A Statistical Approach to Concert Hall Acoustical Design

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ABSTRACT

This paper looks at what information is needed to give concert hall acoustic design a firmer scientific basis: whether there is sufficient, and sufficiently reliable, subjective and objective data on concert halls and whether good halls can be distinguished from poor halls on the basis of geometric or acoustic qualities. In particular, existing indicators of acoustic quality, used in the early stages of a design, are investigated to see whether their use can be justified. Based on limited subjective assessments of concert hall acoustic quality, objective acoustical measurements and geometrical parameters it is shown, using a statistical test, that commonly used parameters such as the volume per seat are not statistically significant indicators of acoustic quality while the most reliable indicators are still reverberation time and sound strength, $G_{mid,}$ (and variants on these). These two parameters can be simply and accurately calculated using neural networks with very limited input data. Some “geometric” parameters are also significant, the best of these being width, W, for rectangular halls.

INTRODUCTION

It is a century since an expression for reverberation time was developed (Sabine 1922). While there has been a plethora of papers published on auditorium acoustics in the interim the galling fact is that some of the most respected halls, acoustically speaking, were designed and built before Sabine or with little or no credible scientific input. During the same time there have also been acoustically unsatisfactory concert halls designed with the aid of sophisticated physical and numerical models.

One reason why it is still difficult to guarantee successful acoustical designs is probably that the most important decisions about the design of a concert hall, such as size, shape and number of seats, are made at the early stage of a design. Such decisions cannot readily be changed by the time there is sufficient information to support a numerical model investigation. What is needed are better design guidelines, rules of thumb or other methods of ensuring sound decisions are made at the outset. It is the search for such information that this paper is about.

There are of course many reasons why concert hall acoustics is more of an art than a science. There are so many factors to be considered (if there are less than six parameters it is science and if there are more than seven it is art), some of which are contradictory, that acoustic design will remain an art for many years to come and so concert hall researchers can rest assured that they won’t be put out of business soon.

Amongst the issues faced by researchers and designers are:
1. The difficulty in obtaining reliable subjective assessments of different concert halls.
2. Who should assess the acoustics; musicians, audiences or music critics for instance?
3. The variability in assessments of optimal acoustical conditions.
4. The dependence of acoustical measurements and subjective assessments on seat position. Are acoustical judgements made on the basis of the best, worst or average seat or on the stage?
5. Insufficient data or inaccurate data on halls.
6. The influence of performers and repertoire on assessments and design requirements.
7. The importance of non-acoustical factors such as aesthetics, lighting, seat comfort, thermal conditions and sightlines on acoustic quality judgements.
8. Antiquity factor; older halls tend to have better reputations than newer halls.
9. Measurements as simple as reverberation time and strength factor are sometimes not reproducible within acceptable tolerances
10. Measured data and recommended values are usually for empty halls whereas subjective assessments are probably based on occupied halls.

The most important of these issues is almost certainly related to the subjective assessment of concert halls. While there have been attempts to use audiences to evaluate the acoustics of halls these have yielded little useful information. There are four broad alternative methods of subjectively assessing concert hall acoustics that have been used:
1. Single person qualitative evaluations (with or without consultations with musicians, critics etc) such as that carried out by Beranek 2004.
2. Quantitative laboratory assessments based on measured or computed room impulse response functions convolved with anechoically recorded music excerpt(s), such as that undertaken by Schroeder et al 1974 and Ando 1985.
3. Quantitative surveys of musicians and music critics on the acoustic quality of halls such as that undertaken by Fricke & Haan 1995.
4. ‘Expert’ group assessments (acoustical consultant and others) during live performances (Barron 1988)

These methods all have their limitations. Beranek’s assessments are unlikely to be reproducible and may be influenced by factors other than the acoustics of the halls. Schroeder’s method requires enormous resources if many halls, musical excerpts and seat positions are to be assessed. Even then reproduction of sound in an anechoic space cannot reproduce some properties of the sound, such as sidewall reflections, without many loudspeakers. Surveys of musicians are coloured by many unknown factors such as where and when and what music the assessments were based on and there are temporal and geographical limits, amongst other matters, to getting a group of experts together to hear the same concert performed in different places.

EXISTING DESIGN GUIDLINES

Design guidelines can be categorized as either acoustical or geometrical. The two categories are obviously linked as the acoustics of a space are determined by the size, shape and surface finishes of a room. While the surface texture and materials of hall surfaces can vary significantly from hall to hall the main influence on the acoustics, besides the size and shape of the hall is the absorption of the audience/seating, provided that the walls and ceiling are reflective (ie. sound absorption in a concert hall is largely determined by the number of seats in it) and are not flat or concave. Acoustical guidelines have the advantage there are less of them and that they give designers more flexibility in determining the size shape and surface finishes. Geometrical design guidelines however are usually preferable because of their simplicity and applicability, particularly at the early design stage.

Examples of the main existing geometrical guidelines are:

Volume per seat: $6<V/N<8$ m^3

Rectangular halls are better than other shapes

Long narrow rectangular halls are better than short wide ones

There should be less than 3000 seats

Seats should have similar sound absorbing properties to people sitting in the seats

The walls and ceiling should not be flat or concave and they should have diffusing elements on them.

The stage area should include a shell or overhead reflectors

Balconies should be shallow

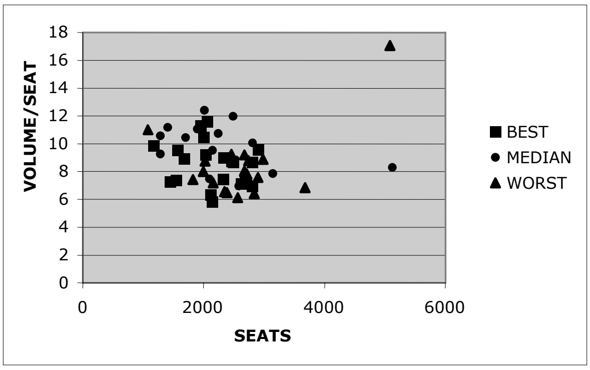

***Figure* 1.** The design guideline of 6<V/N<8 does not guarantee a successful hall but it does eliminate a few of the worst and many of the best.

Examples of the main existing acoustical guidelines are:

Unoccupied reverberation time approximately 2 seconds. This is sometimes specified as an EDT where $EDT_{mid} \approx 1.1*RT_{mid}$ (Mehta 1999)

Background noise < NC 20

A large spatially averaged G_{mid} (> 5dB)

Binaural quality: $(1\text{-}IACC_{E3}) > 0.6$

Bass ratio: $BR > 1.1$

Clarity: $-5 < C_{80} < -1$ dB

Stage support: $-14 < ST1 < -12$dB

Initial time delay gap: $t_I < 25$ms

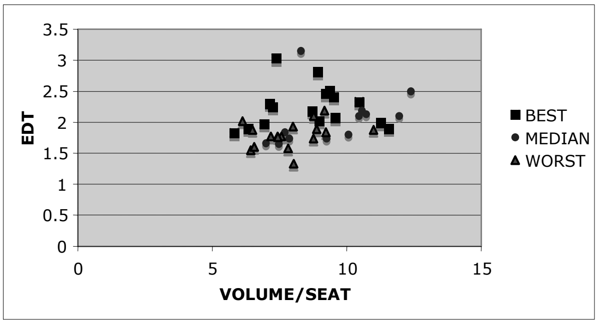

***Figure* 2.** Reverberation (EDT) is a better indicator of acoustic quality but does not guarantee success even when combined with V/N. Note that the *Best* halls are in the range 6<V/N<12 and an EDT>2.2 largely ensures a high acoustic quality but an EDT<2.2 does not preclude a high acoustic quality.

Perhaps because of their simplicity and ease of calculation the most used guidelines appear to be $6<V/N<8$ m^3 and $1.8<RT<2.2$ but, as shown in *Figure* 1 and *Figure* 2, these are not good indicators of acoustic quality.

METHODOLOGY

The approach used in the present study is a very basic one. There is published data available (Beranek 2004) on the size, shape, seating capacity, subjective acoustical quality and objective acoustical characteristics of many concert halls. Beranek also gives acoustical quality assessments of 58 halls. This information, which forms the basis of the current study was used is because it gives a "consistent and current" evaluation of the acoustic quality of concert halls even though the data may not be as objective as one would wish.

The subjective evaluations of Beranek were used in the present analysis using his three groupings (*Best*, *Median* and *Worst* quality halls) with a minor change: four. Four halls were omitted from the analysis, three because of insufficient information and one because it was an opera hall. Acoustical information on some of the 54 halls used was incomplete.

A statistical analysis of the relationship between the available "geometrical" and "acoustical" data on the halls in the three acoustical quality categories was undertaken using a Student t-Test of significance. Ideally there would be significant differences (Pr < 5%) between the average values of the different parameters in the three categories, though it has been shown (Fricke 2000) that there appear to be non-linear interactions between these parameters which may mean this type of analysis does not yield useful information. Nevertheless the analysis should be considered before more complex, data hungry, analyses are carried out.

The hypotheses to be tested are that:

1. There are better geometric predictors of the acoustic performance of concert halls than those commonly used at present.
2. Sound strength (or strength factor as it is often called) is the most important acoustic discriminator between the

acoustically *Best* concert halls and those in the other two categories.

When testing for significance of differences, in mean values of parameters, in the *Best* (*B*), *Median* (*M*) and *Worst* (*W*) halls a two-tailed, two-sample equal variance test was used (One-tailed F-Tests were undertaken to check that the variances in each grouping used were not significantly different.). Ideally we would like Pr<5% for *B/M, B/W, M/W* and *B*/(*M*+*W*) but as this was not possible Pr<5% for *B/M* and *B/W* was used with Pr<5% for *B*/(*M*+*W*) as the fall-back condition.

The statistical analysis of the average acoustic and geometric properties of three categories of concert halls (*B, M* and *W*) was undertaken to see whether there are significant differences between the parameters that describe halls in the three categories. The analysis was performed on ‘All’ halls and two subgroups, ‘Rectangular’ and ‘Non Rectangular’ halls. If there are significant differences then these can be used as design guides/criteria. Data on the three hall groupings is shown in Table 1

Table 1 Number of halls in each analysis category.

CATEGORY	RECTANGULAR	NON-REC
BEST	**14**	**6**
MEDIAN	**5**	**10**
WORST	**5**	**14**

The distinction is often made between rectangular/shoebox halls and non-rectangular halls. The definition of rectangular halls is not standardized. For the purpose of this study a rectangular hall is one with parallel and vertical side-walls (±5% approx.). Balconies, decorations etc are not considered. A non-rectangular hall is any other shape. Some halls are difficult to categorize, eg Chicago Symphony Hall, while others such as Boston and Berlin are easy to categorize.

The parameters investigated are those included in Beranek’s book (Beranek 2004) and defined by him in Appendices 1and 2. Briefly these are spatially averaged early decay time (EDT), early interaural correlation coefficient ($IACC_{E3}$) and sound strength (G_{mid}), initial time delay gap (t_I), bass ratio (BR), number of seats (N), height of ceiling (H), distance from stage front to rear wall (D), width (W), length (L), volume (V), and audience area (Sa) and combinations of these parameters such as V/N, H/W and V/EDT that have been used previously as indicators of acoustic quality. Had other data been readily available eg unoccupied reverberation time (T_{30}) this would also have been included. Other parameter combinations such as $N*G_{mid}$, t_I/EDT and $D^2/(H*W)$, were also used because they were considered to introduce a normalizing factor or create a non-dimensional parameter that might help make the analysis more general.

Obviously, as far as making decisions in the early stage of a design are concerned, simple geometrical parameters are more useful than acoustical ones and hence the interest in using V/N, for instance. However acoustical parameters may also be of use as it has been shown (Nannariello & Fricke 1999) that these may be calculated using an artificial neural network (ANN) with limited geometric inputs and an estimate of the hall’s absorption properties.

RESULTS OF STATISTICAL ANALYSIS

An example of the results of the statistical analysis is shown in Table 2 for acoustical parameters. It shows that there are significant differences in the mean values of EDT/(V/N), t_I, G_{mid} and $N*G_{mid}$ for the *Best* group and the *Median* group, the *Best* and the *Worst* group and the *Best* and the *Median* and *Worst* group when all the halls are considered. However when the rectangular halls only are considered Table 3 shows that EDT/(V/N) differences are not significant for all three groupings together but $1\text{-}IACC_{E3}$ is. However for the *Best* versus *Median* plus *Worst* comparison EDT, 1-IACC, G_{mid}, t_I, and $N*G_{mid}$ differences are all significant.

Table 2 All Hall Student t-Test probabilities of the means of several acoustical parameters being the same in the *Best* and *Worst* categories (*B/W*), the *Best* and *Median* categories (*B/M*), and the *Best* and *Median* plus *Worst* categories (*B*/(*M*+*W*)). Significant difference probabilities are in bold.

VARIABLE	Pr *B/W*	Pr *B/M*	Pr *B/(M+W)*
EDT/(V/N)	**0.044**	**0.042**	**0.013**
EDT	**0.00007**	0.187	**0.002**
1-IACC	**0.006**	0.173	**0.015**
G_{mid}	**0.0004**	**0.011**	**0.00009**
t_I	**0.00007**	**0.018**	**0.0002**
$N*G_{mid}$	**0.0006**	**0.00008**	**0.000006**

Table 3 Rectangular Hall Student t-Test probabilities of the means of several acoustical parameters being the same in the *Best* and *Worst* categories (*B/W*), the *Best* and *Median* categories (*B/M*), and the *Best* and *Median* plus *Worst* categories (*B/(M+W)*). Significant difference probabilities are in bold.

VARIABLE	Pr *B/W*	Pr *B/M*	Pr *B/(M+W)*
EDT/(V/N)	0.416	**0.030**	0.059
EDT	**0.016**	0.082	**0.006**
$1\text{-}IACC_{E3}$	**0.017**	**0.032**	**0.005**
G_{mid}	**0.010**	**0.032**	**0.002**
t_I	**0.0002**	**0.034**	**0.0004**
$N*G_{mid}$	**0.009**	**0.0008**	**0.0003**

Table 4 Non-Rectangular Hall Student t-Test probabilities of the means of several acoustical parameters being the same in the *Best* and *Worst* categories (*B/W*), the *Best* and *Median* categories (*B/M*), and the *Best* and *Median* plus *Worst* categories (*B/(M+W)*). Significant difference probabilities are in bold.

VARIABLE	Pr *B/W*	Pr *B/M*	Pr *B/(M+W)*
EDT/(V/N)	0.907	0.881	0.968
EDT	0.337	0.976	0.295
$1\text{-}IACC_{E3}$	0.253	0.925	0.564
G_{mid}	0.079	0.202	0.087
t_I	0.260	0.258	0.193
$N*G_{mid}$	**0.012**	0.051	**0.009**

When the non-rectangular halls only are considered only $N*G_{mid}$ has any significant differences in mean values (Table 4) and even the *Best* and *Median* means of this quantity are not significantly different, though it is almost significant. $N*G_{mid}$ is by far the best parameter to use to ensure a *Best* result.

As expected, the results using geometrical parameters are not as good as those using acoustical parameters. The differences in mean values of geometrical parameters between the hall acoustical quality groups are less than for the acoustical parameters. Considering all halls, of the geometrical parameters investigated, only the mean values of W, H/W and L/W are significantly different at Pr<5% for *B/M, B/W* and *B/(M+W).* The mean values of N and D however are different at Pr<5% for *B/W*.

When rectangular halls only are considered there are no significant differences (at Pr<5%) in mean values of any geometric parameters for all three (*B/W, B/M* and *B/(M+W)*) cases. The best indicator of acoustic performance is again W (something which has been noted by other authors) which was significant at Pr<5% for *B/M* and *B/(M+W)* and at

$Pr<6\%$ for *B/W*. Interestingly N and N*W/H were significant at $Pr<5\%$ for *B/W*.

Considering non-rectangular halls only, the situation is that the mean value of no geometric parameter investigated was significantly different in any of the three acoustical quality groupings at $Pr<5\%$ but H and N*D/(H*W) were the two best of a poor bunch (see *Figure*3). Interestingly, V/N was more different than any other parameter at Pr=8% for *B/W* (without the Royal Albert Hall included).

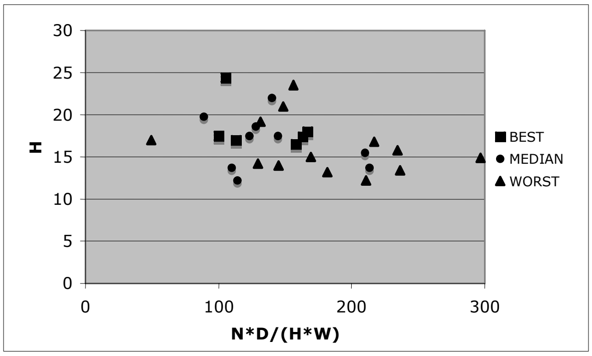

***Figure* 3**. Two of the more significant geometrical predictors of the quality of non-rectangular concert halls are H and N*D/(H*W). While there are no statistically significant values of these parameters which can be used for design purposes the chances of achieving a good acoustic outcome could be improved by using the following combined limits: $100<N*D/(H*W)<150$&$16<H<18$ or $100<N*D/(H*W)<120$ &$15<H<25$ but this would be a high risk approach.

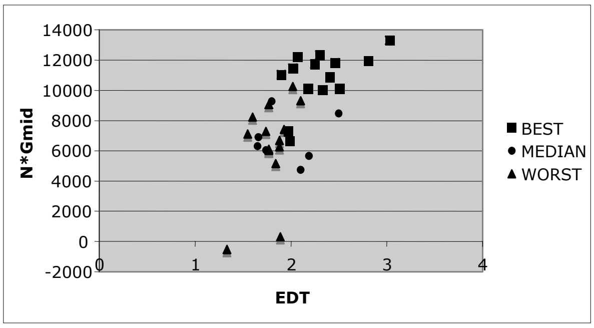

***Figure* 4.** The usefulness of $N*G_{mid}$ is perhaps more apparent when presented graphically. In this *Figure* there are fewer data points than in the statistical analysis because for some halls values of EDT as well as G_{mid} were not available.

On the basis of the above analysis the average values of parameters of most use for acoustic guidelines can be stated as shown in Table 5. Of these the outstandingly useful guideline is $N*G_{mid} > 10{,}000$ as this applies all halls no matter what shape and thus saves having to make this somewhat arbitrary distinction. However it still does not help distinguish the best from the *Median* non-rectangular halls at $Pr<5\%$ and so using $N*G_{mid} > 11{,}000$ may be more appropriate. *Figure* 3 illustrates this point more clearly.

Although not surprising, it is disappointing that no single geometrical parameter can be used as a guideline for all halls, rectangular halls and non-rectangular halls. All is not lost however as artificial neural networks can be used, embedded in spreadsheets, to estimate G_{mid} and other acoustical parameters using a combination of geometric parameters as inputs. ANNs can combine the influence of input parameters on an output (in this case G_{mid}) in ways that are difficult to achieve by other techniques. In particular ANN can handle groups or classes of data and also non-linear relationships.

Table 5 Most useful (most statistically significant) guidelines for *Best* halls.

PARAMETER	ALL	REC	NON-REC
N*Gmid (dB)	>11,000	>11,200	>10,100
Gmid (dB)	>5.5	>6.0	
t_I (ms)	<20	<20	
t_I/EDT	>0.0095	>0.009	
V/EDT (m^3/s)	>8,000		
W (m)	<27	<24	
H/W	>0.7		
L/W	>1.9		

ARTIFICIAL NEURAL NETWORK PREDICTIONS OF G_{MID}

This section presents the results of a neural network model's predictions of the sound strength, G_{mid}, based on a neural-computation concept that was investigated in previous work (Nannareiello & Fricke 2001a & 2001b). Similarly this work has two primary objectives. The first is to develop a method of predicting the mid-frequency sound strength, G_{mid}, value in auditoria using a neural network model. The imperative is that accuracy of the prediction should be within the subjective difference limen (Cox et al 1993) of G_{mid} which is ± 1 dB and should be achieved using a limited number of the most important room variables thus minimizing the internal representation of the network's dimensionality. The second objective is to embed the trained neural network on a standard spreadsheet so that G_{mid} predictions can be made directly in a very transparent and direct fashion utilising the spreadsheet's simple arithmetical formulae (Nannariello & Fricke 2002).

The data used for the present neural network analysis covers a large range of hall shapes and sizes. Concerning the shape of halls used in the 'training set', 27 are 'rectangular', 21 are 'geometric', 9 are 'fan', 5 are 'horseshoe', and 3 are 'elliptical'. The hall volumes ranged from $1824m^3$ to $86650m^3$. Ten halls were used to 'test' the neural networks. The range of data used to 'train', 'verify', and 'test, neural networks is

Table 6 Details of the 10 halls used to 'test' neural networks and for which results are presented.

HALL	TYPE	VOL	L_{MX}	TR	S_T	G_{mid}
TI	Fan	12700	46.5	0.07	1122	5.15
MW	Rec	15000	52.0	0.11	1118	6.86
ED	Hsu	16000	54.5	0.05	1472	4.05
BA	Geo	17750	44.5	0.06	1481	3.57
FH	Rec	21950	52.0	0.12	1975	1.89
CG	Rec	18700	43.5	0.05	1248	5.47
BOS	Rec	18750	54.0	0.09	1522	3.99
CTH	Ellip	20500	46.0	0.05	1596	3.80
AFH	Rec	20400	51.0	0.05	1660	3.80
PAM	Hsu	15100	31.0	0.10	1740	1.45
SOH	Geo	24600	67.0	0.08	1744	*

TI = Tivoli Koncertsal, Kobenhaven;
MW = Grosser Musikvereinssaal, Vienna;
ED = Usher Hall, Edinburgh;
BA = Barbican Large Concert Hall, London;
FH = Royal Festival Hall, London;
CG = Concertgebouw, Amsterdam;
BOS = Symphony Hall, Boston;
CTH = Christchurch Town Hall;
AFH = Avery Fisher Hall;
PAM = Philadelphia Academy of Music;
SOH = Sydney Opera House Concert Hall

shown in Table 6. Acoustical and geometrical details for the concert halls regarding the measurement systems used, the choice of source and the measurement positions both for the source and the receiver have been presented previously (Nannariello & Fricke 2001a).

The four input variables used in the neural network analysis to predict G_{mid}, are the hall volume, V, the maximum length, L_{MX}, maximum width, W_{MX}, the 'tube ratio', TR=D/(W*H) (Gade 1991), (where D is the mean distance from front of platform to rearmost wall and W and H are the mean width and height respectively, calculated according to (Haan 1993) and, S_T, the total audience acoustical area, is Beranek's S_A (Beranek 1996). The use of acoustical parameters as input variables (such as reverberation time) was deliberately avoided. The set-up function used for the neural network analyses was $G_{mid} = f(V, L_{MX}, D/W*H, S_T)$. The procedure described in previous work (Nannariello 2002) was used to embed the trained neural network model in a standard spreadsheet application. The results of the neural network analysis are presented in Table 7.

Neural networks 'trained' with only a few geometrical input variables can make useful and accurate predictions of the seat averaged acoustical parameter G_{mid}. The accuracy of the neural network predictions are reflected in the high correlation coefficient, R^2 and low root mean squared error, *RMS*, standard deviation of the errors, *Std-Err*, being 0.98, 0.31 dB, 0.32 dB respectively (see Table 7). The prediction errors are well below the subjective difference limen for the parameter G_{mid}, which is ±1 dB.

Table 7 Descriptive statistics of neural network trained with the data of 65 halls (Ref. 8) and set up function $G_{mid} = f(V, L_{MX}, D/(W*H), S_T)$ used to predict G_{mid} values for the 10 halls for which the resulting R^2= 0.98[a], Std-Err = 0.32[b], AbAv-Err = 0.27[c] and RMS = 0.31[d].

HALL	MEASURED G_{mid}	PREDICTED G_{mid}	ERROR[e]
TI	5.15	5.06	-0.09
MW	6.86	6.60	-0.26
ED	4.05	4.33	0.28
BA	3.57	3.82	0.25
FH	1.89	2.21	0.32
CG	5.47	5.02	-0.45
BOS	3.99	3.73	-0.26
CTH	3.80	3.89	0.09
AFH	3.80	3.93	0.13
PAM	1.45	2.03	0.58
SOH[f]	*	3.68	*

a R^2 = Correlation coefficient between the measured and NN predicted G_{mid} for the ten halls.

b,Std-Err = Standard deviation of errors between the measured and NN predicted G_{mid} for the ten halls (dB)

c AbAv-Err = Absolute average error between the measured and NN predicted G_{mid}, for the ten halls (dB)

d RMS = Root mean squared error between the measured and NN predicted G_{mid}, for the ten halls (dB)

e, Error = Error between the measured and NN predicted G_{mid}, for the ten halls (dB)

f NN spreadsheet model was used to predict G_{mid} for the Sydney Opera House Concert Hall, SOH, but was not used in the above statistical analysis due to the unavailability of reliable measured G_{mid} data.

CONCLUSIONS AND DISCUSSION

As mentioned previously the two hypotheses to be tested were:

1. There are better geometric predictors of the acoustic performance of concert halls than those commonly used at present.
2. Sound strength (G_{mid}) is the most important acoustic discriminator between the acoustically *Best* concert halls and those in the other two categories.

The first of these hypotheses was partially confirmed. There were three parameters, W, H/W and L/W whose mean values were statistically different in the *Best* and *Median* (*B/M*) and *Best* and *Worst (B/W)* groupings when all halls were considered but none of the mean values of V/N were significantly different. However the *Best* group of halls was dominated by rectangular halls while the *Median* and *Worst* hall groups had more non-rectangular halls than rectangular halls in them which no doubt goes a long way to explaining these differences

Considering only the rectangular halls produced only one parameter, W, the mean value of which was significantly different between the *Best* and *Median* groups and very nearly so between the *Best* and *Worst* groups. This supports previous findings that W is an important parameter. Another parameter, N, which is also considered important was significantly different in the *Best* and *Worst* groups with the *Best* group having less seats on average than the *Worst* group (again something which has been observed by others).

Considering only the non-rectangular halls, no geometric parameter was significantly different in each group with $N*D^2/(H*W)$ being the best available to distinguish between the *Best* and *Worst* groupings (Pr=0.11). The mean value of V/N was different in the *Best* and *Worst* groups (Pr=0.08) when the Royal Albert Hall (a hall in the *Worst* group and by far the largest hall in the study and with the largest V/N) was eliminated from the analysis but when the RAH was left in Pr=0.66. In other words the *Worst* halls tend to have low V/N values but some, such as the RAH, have very large values.

The second hypothesis was also supported but even more importantly the analysis showed that the mean value of $N*G_{mid}$ was significantly different in all cases. Why is $N*G_{mid}$ so good especially when factors such as background noise seat comfort and aesthetics cannot be taken into account by this factor? Why should $N*G_{mid}$ be a better parameter than G_{mid}? What are the implications of this result?

It is possible that $N*G_{mid}$ is a chance result but this is highly unlikely. Beranek may have introduced personal preferences that favoured halls with a high $N*G_{mid}$. Again this is unlikely, or rather less likely than favouring halls with a high G_{mid}. G_{mid} measurements are difficult to make and has been pointed out (Beranek 2004) there are differences between Japanese and European measurements and between measurement made by different workers in a given hall but it is difficult to see how this might favour $N*G_{mid}$ over G_{mid}.

A possible explanation is related to opinions on the acoustic quality of a hall being determined by factors other than acoustical parameters, eg background noise, visual or comfort issues. Perhaps there is an acceptance that halls with a large number of seats will have lower G_{mid} values for instance, although this can only be a partial explanation.

Despite the limitations inherent in the present work there are some general conclusions that are worth stating. The main limitations are that the assessment of the acoustic quality of concert halls is questionable; as always, there is a paucity of usable data; the results only apply within the range of the data on which it is based; and background noise levels were not considered. The following points seem clear however:

- V/N is not a useful predictor of acoustic quality.
- There are a number of geometrical and acoustic parameters that can be used to distinguish between the *Best* and *Worst* halls but the parameters that can distinguish between the *Best* and *Median* halls is more limited.
- While there are both geometrical and acoustic parameters which can distinguish between the *Best* and *Median* halls when all halls are considered this result could be because of the different proportion of rectangular and non rectangular halls in each group.
- It appears from this work that there is a simpler and better way of ensuring good sound quality in concert halls than any parameter or method proposed previously: the use of $N*G_{mid}>11,000$.
- As G_{mid} can be accurately predicted (within 0.5 dB) using a simple artificial neural network with inputs of V, L_{MX}, S_T and D/(W*H) this method appears to be potentially more useful for design purposes than other numerically based methods, especially in the early stages of a design. (As room acoustical parameters are dependent on the room size, shape and surfaces finishes it would seem unlikely that an analysis that does not take into account room surface finishes is unlikely to be useful. However it is likely that the audience and seating provide most of the absorption and much of the diffusion in concert halls and hence is represented by the S_T value.)
- For rectangular halls the best geometric parameter for use as a guideline is W<24m.
- For non-rectangular halls there is no justifiable geometrical design guideline.

Finally, although the parameter $N*G_{mid}$ seems to be the best available one to use for the acoustic design of concert halls it must be remembered that other factors such as reverberation time, diffusion and background noise levels also have to be considered to achieve a satisfactory outcome. EDT is reasonably well correlated to G_{mid} (r=0.74). Both diffusion and background noise appear to be adequately catered for in most concert halls whether they are judged good or bad acoustically. Background noise is perhaps over-designed for as the recommended levels are below NC 20 while the breathing noise of an audience is greater than NC 25 (Kleiner 1980). Perhaps, like audiences in an NC 15 hall, we should hold our breath at this point.

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