**PRESENTS**

# QUEEN ELIZABETH THEATRE, VANCOUVER: ACOUSTIC DESIGN RESPONDING TO FINANCIAL REALITIES

by J O'Keefe

**akuTEK navigation:**
Home
Papers
Title Index
Stage Acoustics
AKUTEK research
Concert Hall Acoustics

# QUEEN ELIZABETH THEATRE, VANCOUVER: ACOUSTIC DESIGN RESPONDING TO FINANCIAL REALITIES

John O'Keefe Aercoustics Engineering Ltd, Toronto, Canada
Daniel Ruvalcaba Aercoustics Engineering Ltd, Toronto, Canada

8th International Conference on Auditorium Acoustics
http://www.ioa.org.uk/events/event.asp?id=91

## 1 INTRODUCTION

Like so many other performing arts centres, the renovation of Vancouver's Queen Elizabeth Theatre (QET) took a very long time. Two previous versions of the renovation design have been published[1,2,3], in 1999 and 2007, both of which fell victim to budget constraints. The 2007 version included; two new balconies (for a total of three), large lateral reflectors in the ceiling space (similar to the Michael Fowler Centre in Wellington New Zealand[4]), a terraced seating level in the stalls (inspired by the Berlin Philharmonie[5]), and a novel design to control low frequency reverberation. The Sound and Light Locks surrounding the sides of the room would be treated like the coupled volume chambers found in some new concert halls, only in this case they wouldn't be reverberant chambers, they'd be absorbent chambers, and the absorption would extend down to low frequencies. Two weeks before the 2007 design was presented to the Madrid ICA symposium, financial disaster struck. Hazardous materials on the site, in the form of lead dust, and a major source of funding that failed to materialize, combined to reduce the budget by 30%. The two new balconies had to be deleted from the design, as were the terraced seating and coupled volume low frequency absorbing chambers. Another year was added to the construction schedule, the beginning of which involved a rather desperate effort to regain all the lateral reflecting surfaces we had lost. The results, described below, show how relatively small but very carefully positioned reflectors can compensate for the much larger – and much more expensive – reflectors implied by the previous tiered seating levels.

## 2 GEOMETRIC OPTIMISATION

Acoustician Derek Sugden once claimed that he never liked the look of a room which announced, "acoustician has been here"[6]. The authors fully agree with this sentiment: constrained however by an existing room that had to seat 2,750, could no longer be narrowed with tiered seating and with an enclosed volume in excess of 30,000 m$^3$, there was little choice but to introduce acoustical intervention into the visual aesthetic. A view of the finished room is shown in Figure 2. Ceiling and side balcony front reflectors are clearly expressed. But there is more here than meets the eye. The room is very wide. By the time the design was complete, virtually every available surface that might improve early lateral reflections had been employed – all of it cleverly disguised by the architects, Proscenium Architects + Interiors. The renovated QET is, most certainly, a Directed Energy hall. Presumably of the ilk that Sugden might not approve – at least not visually. But in the QET, most of the tell tale "acoustician has been here" signs have been hidden.

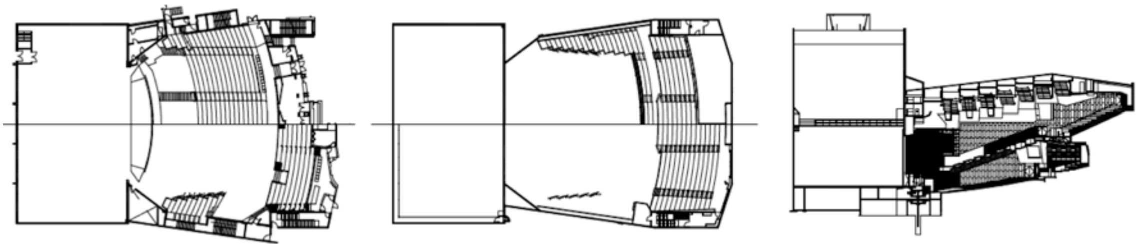

**Figure 1** Composite Plans and Longitudinal Section

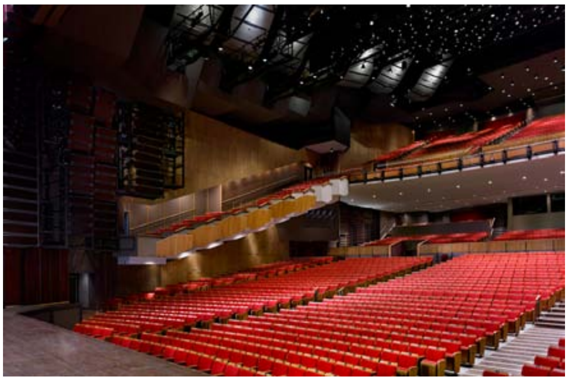

**Figure 2** View of the renovated Queen Elizabeth Theatre from the stage. Lateral reflectors can be seen in the ceiling and on the face of the side balcony.

Figure 3 is larger version of Figure 2. Please see Figure 4 as well. Lateral reflector zones have been identified and will be discussed below. An attempt has been made to lighten those zones buried in darkness. (Please note these lightened zones will be easier to see in the electronic version than on printed paper.) Not shown in these images are further lateral reflecting surfaces in the ceiling above the balcony.

Optimizing the size and, especially, the location of so many lateral reflectors was a very arduous task, made infinitely easier by modern 3D computer modelling techniques. Reflectors in zones 5 and 6 come from the 2007 design. They were aimed by manipulating text files in CATT Acoustic Version 8.0b. Shortly after the 2007 budget crisis, the second author introduced us to a software package that, interestingly enough, is not really intended for acoustics. Its primary purpose is as a design tool to get more natural light into green buildings. But it also allows us to do one crucial thing, align reflectors in 3-D space in real time. The dexterity of design that this affords us cannot be overestimated. Using this software, the myriad of small reflectors in Zones 1, 2 and 4 could be focused – sometimes to within a fraction of a degree – optimising the crucial lateral energy in this very wide, high volume room.

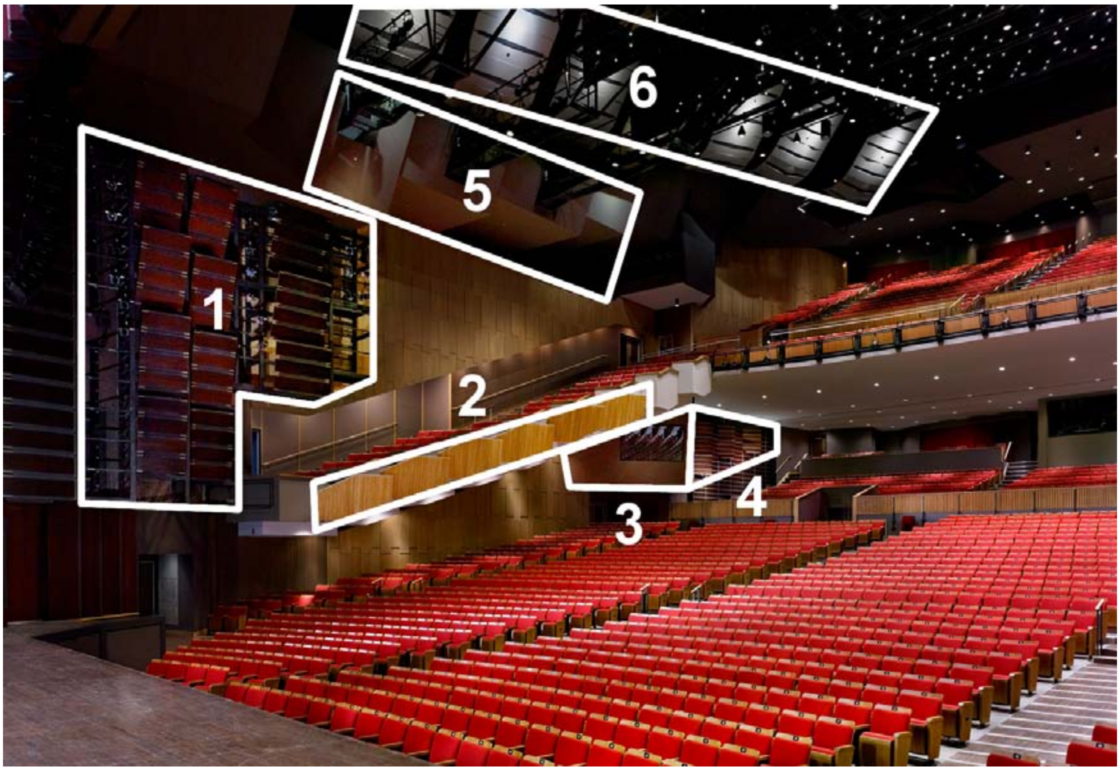

**Figure 3** Same as **Figure 2** with the lateral reflector zones identified and, in some cases, enhanced for a better view.

Let us now discuss the lateral reflector zones:

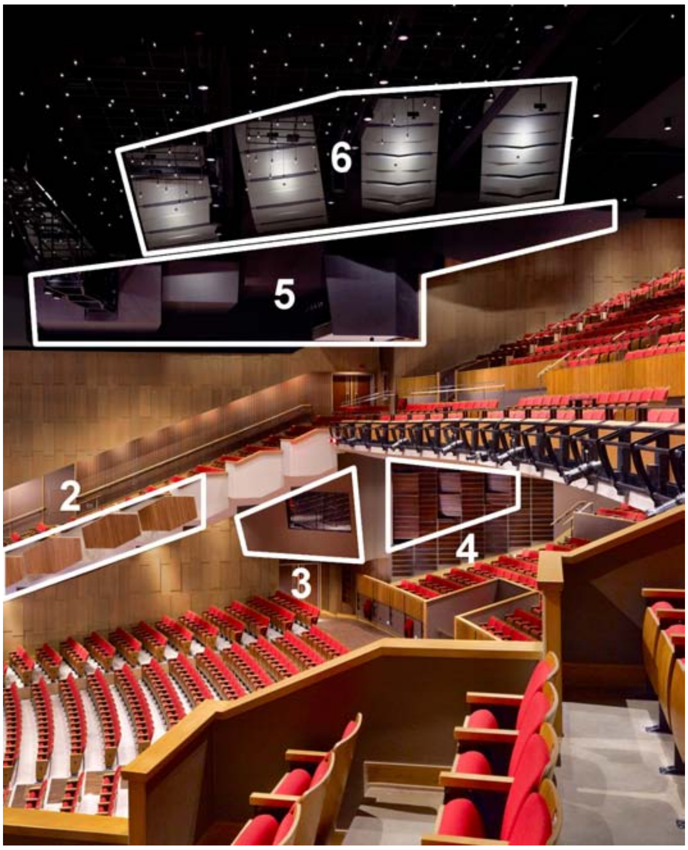

**Figure 4** A view from the side box, with reflector zones identified and enhanced.

1. This array of reflectors is shared with technical space usually dedicated to production lighting. These small reflectors, in concert with the even smaller and fewer Zone 4 reflectors, cast lateral reflections to almost all of the stalls and all of the mezzanine. (The mezzanine is the area of seating immediately adjacent to the Zone 4 reflectors.) An animation of this particular reflector coverage is currently available online[7].

2. This zone of balcony facia reflectors really demonstrates how far computer aided acoustical design has evolved in the last few years. Six years ago, prior to the final design, the first author had written this zone off, but not before a very long exercise attempting to make it work. In 2008, with the crucial advantage of new software capable of aiming reflectors in real time, the facia reflectors became a critical component of the acoustical design solution. The location of each reflector has been optimised so that it is not in the shadow of the reflector in front of it. As the array of reflectors moves toward the back of the room, this forces each successive reflector further into the house, towards the centre-line; as can be seen in Figure 5. Note that the array appears to be missing its last two reflectors, seen in the middle of Figure 4, just above Zone 3. For lateral reflectors to work in this location, they would have to be positioned so far towards the middle of the room as to block sight lines for patrons in the back corners of the balcony.

**Figure 5.** Zone 2 balcony facia reflectors are seen in the foreground. Note how they progressively move toward the centre-line of the room. The Zone 1 proscenium reflectors are seen in the background.

3. This is a booth for the handicapped. While there are plenty of wheelchair locations inside the auditorium, a location was required for those who might have problems with involuntary vocalisations or physical ticks that would disturb other patrons. Indeed, one of the Vancouver Opera's longstanding subscribers already fits this description. The acoustic design took advantage of this room and its symmetric partner on the opposite side, rotating the front face in plan and tilting it down in section to direct lateral energy to the back of the stalls, just in front of the cross-aisle.

4. These few reflectors are perhaps the most strategically important in the building. Although small in size and number, they cover a good part of the mezzanine

level, an area underneath the balcony overhang and thus not visible to many of the other reflectors in the room.

5. This is a bulkhead for return air ductwork. Exposed ductwork would have acted as a low frequency absorber so it was covered with 3 layers of 16 mm gypsum board. These large surfaces were put to further acoustical advantage and, after proper aiming, cover a good part of the balcony that the Zone 6 reflectors could not. Note also the catwalk at the top left hand corner of Figure 4. Having spent a lot of money removing the ceiling, the designers didn't want to lose that volume to a tangle of ductwork, catwalks and the like. The floor of all three catwalks is actually a wire cable tension grid and, as such, is much more acoustically transparent than a traditional catwalk.

6. These are the overhead reflectors inspired by the Christchurch and Wellington halls. Conceptually they were the first part of the Directed Energy solution and, aesthetically, remain the most visible. But, although they play a crucial role, the building simply wouldn't have been successful without the other reflectors described above: Many of which, it should be noted, are very well hidden!

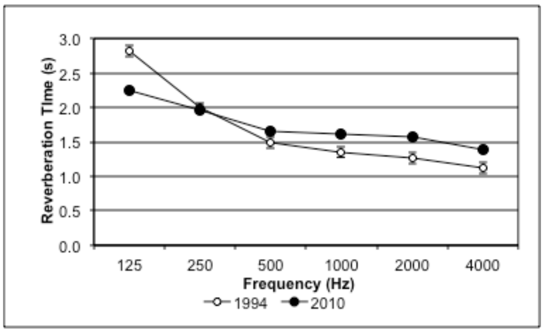

**Figure 6** Reverberation Times measured before and after the renovation.

# 3 MEASUREMENTS

Having spent so much time and money removing a ceiling and associated structure, replete with hazardous materials, it would be interesting to see how this improved Reverberation Times. A before and after comparison is shown in Figure 6. The vertical error bars in the graph indicate the subjectively significant Just Noticeable Differences (JND)[8]. The renovated room exceeds the JNDs so one would expect this improvement to be noticeable. The subjectively more salient Early Decay Times (EDT) will be discussed below. Note that the only decrease in Reverberation Time is seen in the 125 Hz octave, a subject that will also be discussed below.

A lot of time and effort was also spent on compensating for a very wide room with the appropriate lateral reflected energy. As can be seen in Figure 7, Lateral Energy Fractions have improved significantly, past the JNDs in all octave bands.

Strength (G), of course, is also a very important component of good sound in a room. Revised Theory[9] tells us that Strength is governed by three components: Volume, Reverberation Time and Distance. This suggests that it is very difficult to achieve adequate Strength in a large room like the QET where the volume is too big, the distances too long and, compared to a concert hall, the Reverberation Times too short, a topic that is discussed further in [2]. Nonetheless, Figure 8 shows that acoustic Strength has been improved significantly in the renovated QET.

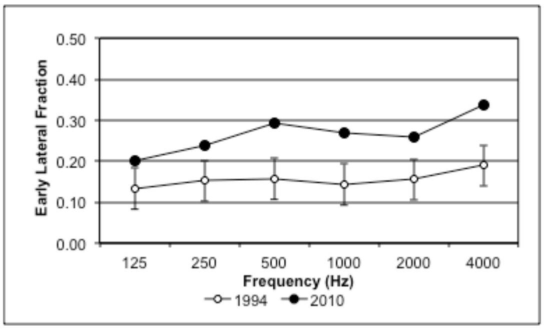

**Figure 7** Early Lateral Fractions before and after the renovation. The error bars indicate the Just Noticeable Differences (JND) so the improvements are surely subjectively significant.

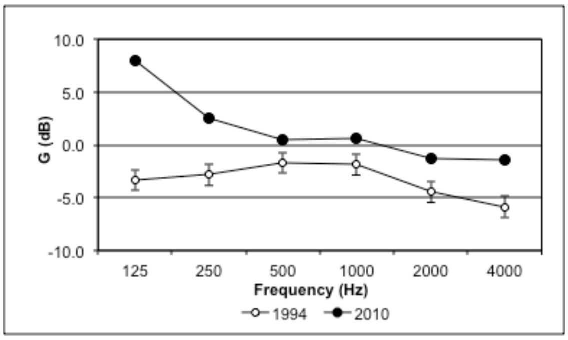

**Figure 8** Acoustic Strength (G) measured before and after the renovation. Again, the JND error bars indicate that the improvements are subjectively significant.

# 4 ANALYSIS

## 4.1 Reverberance in Directed Energy Halls

One of the concerns with a Directed Energy hall is that the first few reflections are sent to the acoustically absorbent seats, which presumably precludes the opportunity for further reflections that would eventually embellish the later part of the decay. Even in a shoebox shaped room, some have discouraged raked seating for this very reason. The concern is legitimate on an intuitive level but not very far beyond that. The real story is, as always, more nuanced.

Sometimes a Directed Energy room (or a steeply raked room) doesn't sound as reverberant as it should. And, while it is true that Early Decay Times (EDT) are shorter than the Reverberation Times (RTs) in a Directed Energy hall, one must keep in mind that Early Decay Times, by definition, concentrate on early sound. There may be another explanation.

In the late 1990s, as we struggled to improve EDTs in the Queen Elizabeth Theatre, we noticed that the room, in its original state, was very wide and not very tall. Could this be the reason for the short EDTs? A series of computer and scale model studies revealed that this, indeed, was the case[1]. Figure 9 shows the relationship between room Height to Width Ratios and Early Decay/Reverberation Time ratios. In these very simplified models there is a clear causal link between the two. Tall narrow rooms have an EDT/RT ratio close to 100%, suggesting that they will sound more reverberant.

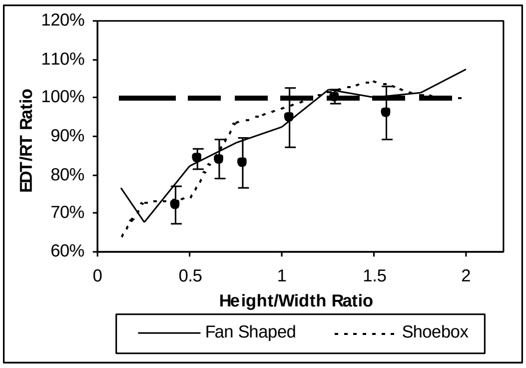

**Figure 9** EDT/RT ratios vs. Height/Width ratios measured and calculated by scale and computer models.

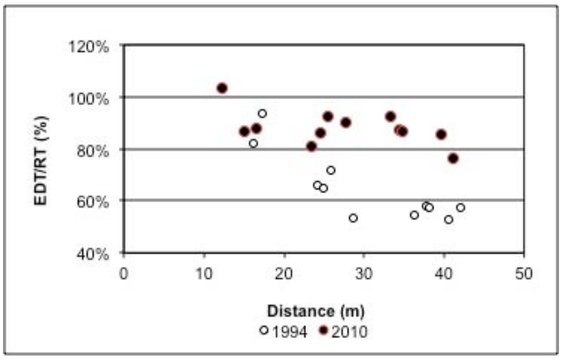

**Figure 10** A comparison of EDT/RT ratios before and after the renovation.

Real rooms, of course, are not this simple. However, the experiment, deliberatively reductive as it is, does indicate a pattern worth considering. One could describe the original room as having a poor Height/Width ratio. The new building definitely falls into the category of a Directed Energy hall. It does not have a Height/Width ratio per se; its geometry is too complicated to fit within the confines of the experiment described in reference [1]. But, with the ceiling removed, the room is taller and, with all the lateral reflectors, it is acoustically "narrower". Figure 10 shows a comparison of EDT/RT ratios for the new and original rooms. The new room has consistently higher EDT/RT ratios, even though it is a Directed Energy hall, where one would expect lower EDTs. The original room, with its poor Height/Width ratio, has lower EDT/RT ratios. It appears that the Height/Width ratios influence EDTs more than the well known deleterious effects of Directed Energy.

## 4.2 Strength in Directed Energy Halls

Let us return to the concern about the absorption of early reflections before they can become late reflections. Is a Directed Energy hall or, indeed a steeply raked shoebox hall, doomed to low late energy levels? The question's answer is informed by Toyota's[10] studies on what he called Reflected Energy Cumulative Curves (RECC). Toyota noted that the rank ordering of acoustic Strength levels was established by about 80 to 100 ms into the impulse response. This is a powerful observation because it means that if one can improve early sound levels (G80), as one would do with the spatially optimised reflectors in a Directed Energy hall, those improvements will still be there in the late field.

Hyde expanded on this idea in 1999 using measurements from one of the classic Directed Energy rooms, Segerstrom Hall in Costa Mesa, USA.[11] He found strong correlations between early sound levels (G80) and the total sound level (G). Even stronger correlations are found with the QET data, both before and after. Please see Figure 11. Hyde's correlation coefficients were in the range of 0.91. In the new QET they are 0.97. An average increase in G80 of 1.8 dB was achieved with the new optimised lateral reflectors. This translated into an average increase in G of 2.5 dB. Given that the Just Noticeable Difference (JND) for G is about 1.0 dB, this represents a formidable improvement.

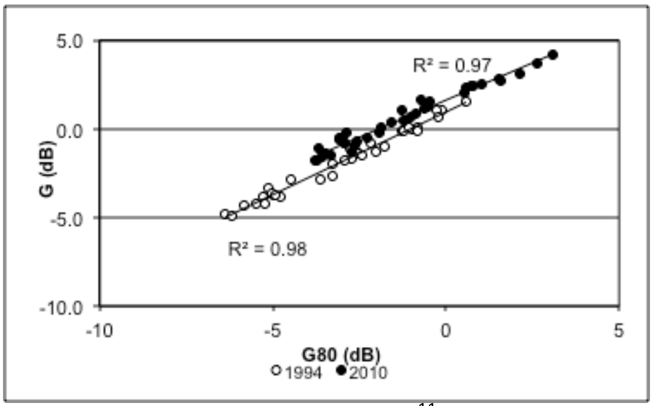

**Figure 11** As suggested by Hyde[11], there is a strong correlation between early reflected sound (G80) and the total Strength (G). In the renovated QET, a 1.8 dB increase in G80 has generated a 2.5 dB in G. Popular wisdom would suggest the opposite. (1 kHz octave)

The ideas developed by Toyota and Hyde strongly influenced the acoustic design decisions for this building. It is often thought that a concert hall or opera house won't work if it has to seat more than 2,000. For financial reasons, limiting the number of seats to 2,000 was simply not an option. This was a room being acoustically optimised for opera but it was, and is, a multi-purpose room nonetheless. 70% of the time, the bills are being paid by popular music acts that that can fill a lot more than 2,000 seats. One of the room's biggest challenges was its lack of total acoustic Strength (G). The overly wide room also needed as many lateral reflections as it could get. Received wisdom, at least in North America, suggests the two requirements are at loggerheads. Directing too many early reflections to the seating would, supposedly, rob the room of later reflections and, hence, acoustic Strength (G). Toyota and Hyde's work – based, it should be noted, on measured data – suggests otherwise. This gave the designers the confidence to move forward with the Directed Energy concept. In the end, measurements in the completed hall agree completely with Toyota and Hyde's observations.

### 4.3 Perception of Bass

McNair[12], in 1930, was probably the first to suggest a link between objective measurements and what later became known as Warmth or the Perception of Bass. He recommended that, for a more natural sounding decay, Reverberation Times in the 125 Hz octave should be 50% higher than those in the 500 Hz octave. Later, Beranek[13] attempted to codify this with a "Bass Ratio" of low to mid-frequency Reverberation Times. The concept – which was never more than a postulate – became one of those acoustical canards so often repeated that, well, it just must be right! Both ideas, although later proved fallacious, can be excused on the grounds that, in their day, Reverberation Times were about the only thing that could be safely measured or, for that matter, easily predicted.

In 1997, Bradley et al.[14] elevated the discussion beyond postulation and found a very good correlation between low frequency Strength (G) and what they called the Perception of Bass. They developed a concept known as Weighted G (Gw):

$$Gw = 10\log\left[E80_{125} + 3Elate_{125} + 0.5\left(E80_{250} + 3Elate_{250}\right)\right] \qquad (1)$$

where: $E80 = 10^{(G80/10)}$
$Elate = 10^{(Glate/10)}$

Measurements from a number of opera houses and three of the world's favourite concerts halls place the improvement in the QET's Gw into context. Please see Figure 12. Before the renovation, Gw for the QET is lower than all of the opera houses and concert halls. After the renovation it is better than all the opera houses and only one of the three concert halls, Vienna's Musikvereinssaal, exceeds it.

Interestingly enough, if one were to calculate a Bass Ratio using unoccupied Reverberation Time data from the renovated room, it would suggest a decrease in Warmth: from 1.69 to 1.29. This is contrary to the subjective assessment of the renovated room.

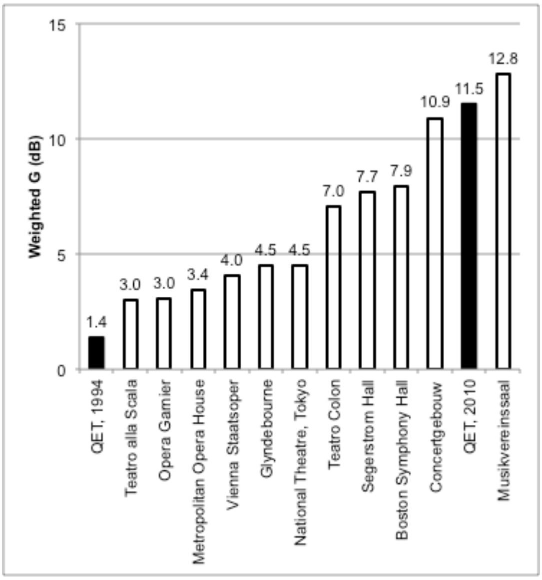

**Figure 12** Weighted G (Eq. 1) has been shown to have a very strong correlation with Perception of Bass. Measurements before and after the renovation suggest that the QET has gone from one of the worst to one of the best

# 5 INTIMACY

Acoustic Intimacy is an extremely difficult parameter to quantify with objective measurements. It is, perhaps, the only important subjective parameter left that cannot be measured objectively. Barron, in his Survey of British Auditoria, found that Intimacy is best correlated with the total sound level (G)[15,16]. Hyde[17], commenting on this finding, states that a "connection between Intimacy and distance (a visual impression) is strongly suggested". Many now think of Intimacy as a so-called multi-modal percept. That is, the neural process that decides whether a room is Intimate or not, involves both visual and aural stimuli. The postulate is that visual stimuli leads to a certain expectation as to how loud the room might be. If the sound turns out to be louder than that, we get the impression of being closer to the sound; i.e. more Intimate.

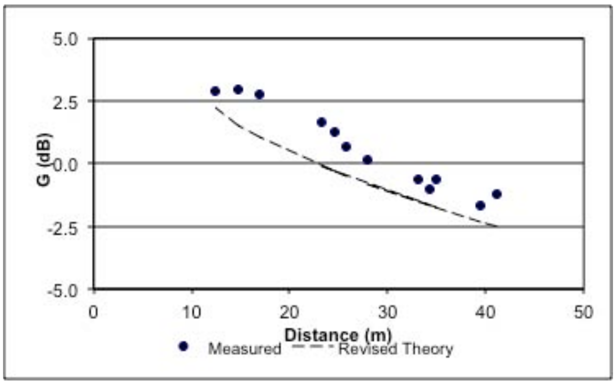

**Figure 13** Measured Strength (G) compared to a Revised Theory prediction might explain the better than expected Intimacy. (1kHz octave)

The Intimacy of the renovated QET came as a pleasant surprise to the design team. One explanation for the Intimacy might be found in Figure 13. Revised Theory[9] has proved to be an accurate predictor of sound levels in a room. As such, it's a good predictor of what people might expect in a room of a given size at a given distance from the sound source, i.e. a good predictor of the visual stimuli that may be part of Intimacy judgment. Figure 13 shows that measured Strength (G) in the renovated room is consistently higher than the Revised Theory prediction, suggesting that the aural experience may be louder than the visual stimuli might expect. This would, in turn, suggest good Intimacy.

Another possible explanation for the good Intimacy in the QET comes from Kahle[18], who found a correlation between Intimacy and low frequency perception of loudness. Section 4.3 of the current paper suggests that perception of low frequency loudness is very good in the QET.

# 6 CONCLUSION

The theme of this meeting of the Institute of Acoustics is how modern acoustic science can respond to increasingly novel design challenges presented by architecture. For the QET the shoe was on the other foot. The architectural team responded to the acoustical design in any and every way that was practical. The design challenges were not architectural, they were financial. The capital costs had been cut by 30% and the operating costs dictated a room that was too wide and had too many seats. The challenges presented by this project were formidable. It is clear, at least to the authors, that these challenges could not be resolved with out recourse to modern acoustical science and technology.

# 7 ACKNOWLEDGEMENTS

Many of the key players who participated in the project have been noted in Reference [3]. Their contributions are still appreciated. Thanks also go to Sarah Mackel for her help with the drawings and data analysis. The 1994 measurements were performed by John Bradley and Gilbert Soulodre.

# 8 REFERENCES

1. J. O'Keefe, 'The Influence of Height to Width Ratio and Side Wall Boxes on Room Acoustics Measurements', Proc. Inst. Acoustics, Vol. 21. Pt. 6, 137-143, Manchester (October 1999)
2. J. O'Keefe, 'Acoustical Problems in Large Post-war Auditoria. Proc. Inst. Acoustics', Vol. 24. Pt. 4, London, (July 2002).
3. J. O'Keefe, 'Acoustical Renovation Of The Queen Elizabeth Theatre, Vancouver: Spatial Sound In A Wide Room', Proc. 19th ICA, Madrid, (Sept. 2007).
4. A.H. Marshall, J. Hyde, 'Some Preliminary Acoustical Considerations in the Design for the Proposed Wellington (New Zealand) Town Hall', J. of Sound and Vibration, Vol. 63. Pt. 2, 201-211 (1979).
5. L.L. Beranek, 'How They Sound Concert and Opera Halls', Acoustical Society of America 245-248 (1996).
6. D. Sugden, Closing Ceremony Speech at the Opera and Concert Hall Acoustics meeting of the Institute of Acoustics, London, (1995).
7. Reflector design animation: http://aercoustics.com/files/2009/11/QET_Final.gif
8. T.J. Cox, W.J. Davies, and Y.W. Lam, 'The sensitivity of listeners to early sound field changes in auditoria', Acustica Vol. 79, 27-41 (1993)
9. M. Barron and L-J. Lee, 'Energy relations in concert auditoriums, I'. J. Acoust. Soc. Am., Vol. 84, 618-628 (1988).
10. Y. Toyota, et al., 'A study on the characteristics of early reflections in concert halls', J. Acoustical Soc. Am., Vol. 84, (S1) (1988).
11. J. Hyde, 'A look at components of sound strength in concert halls through acoustical measurements and computer modelling', Proc. Inst. Acoustics, Vol. 21 Pt. 6, 145-152, Manchester, (October 1999).
12. L. Cremer, H. Muller, (translated by T.J. Schultz), 'Principles and applications of room acoustics, Vol. 1'. , p 459, Applied Science, London (1982).
13. L.L. Beranek, 'Music Acoustics and Architecture', John Wiley & Sons, Inc., p. 435, (1962).
14. J.S. Bradley, G.A. Soulodre, and S. Norcross, 'Factors Influencing the Perception of Bass', J. Acoust. Soc. Am., 101 (5) Pt. 2, 3135 (1997).

15 M. Barron, 'Subjective study of British symphony concert halls', Acustica, Vol. 66 (1988).

16. M. Barron, 'Intimacy, loudness and sound level in concert halls', Proc. 12th ICA, Toronto, Paper E4-3, (1986).

17 J. Hyde, 'Acoustical intimacy in concert halls: does visual input affect the aural experience?' Proc. Inst. Acoustics, 24, Part 4 (2002).

18. E. Kahle, 'Validation d'un modele objective de la perception de la qualite acoustiaue dans des salles de concert et d'operas', PhD dissertation, Univ. LeMans, 1995.

**akuTEK navigation:**
Home
Papers
Title Index
Voice Acoustics
Speech Acoustics
AKUTEK research