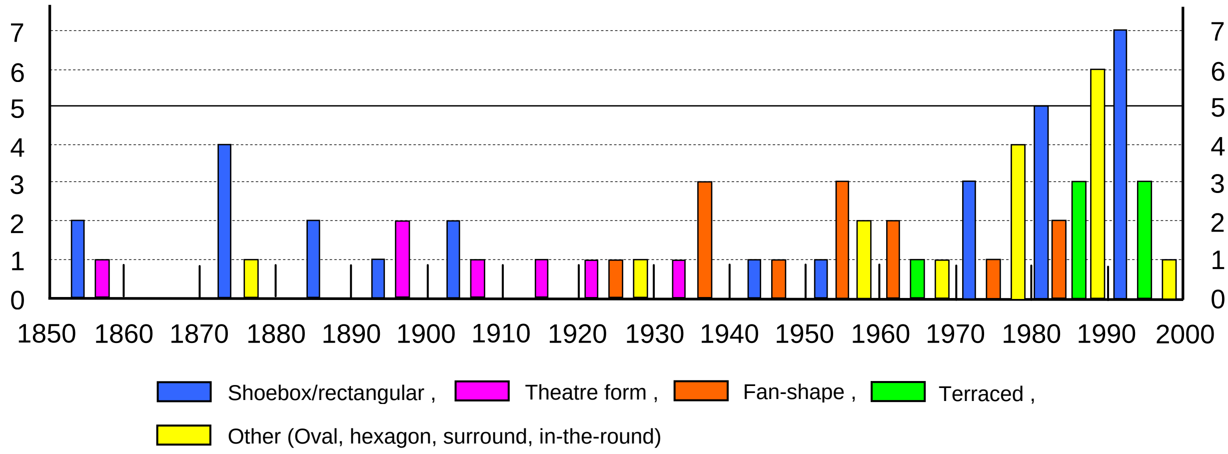


Figure 9. Numbers of concert halls built during decades between 1850 and 2000 of different forms.

The new favourite form in the 1920s was the fan-shape plan, such as the Salle Pleyel in Paris, the form most closely associated with the Modern Movement in architecture. The plan form allows for a maximum audience within a certain angle centred on the stage. Its acoustic limitations, particularly spatial and reverberant, have gradually become apparent yet new examples were still appearing in the 1980s.

Of especial interest is the history of the rectangular concert hall. In the first 60 years of the 20th century the form was all but abandoned, as is clear in Figure 10 which has been extracted from Figure 9. Presumably this was due to these halls being associated with out-of-date architecture. Finally in 1971, the rectangular plan form was revived by C.M. Harris for the Kennedy Center Concert Hall, Washington, DC (Harris, 1972). The parallel-sided plan was subsequently taken up by R. Johnson for the new concert hall for Dallas of 1989. Since then it has been one of the most popular forms for new concert halls.

The realisation that the classical rectangular halls had the most reliable reputations led to return to that form in the 1970s to the present. Also shown in Figure 10 is the growth in terraced concert halls, pioneered in the Berlin Philharmonie of 1963. The period around 1975 – 80 can be seen as a watershed, when the role of the acoustician became more dominant in the design of auditoria and design became more conservative, with less risk taking. The rectangular and terraced hall can be considered to be the main precedents today (Barron, 1993).

Halls which are categorised as ‘Other’ in terms of their form cannot be combined easily as a group, other than noting that halls in this category are generally examples of experimentation in design.

Plan form	Dates
Shoebox/rectangular plan	1850 – 1905, 1970 – present
Theatre form	1850 – 1935
Fan-shaped plan	1925 – 1985
Terraced hall	1960 - present

Table 3. The principal periods for concert halls of different plan forms.

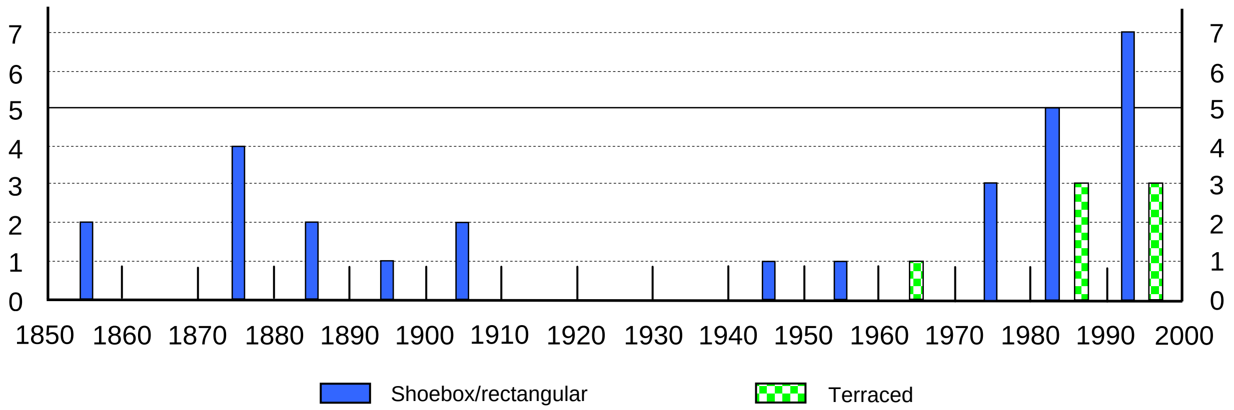


Figure 10. Shoebox/rectangular halls and terraced halls extracted from Figure 9.

With two concert hall forms dominating present design, what are the pros and cons of these two forms?

The rectangular concert hall	
Advantages:	Acoustics are pretty reliable
	A known 'quantity' expected to have good acoustics
	Liked by many musicians
Disadvantages:	Formal relationship of audience to performers
	Limited involvement of the audience
	'Looking through a tunnel' from rear audience seats
	Poor sightlines at high levels on the sides
	Limited seat capacity

Table 4. The advantages and disadvantages of the rectangular concert hall form.

The terraced concert hall	
Advantages:	Acoustician has more control over acoustics
	Involving relationship between performers and audience
	Good sightlines
	Larger audience capacity possible
	Greater freedom in design
Disadvantages:	Poor balance for audience to the sides of the stage
	Demanding to get good acoustics

Table 5. The advantages and disadvantages of the terraced concert hall form.

The safe solution is the rectangular hall, while the terraced hall offers greater freedom of design and potentially more exciting performance spaces. A design currently under development is that for the new Paris Philharmonie, due for completion in 2012, Kahle *et al*. (2007). The acoustic consultants, Marshall Day Acoustics, are working on a design where the enclosure is essentially outside and largely independent of the seating areas. This can be seen as an attempt to achieve high clarity with a long reverberation time. It promises to be an interesting development from the current precedents.

6 CONCLUSIONS

It is probably fair to consider that objective concert hall acoustics has reached a certain maturity. Whereas the art of concert hall design is locked in the heads of certain individuals! Yet as already mentioned, the designs being used today show closer adherence to precedents than was the case in the 1970s and '80s. The result has been many fewer new halls with disappointing acoustics.

The degree to which designers rely on science varies considerably. Most consultants use computer simulation modelling, some extend this analysis into auralisation. Some consultants build and test acoustic scale models, which are generally considered to be more reliable than computer models. The appropriate use of scattering on room surfaces remains a big enigma.

Whereas sound systems in auditoria can be adjusted and are often replaced at regular intervals, refurbishment of auditoria for concert acoustic purposes is both expensive and often disappointing. Many halls refuse to respond to minor modifications and continue to exhibit the same faults they always had. Adjustable acoustics with movable elements is an attractive possibility which clients often find appealing, but in reality they often do not live up to the promises made. The search for perfect acoustics goes on!

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