Predicting the Acoustics of Concert Halls Using an Artificial Neural Network

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Abstract: An alternative approach to the design of concert halls, using artificial neural networks, has been investigated. As part of the study, visiting musicians and conductors were asked to complete a questionnaire on their preferences for over 60 concert halls, most of which were located in Europe and North America. A similiar survey was carried out using members of the Music Critics Association in the USA. These results were used to correlate hall preferences with physical features of the halls. It was found that the single most important feature affecting the acoustics of halls was the diffusion of the interior surfaces. A preliminary neural network analysis showed a high correlation between the predicted and assessed acoustical ratings of halls when only seven geometrical factors were used to describe the halls used in the study. The paper also reports on the comparison of evaluations of concert halls by musicians and music critics and the preferences of both groups for different types of halls.

1. INTRODUCTION

There appear to be several ways in which the complexity of acoustic design of concert halls is handled. One way is to copy or modify an existing building, another is to measure acoustic parameters in existing, model or virtual buildings and then to reproduce these parameters in the new concert hall. None of these is very satisfactory as there are many reasons, not the least of which are cost and inaccurate modelling and measurement, which mean that exact replicas of halls, or exact prototypes, cannot be built (or are not built). Often the acoustic design of a hall comes down to the experience of the designer who over the years gains a feel for what works and what doesn't or who has an innate understanding of what to do.

Sabine's (1900) work on reverberation time was of fundamental importance in the application of science to architectural design. Unfortunately the use of Sabine's work does not guarantee good acoustics and it would seem that despite the best efforts of Beranek (1962) and others to provide an analytic approach to acoustical design, involving factors other than reverberation time, there is still no reasonable expectation that a new concert hall's acoustic will be praised by musicians and audiences.

Concert hall acoustics is a multi-criteria and multi-parameter issue. The requirements for one criteria may be contrary to those for another. For example it is considered that a long narrow hall gives the best conditions for strong lateral reflections which have been shown to be important. The same long narrow hall would not give good conditions for intimacy which is also sought after. A longer than optimum reverberation time may be acceptable in a large hall but unacceptable in a small hall. There is little understanding of these and other interactions and the search for a single measure of acoustics continues with the religious fervour of true believers.

While there is always the hope that some quantity, such as the Interaural Crosscorrelation Coefficient (IACC), will turn out to be a single suitable acoustic measure, it seems unlikely. As described by Ando (1985) the IACC measurement requires a dummy head to face the centre of the stage in an auditorium as the measurement is dependent on direction. In some concert halls the position of the performers can be changed and in all concert halls the members of the audience can move their heads without the perceived acoustic changing. While this anomaly should not rule out the possibility of the success of IACC, or similar binaural measures, it is unfortunate if a measure of performance cannot be directly related to perceived conditions. For this and other reasons, such as the lack of success in applying conventional parametric techniques to auditorium design, it seems worth investigating other approaches.

One such approach which formalizes the successful designer's approach is the use of artificial neural networks to seek out the interrelationships in complex situations. The way in which neural networks operate has been described recently by Baillie and Mathew (1994) and so this will not be covered in this paper. Suffice to say that the use of artificial neural networks obviates the need to specify, calculate and measure acoustic quantities. The acoustics of a space depends on the size, shape and surface finishes of that space and if these factors can be adequately specified and if there are adequate examples of existing concert halls where these factors are known, and where subjective acoustic ratings have been obtained, then artificial neural networks can be used to predict how well a new hall will be perceived.

This paper should only be considered as a first attempt at applying a neural network approach as there are a number of issues which need refining.

2. SUBJECTIVE RATING OF HALLS

For this study a subjective rating of concert halls had to be obtained. It is inordinately difficult to obtain subjective comparisons of different auditoria. This is partly because people have limited knowledge of halls, partly because people tend to prefer the halls they know and partly due to a host of other factors. One of these is that the acoustical conditions in a hall vary from seat to seat and now, with halls having variable acoustics, from performance to performance and even within a performance.

Ideally a group of performers and listeners should be taken blindfolded to many halls around the world and they should play and listen to the same music in each hall and in different seats in each hall. Even this ideal scenario is unlikely to produce much useful information because of the difficulty in remembering the different halls and performances and becoming accustomed to the music. Unfortunately there is no musical equivalent of the speech intelligibility test.

The alternative is to record music played in halls, using a dummy head, and reproduce it in an anechoic laboratory where subjects can make preference judgements between pairs of "halls" without moving and without the use of semantic scales. This has been done by Schroeder (1974), Plenge (1975), Ando (1985) and others but there is always the concern that the virtual acoustics may not be the same as the actual acoustics and that there may be important non-acoustical factors which influence judgements.

Somerville (1953) argued that the best group of subjects for surveys on the acoustical quality of halls are music critics because they gave more concordant answers than performing musicians, engineers, and the general public. But, in his research, only ten concert halls in the U.K. were considered. Parkin (1952) also insisted that the artists tend to evaluate the halls only from their experience on the stage where the acoustic conditions could be quite different from those at the seats of the listeners. Surprisingly there does not appear to have been an attempt to correlate the judgements of musicians and critics about existing concert halls to test these contentions. Such a comparison is reported in this paper.

In practice, if the acoustic evaluation of concert halls is to be extended beyond national borders, to maximize the range of designs studied and minimize prejudices, some of the best people to make these evaluations are internationally acclaimed conductors and soloists as they have the knowledge of halls, the expertise to evaluate them, many opportunities to visit halls, due to regular concert engagements, and the need to consider what the audience hears rather than just the stage acoustics. It could be argued too that if musicians don't like the stage acoustics the acoustics in the auditorium are unlikely to be judged as excellent as the music played in the hall will be adversely affected by the stage acoustics.

Past questionnaire surveys have been of two types: one favouring preference comparisons, the other semantic differential ratings. Preference comparisons were undertaken by Hawkes and Douglas (1971) and Schroeder et al.(1974) whilst semantic scales were used by Wilkens (1975) and Barron (1988).

Parkin et al.(1952) described a subjective investigation of ten British concert halls by means of a questionnaire sent to people who were music critics, music academics and composers. Of the 170 questionnaires sent out 75 were returned. Only 42 of these responses could be used to be evaluate halls because the rest had experience of less than three of the named halls in the questionnaire. This study is the first known attempt to rate the general acoustic quality of halls numerically using subjects from the music profession. The evaluation of the halls was made using a three point scale (good, fair and bad).

Beranek (1962) interviewed 23 musicians and 21 critics to judge the acoustic quality of the 54 halls (ie. 35 concert halls, 7 opera halls and 12 multi-purpose halls) in his study. These acoustic quality judgements were used to construct numerical rating scales of acoustic attributes. The 54 halls were classified into five groups based on the musicians' impressions and evaluations. Beranek interviewed outstanding musicians as a first source of reliable information in his study of halls for music.

In the present study it was decided to ask musicians to evaluate the acoustics of halls using a self-administered questionnaire. The present survey was designed to reassess the acoustics of many halls used in Beranek's study and also to include as many different shapes of halls as possible in order to investigate the effects of hall geometry on the acoustic quality.

3. THE QUESTIONNAIRE

The present work appears to be the first international study of halls, undertaken since Beranek's in 1962, to quantify acoustic quality from systematic subjective responses. The questionnaire used in the study employed a three point scale (like Parkin used) and included concert halls only.

3.1 Questions

In the survey, using a self-administered questionnaire, respondents were asked to express their opinions on the acoustics of up to 75 concert halls. Respondents were asked to make judgements about the acoustics of halls for classical symphonic music. The questionnaire included questions about preferences for music and concert halls. A list of concert halls was included and respondents were asked to rate them acoustically, based on their experience, as either excellent, good or mediocre. The terminologies used for three levels of acoustic quality were suggested by Lawrence (1983).

A three point scale was employed for rating acoustical quality of the halls because it simplifies the subject's task and makes the difference clear. As all the listed halls in the present survey are well known and are regularly used for concerts the acoustics of these halls are not likely to be bad. Thus the ordering scale was designed to start from "mediocre" and used "good" and "excellent" as the other two steps.

3.2 Selection of Halls

Most of the halls listed in the questionnaire were located in Europe and North America. The halls were chosen because information about them was readily available in the literature and because they are well known, so the sample is not a random one. The list of halls includes halls with four different shapes, ie. rectangular, fan, horseshoe and geometric, although categorization into one of these was not always easy. The list of halls was altered slightly during the three years in which the questionnaire was administered so that the number of assessed halls could be maximized. A sample of the concert halls which were listed in the questionnaire, and for which there were sufficient responses to make evaluations, is shown in Table1.

3.3 Respondents

The subjects for this survey were drawn from two groups: musicians who performed in Australia during the 1990, 91 & 92 concert seasons and members of the Music Critics Association in the USA. The music critics' results were used to compare the ratings of musicians with music critics and, to some extent, the stage acoustics with the auditorium acoustics of halls.

Most of the musician questionnaire respondents were conductors and soloists from Australia, Europe, Japan and North America, who have performed as guest artists with many different orchestras in many auditoria in many countries. One of the added advantages of using this cohort of musicians is that the results should not be influenced by local cultural factors. A total of 110 questionnaires were sent to musicians. Thirty five responses were obtained (ie. a 29 % response). The respondents came from 12 countries and comprised 16 conductors, 13 soloists and 3 other musicians. All the musicians were professionals who performed regularly in many auditoria. Among the 32 musicians, 21 performed more than once a week and the rest performed at least once a month.

A second evaluation of concert halls was undertaken using members of the Music Critics Association of the USA. Despite the limitations of a poor response rate (approximately 10%), limited knowledge of halls outside the USA, possible preconceptions and other confounding influences, overall there is a strong correlation between the opinions of the musicians and the critics. Opinions on individual halls did differ between the two groups but the most notable point was the spread of opinions on a number of the halls within each group of respondents.

4. ACOUSTIC QUALITY INDEX OF HALLS

Respondents commented on 60 of the halls listed in the questionnaire. The largest number of halls any individual respondent rated was 41. A total of 805 ratings were obtained from the musicians. The average number of ratings for each hall was fifteen with a maximum of 30 for the Sydney Opera House Concert Hall. For the evaluation of the acoustic quality of a hall at least 5 responses were required.

For estimating the goodness of the halls a value of 1 was assigned to those assessed as 'Excellent', 0.5 to 'Good' and 0 to 'Mediocre'. An acoustic quality index (AQI) for each hall was calculated by averaging the rated values. The "musician" AQI values of halls are distributed in the range 0.22 (Henry & Edsel Ford Auditorium, Detroit) to 0.98 (Grosser Musikvereinssaal, Vienna) while the "critic" AQIs ranged from 0.19 (Gasteig Philharmonie Hall, Munich) to 0.94 (Symphony Hall, Boston). The "musician" AQI values for each hall are listed in Table 1 with the details of the number of responses on which the AQI was based.

The acoustic quality of halls, as rated by the music critics, is compared with the ratings of the same halls by musicians in Fig 1, for the halls for which there were sufficient responses from both groups. The agreement is surprisingly good considering that the acoustics of the stage and auditorium in a given concert hall could be very different. There appears to be better agreement between the ratings of critics and musicians in conventional shaped halls than in fan or geometrically shaped halls such as the Berlin Philharmonie.

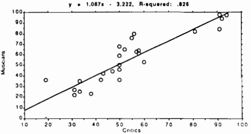

Figure 1. Scattergram of hall AQIs as determined by critics and musicians.

5. ACOUSTIC QUALITY DEPENDENCE ON HALL GEOMETRY

To undertake a neural network analysis it is not necessary to investigate the correlation between different parameters and the acoustical quality of the auditoria but such an analysis is of general interest and so some of the relationships are reported on below. In the present study 28 of the 32 musician respondents said they had a particular preference for hall shape for symphonic music. Regarding the hall type it was found that 21 of the 28 musicians (75%) who answered this question preferred rectangular concert halls. The second most common preference was for horseshoe type halls. This is in accordance with the finding of Gade (1981) who indicated that musicians preferred shoebox type halls as an ideal room shape. Nine of the twenty halls (45%) which have AQI's of 0.60 or better are rectangular in shape whilst only 19 of the 53 halls surveyed were rectangular halls (36%). As might be expected this is a similar trend to that for the musicians preferring rectangular halls.

While the overall acoustic impression of symphonic music played in halls was used to estimate the acoustic quality index of each hall, the appropriate shape of halls for other types of

Table 1. Acoustic quality index of concert halls.

Concert Hall	Hall Type	Total	E	G	M	AQI (musicians)	AQI (critics)
			(musician responses)				
Grosser Musikvereinssaal, Vienna	REC	26	25	1	0	.98	.91
Symphony Hall, Boston	REC	16	15	1	0	.97	.94
Concertgebouw, Amsterdam	REC	26	23	3	0	.94	.92
Carnegie Hall, New York	HSU	28	19	9	0	.84*	.91
Severance Hall, Cleveland	HSU	11	8	2	1	.82	.81
Gewandhaus, Leipzig	GEO	10	6	4	0	.80X	.56
Concert Hall De Doelen, Rotterdam	GEO	17	9	8	0	.77	
Berliner Philharmonie Hall, Berlin	GEO	23	14	7	2	.76	.55
Derngate Center, Northampton	REC	10	5	4	1	.70X	
Herkulessaal, Munich	REC	19	9	8	2	.68	.50
Orchestra Hall, Chicago	HSU	20	7	12	1	.65	.52
Grosser Tonhallesaal, Zurich	REC	18	6	11	1	.64	.58
The Mechanics Hall, Worcester	REC	8	2	6	0	.63	.57
Concert Hall, Haarlem	REC	9	4	3	2	.61X	
Royal Concert Hall, Nottingham	GEO	9	3	5	1	.61X	
Concert Hall De Oosterpoort	FAN	9	2	7	0	.61X	
Philadelphia Academy of Music	HSU	14	4	9	1	.61	.58
Carl Nielsen Hall, Odense	REC	10	2	8	0	.60X	
Neues Festspielhaus, Salzburg	FAN	16	3	13	0	.59	.50
Stadt-Casino, Basel	REC	12	3	8	1	.58	
Oslo Concert Hall, Oslo	FAN	8	2	5	1	.56X	
Concert Hall,Sydney Opera House	GEO	30	6	21	3	.55X	
Concert Hall, Stockholm	REC	12	3	7	2	.54X	
Palais de la Musique, Strasburg	GEO	13	2	10	1	.54X	
Usher Hall, Edinburgh	HSU	18	2	15	1	.53	.60
Liederhalle Grosser Saal, Stuttgart	GEO	14	3	8	3	.50	
St. Andrew's Hall, Glasgow	REC	13	2	9	2	.50‡	
Berwald Hall, Stockholm	GEO	8	1	6	1	.50X	
Lyric Theatre, Baltimore	REC	7	0	7	0	.50	
War Memorial Opera House, S.F	HSU	8	0	8	0	.50	.50
Philharmonic Hall, Liverpool	FAN	18	2	13	3	.47*	
National Concert Hall, Dublin, Eire	REC	13	2	8	3	.46X	
Melbourne Concert Hall, Melbourne	GEO	25	5	13	7	.46X	
Tivoli Koncertsal, Copenhagen	FAN	12	0	11	1	.46	.50
Concert Hall, Kennedy Center	REC	18	3	10	5	.44X	.47
Colston Hall, Bristol	REC	15	1	11	3	.43	
Eastman Theatre, Rochester	FAN	12	0	10	2	.42	.43
Concert Hall, Music Center, Utrecht	GEO	11	0	9	2	.4	
Radiohuset Studio 1, Copenhagen	FAN	9	1	5	3	.39*	
Royal Festival Hall, London	REC	29	6	9	14	.36	.50
Free Trade Hall, Manchester	REC	18	1	11	6	.36	
Palais des Beaux-Arts, Brussel	HSU	18	1	11	6	.36	.42
Gasteig Philharmonie, Munich	FAN	14	2	6	6	.36X	.19
Beethovenhalle, Bonn	GEO	17	2	8	7	.35	.33
Roy Thomson Hall, Toronto	GEO	10	2	3	5	.3	.19
Maison de Radio France, Paris	FAN	16	0	11	5	.34	
Grosser Sendesaal, Berlin	FAN	11	1	4	6	.27	
Avery Fisher Hall, New York	REC	26	2	10	14	.27*X	.31
Boettcher Concert Hall, Denver	GEO	10	0	5	5	.25X	.33
Barbican Concert Hall, London	GEO	26	1	10	15	.23*X	.38
Henry Ford Auditorium, Detroit	FAN	9	0	4	5	.22‡	.31

* All or part of these subjective evaluations may have been made before recent changes in the halls.

‡ Hall no longer exists.

X Hall less than 30 years old.

Where, the abbreviations used in this Table are as follows ;

REC : Rectangular hall FAN : Fan shaped hall HSU : Horseshoe (U shaped) hall GEO :Geometrically shaped hall

Total : Total number of respondents

E: Excellent G: Good M: Mediocre AQI: Acoustic quality index musical performances was also investigated. The questionnaire respondents were asked to indicate the best shape for three forms of music; symphonic, chamber & solo recital and opera. Table 2 shows the number of respondents who preferred particular hall shapes for particular music forms. The survey showed that more than half the musicians also preferred rectangular halls for chamber music and solo recitals. As expected, horseshoe type halls were preferred for operatic performances. The geometric and arena halls are obviously not popular and this preference should be considered as being more significant than the often expressed preference of musicians for wood lined interiors.

Table 2. Survey results on the preference for hall type for different types of musical performance.

Forms of Music Hall Types	Symphonic	Chamber & Solo Recital	Opera	Suitable for nothing
Rectangular	17	10	2	1
Fan Shaped	4	3	4	4
Horseshoe Shaped	6	3	8	1
Geometric & Arena	4	1	3	10
Sub Total	31	17	17	16

There is a clear preference, shown in Table 2, for rectangular and horseshoe shaped halls compared with fan and geometrically shaped halls. An analysis of preferences for hall shapes in Table 1 also shows this trend but not so clearly. Grouping the rectangular and horseshoe halls together and the fan and geometric halls with AQIs $\leq$ 0.5 and >0.5 and applying a X^2 test to the musician responses shows that the difference is significant at the 1% level (DF=1, X^2=6.878, $0.001<p\leq0.01$).

The most significant factor, by far, in producing good acoustics appears to be the degree of diffusion by the walls and ceiling. This relationship is a paper topic in itself but an example of the relationship between the acoustic quality index and a subjectively determined area weighted surface diffusivity index (SDI a.w.) is given in Fig 2 for rectangular halls. Further information is given in the following section.

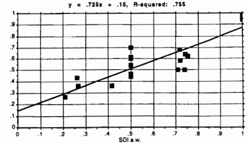

Figure 2. Scattergram of Acoustic Quality Index (AQI) against area weighted Sound Diffusion Index (SDI a.w.) for rectangular halls.

This relationship may have a non-acoustical aspect as well as an acoustical aspect. The design effort required for a hall with surface ornamentation may be an indication of the attention paid to the overall design as well as be visually more stimulating than plainer treatments.

6. OTHER FACTORS INFLUENCING PERCEIVED ACOUSTIC QUALITY

Most concert halls (94% of all halls used in the present work) have a reverberation time of more than 1.5 sec when they are occupied. The mean value of reverberation time of concert halls used in this work is 1.77 sec with the minimum reverberation time of 1.3 sec. It has been acknowledged (Beranek, 1962) that sufficient reverberation time is a crucial requirement for good acoustics. If it is assumed that good halls have adequate diffusion a long reverberation time would not be an essential condition for a diffuse sound field. When the acoustic quality index was plotted as a function of reverberation time of halls, a very low correlation coefficient was obtained (refer to Fig.3) with a large amount of scatter. This indicates that a long reverberation time is not, on its own, a satisfactory indicator of acoustic quality. This point has been made previously eg. Barron (1988) and Beranek (1962). Also it is shown in Parkins' study (1952) where the distribution of reverberation time and volume of halls are very widely scattered, regardless of the quality of halls.

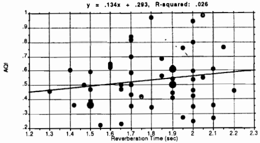

Figure 3. The scattergram of acoustic quality index against reverberation time of halls.

Interestingly, of the halls listed in Table 1, the five top rated halls were all over 30 years old (at the time of the study) and there were only two halls less than 30 years old in the top 10 halls. Of the halls listed, for which there were more than 5 responses, 23 were less than 30 years old and 30 greater than 30 years old. It should be noted that a number of the older halls have been renovated and it it is not clear whether these should be classified as new or old halls and whether the respondents were rating the halls before or after the renovations. However there is a better correlation of acoustic quality with the age of the hall than there is with the reverberation time (see Fig 4).

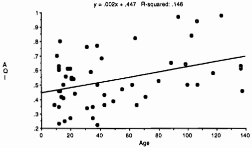

Figure 4(a). Acoustic quality of all halls as a function of age (years).

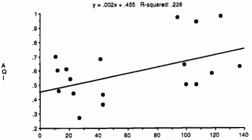

Figure 4(b). Acoustic quality of rectangular halls as a function of the age of halls (years).

It was considered possible that the judged quality of an auditorium might be related to the distance the respondent lived from the hall. There are several reasons for this including a "cultural cringe" factor (halls further away are more highly regarded) and the halls that are most familiar (near halls) being judged to give the best sound. Two analyses were undertaken using information from the music critic survey: a correlation between how good a hall is judged and the average distance away that the hall is (for all the respondents living in North America) and a second test using only the east coast critics and halls. For all the respondents there was a slight correlation ($r^2=0.2$) with the more distant halls being considered lower quality. The result was significant at the 10% level only and the relationship is considered to be an artifice of the distribution of halls and respondents (most halls and respondents lived on the east coast and most of the better halls used for the study were in the east of the USA).

Of the respondents living in the east and commenting on the east coast halls distance is not important when a Chi-squared test is carried out on two groupings: ≤250 miles distant and >250 miles distant (DF=2, $X^2=2.468$, $0.20<p\leq0.30$). If the "good" and "mediocre" categories are combined the effect of distance is significant only at the 20% level: DF=1, $X^2=2.29$, $0.10<p\leq0.20$. It might be useful to correlate judgements with the place where the respondent grew up but one can hardly design using this information and so the only possible value of it would be to indicate how important external factors are in the evaluation of halls.

Using a Chi-squared test there is a $p<.001$ that the hall ratings are from the same populations when a breakdown of halls is used such that the halls in which the five most well known orchestras usually play are separated into one group and the five other best known halls are used as the second group. (Each hall had at least 10 individual ratings and the total number of ratings for each group was 133 and 130.)

Table 3 Comparison of hall ratings with resident orchestras

Hall Rating	A Halls	B Halls	A Halls	B Halls
Excellent	79	23	Boston	Meyerhoff
			Chicago	Avery Fisher
Good	40	68	Severance	San Francisco
			Carnegie	Kennedy Centre
Mediocre	14	39	Philadelphia	Rochester

This is not very convincing evidence that it is the orchestra that determines what respondents think of the acoustics of an auditorium because it could well be that the better orchestras evolve around the better halls and besides it is not known what orchestras were playing in the halls when the respondents made their judgements (the New York Symphony Orchestra plays in the Avery Fisher and the Philadelphia Orchestra plays in Carnegie Hall, for instance, and all orchestras go on tour).

7. NEURAL NETWORK ANALYSIS

For the neural network analysis only the musician responses were used as the music critics did not comment on sufficient halls for which other data was available.

A neural network analysis was undertaken to find the best combination of parameters for the prediction of good acoustics of halls. Neural network analyses are mathematical models of theorised mind and brain activity which learn knowledge on interconnected variables by adaptive simulation. The neural network is applicable to situations where only a few decisions are required from a massive amount of data and situations where a complex nonlinear mapping must be learned (Simpson 1990). In the neural network analysis only geometrical data on the halls were used for the prediction of the acoustic quality of halls.

Geometrical data on 53 concert halls was obtained together with subjective evaluations. The halls used in this study are those for which published data is readily available in publications and for which scaled drawings are available. The plan and section in the 1/400 or 1/500 scale was used to measure the geometric properties of halls. The sample, therefore, is unlikely to be random. The geometrical parameters used are shown in Table 4 with the abbreviation for each.

Hall depth (HD) is defined as the distance between the proscenium wall and the rear wall. HW is the horizontal distance between the side walls in rectangular halls. In the case of non-rectangular halls, the hall width is the average

Table . Auditorium parameters used in the investigation.

No	Geometrical Parameters of Auditorium	Abbreviation	Unit
1	Room Volume	V	m3
2	Number of Audience Seats	N	seats
3	Total Floor Area	St	m2
4	Audience Seating Area	Sa	m2
5	Volume per Seat	V/N	m3/seat
6	Volume per Floor Area	V/St	m
7	Seating Density	Sa/N	m2/seat
8	Hall Depth	HD	m
9	Average Hall Width	HW	m
10	Average Hall Height	HH	m
11	Depth to Width Ratio	D/W	
12	Depth to Height Ratio	D/H	
13	Width to Height Ratio	W/H	
14	Angle of Side Walls	ASW	degree
15	Maximum Rake Angle of Seating	XRA	degree
16	Mean Rake Angle of Hall	MRA	degree
17	Surface Diffusivity of Hall	SDI	

width of the plan which is converted to rectangular one that represents the same area of the original hall where the HW is calculated based on fixed HD. The hall height, HH, is the mean distance between the floor and the ceiling. The angle of the side walls, ASW, is a simple measure of the shape of the halls. ASW is the included angle of the side walls which is 0 for rectangular halls. Two rake angles of the seating were used; the maximum rake angle of the seating, XRA, and the mean rake angle, MRA. The surface diffusivity of a hall is a measure of how irregular the surfaces are. For this study the evaluation of diffusivity of surfaces was undertaken by visual inspection. A simple categorisation was used as it is difficult to subjectively differentiate surfaces using more than a three point scale. Surfaces were placed in one of three categories depending mainly on the irregularity of the surfaces and to a lesser extent on the absorption of those surfaces. The three categories used were high, medium or low diffusivity. The criteria for the classification of diffusiveness of surfaces and weighting procedures are presented in a previous paper (Haan 1993). For numerical evaluation of the effect of diffusivity of the surfaces a value of 1 was assigned to the 'high', 0.5 to 'medium' and 0 to 'low' diffusing surfaces. A surface diffusivity index (SDI_{av}) for each hall was calculated by averaging the diffusivity of the ceiling and walls to obtain an SDI_{av} in the range 0 to 1. It should be mentioned that the categorisation used in the present work is a first attempt at a simple method of defining diffusivity of surfaces and that better ways of defining and categorising of surfaces should be attempted. Likewise, better ways of defining the geometry of halls also need to be investigated.

Using the above, easily determined, parameters a correlation matrix was formed. The parameters with the highest correlations with AQI were used in the subsequent neural network analysis. The correlation matrix is shown in Table 5.

Table 5 Correlation matrix of geometrical parameters and AQI.

	AQI	V/N	Sa/N	D/W	W/H	ASW	MRA	SDI
Acoustic quality index	1							
Volume/seat	-.052	1						
Seating density	-.116	.657	1					
Hall depth to width ratio	.353	-.234	-.352	1				
Hall width to height ratio	-.408	.353	.455	-.592	1			
Angle of side wall	-.425	.282	.093	-.304	.319	1		
Mean rake angle	-.135	.280	.312	-.417	.156	.198	1	
Surface diffusivity index	.783	.078	-.100	.302	-.440	-.240	-.249	1

There are two stages in the procedure of neural network analysis ie. training and testing. The training of a network is the making of a network model which learns the pattern of input data and stores the weights which contain knowledge about the correlation between the network configuration and the characteristics of input data. Fig. 5 illustrates the flow diagram of neural network procedures undertaken in the present study. The geometric data described earlier in this section were adopted as input variables for analysis.

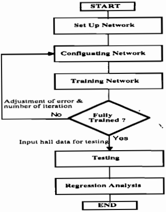

Figure 5. Flow diagram for simulating procedures of a neural network.

The program used in the present study was Dime (version 1.2) which was designed for especially estimation and approximation purpose. The neural network analyses were carried out using a micro Sun workstation.

It is important to have even distribution of sampled data for the both training and testing sets of halls. The data on input and output variables should be evenly distributed in order that the information covers the full range of possible values. Two basic criteria were used to select halls for both the training and testing sets. The percentage of each hall type of hall in each set should be similar (approximately 20%) and the AQI values of halls for testing should cover the AQI range used for network training. Table 6 shows the required number of halls for testing. Ten of the 53 concert halls were chosen as halls for testing networks. And the rest of the halls (ie. 43 halls) were used for training the networks.

Table 6. The number of halls for testing networks.

Hall Type	Number of Halls in Sample	Number of Halls for Testing	Percentage of Halls used for Testing (%)
Rectangular	19	4	21.0
Fan	11	2	18.2
Horseshoe	7	1	14.3
Geometric	16	3	18.8
Sub-total	53	10	18.9

The ten concert halls which were selected for testing networks are listed in Table 7. The geometric halls included one circular hall. The average acoustic quality indices of the both sets of halls are shown in Table 8 with the range of the values.

Table 7. The list of concert halls used for testing the network model.

No.	Hall Name	Type	AQI
1	Concertgebouw, Amsterdam	Rectangular	0.942
4	Carl Nielsen Hall, Odense Concert House	Rectangular	0.600
3	Stadt-Casino, Basel	Rectangular	0.583
2	Royal Festival Hall, London	Rectangular	0.362
5	Tivoli Concert Hall, Copenhagen	Fan shaped	0.458
6	Grosser Sendesaal, Sender Freies Berlin	Fan shaped	0.273
7	Philadelphia Academy of Music, Phil.	Horseshoe shaped	0.607
8	Concert Hall De Doelen, Rotterdam	Geometrical	0.765
9	Berwald Hall, Stockholm	Geometrical	0.500
10	Roy Thomson Hall, Toronto	Circular	0.350

Table 8. The average AQI of both sets of halls used for training and testing networks.

	Halls for Training	Halls for Testing
Number of Halls	43	10
Mean AQI (Std. Dev.)	0.531 (0.183)	0.544 (0.203)
Range of AQI	0.222 - 0.981	0.273 - 0.942

8. RESULTS

The seven major geometrical attributes (highest correlations with AQI) were used as input variables for the neural network analysis. Thus a network function was set up as follows ;

AQI = f (V/N, Sa/N, D/W, W/H, ASW, MRA, SDI)

For the calculation of acoustic quality, based on the geometry of the halls, the data on the geometry of 43 halls were used to train the networks. For the learning procedure the convergence criteria was set to 0.000001 (error margin) and the number of iterations started from 1,000,000 times. If the network converged (ie. the network is fully trained by the input data) the calculated acoustic quality of the trained halls should be the same as the real acoustic quality index of the halls. Fig. 6 shows the training regression line which has an r-squared value of 1. This indicates that the network model used was fully trained that the prediction of acoustic quality of the new halls would be possible to undertake.

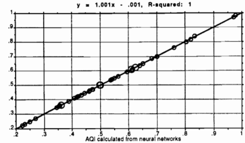

Figure 6. The scattergram of acoustic quality index against calculated acoustic quality of 43 halls which were used for training of the neural network.

Further analysis showed that the highest correlation coefficient was obtained when 5 geometric parameters (D/W, W/H, ASW, MRA, SDI) were used. Except for MRA, all these parameters have a high linear correlation with the acoustic quality of halls. Fig. 7 shows an r^2 value of almost 0.7 (r=0.835) when these parameters were used as input variables for the neural network analysis.

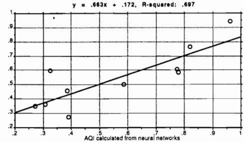

Figure 7. The scattergram of acoustic quality index against calculated acoustic quality of 10 concert halls which were predicted by neural network analysis.

8. DISCUSSION AND CONCLUSIONS

The present study indicates that musicians and music critics have very similar opinions of halls. Previous concerns that the perceptions of players and audience members could be very different do not appear to be justified, with the possible exception of "geometrically" shaped auditoria. What is of more concern is that there are pronounced differences in opinion on the quality of the acoustics of a given hall. In some cases there were approximately equal numbers of musicians (and music critics) rating a hall as "excellent", "good" and "mediocre". Examples of such cases are Berlin Philharmonie

Hall, Berlin, Roy Thompson Hall, Toronto, NHK Hall, Toyko, the Academy of Music, Philadelphia and Joseph Meyerhoff Symphonie Hall, Baltimore. The shape of the hall is significant. There is a marked preference for rectangular and horseshoe shaped halls over fan and geometrically shaped halls. More important appears to be the decoration and surface finishes in the halls which, besides influencing the diffusion of sound, also may be an influence on responses in other ways.

An individual's rating of an auditoria appears to depend on personal experiences and on factors other than just the hall's acoustic characteristics, as indicated by the dependency on the resident orchestra and the distance the respondent is from the hall on the acoustical rating and expressions of preference for rectangular halls. The reverberation time of a hall does not appear to be important though it must be stressed that the range of reverberation times was small. The age of an auditorium is of minor importance with the older halls being considered better.

Whatever acoustical analysis is carried out for the design of a concert hall ultimately there is a need to establish a relationship between the geometry and the acoustic quality of halls. Using an artificial neural network this has been done. The reason for undertaking the analysis in this way is because this analysis is of greater use for designers, at least in the initial stage of the design, as it directly links physical form with acoustic performance. This is, however, at the expense of understanding what is going on and designing within the limits of parameters used in existing auditoria. The analyses carried out indicate that there is a good basis for using hall geometry as a measure of acoustic performance. This paper also indicates the importance of the several geometrical factors on the acoustics of halls. It appears that the present predictions are better than any based on acoustical measures of concert hall acoustics.

It should be also mentioned that most of the halls used in this paper are well known halls which are regularly used for concerts. This means that most of the halls are acoustically good. Although the results clearly show a relationship between acoustic quality of halls and the geometrical properties of halls it should be reemphasized that the halls chosen for this study can not be considered a random sample. The halls are all 'good' halls and so the geometry of these halls can only be considered to influence how good the good halls are. The present paper, nevertheless, shows the importance of shape and other geometrical properties in concert hall design.

There is a need for further work. The most obvious is the need to put objective measures of hall shape and surface finishes into the analysis. This work will be undertaken together with the development of a "music intelligibility test" for auditoria which, if successful, would obviate the need for surveys such as that described early in this paper. Finally, although both musician and music critic opinions were sought for the present analysis, only the musician results were used in the neural network analysis. It would be interesting to extend the analysis for strictly auditorium rather than "stage end" acoustic design but this is also possibly pointless. After the musician survey had been carried out Leo Beranek was critical of it because it was going to be stage-end biased. At his instigation the survey of music critics was carried out. When shown the good correlation between the two surveys Beranek commented to the effect that it was to be expected as music critics formed their opinions based on what they heard from musicians!

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