ON THE STRUGGLE TO FIND A SET OF ROOM ACOUSTICAL PARAMETERS THAT EXPLAINS AND PREDICTS SUBJECTIVE RANKING OF CONCERT HALLS

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1 INTRODUCTION

During the 20th century a huge number of room acoustical parameters to describe concert hall acoustics were suggested. Too many, in the opinion of acousticians, who by the beginning of millennium arrived at some consensus expressed by the proposed set of five parameters now found in ISO 3382. One should expect that this quintet would prove to be able to explain and predict the subjective ranking of concert halls, e.g. Beranek's extensive rank-ordering of 58 concert halls. Indeed, Beranek has found high correlation between objective and subjective parameters, though not with the five aforementioned ISO-parameters. This author has (ICA 2010) pointed at some unsettling issues regarding former approaches, including the assumption of linearity and the uncritical use of hall average values representing the noticeably different listening conditions found throughout high-ranked halls (IOA Oslo 2008). Among the objectives addressed in this paper is a recent study based on Gade's 126 impulse responses measured in 11 European halls[4], Beranek's 58 hall rank ordering[3], a critical comment on linearity and orthogonal parameters, and a new method for testing parameter relevance, suggested by this author. A hundred years of reverberation time, but we still haven't found what we are listening for (sic). This paper is a status report on the struggle to find a set of acoustical parameters that explains and predicts the subjective ranking of concert halls.
Details regarding parameters and hall data are given in Annex.

2 PREVIOUS WORK

2.1 Hall averages values vs values at listeners' ears

It has been common to describe the acoustical qualities of a hall by its average parameter value, e.g. the average reverberation time (RT) measured with different source-receiver positions. While the hall average could be an adequate representation of a global parameter like the RT, this is not evident for the parameters in general since most of them are spatially dependent. The parameter for sound strength, G, tend to change by at least 1dB per 10 meters as source receiver distance changes, even in concert halls with preferred reverberance. The dryer the hall, the more does G change in dB per meter. In dryer halls the rate of change is even more. Closer to stage, where direct sound dominates over reverberant sound, both sound strength G and clarity C will increase dramatically. In many halls, G measured over the whole seating area may vary in the range of 0 to 10dB. In terms of just noticeable differences (JND), the latter corresponds to a variation of 10 JND. Similar noticeable variations in parameters over the seating area in concert halls can be seen in general. Therefore, it is to be expected that parameter values at listeners' ears are noticeably different from the hall average.
Skålevik (2008) [6] reported results from a computer simulation study indicating that in the case of Musikvereinsaal in Vienna, only 9% of the listeners experience acoustic conditions that can be described by the 5 hall averages of parameters corresponding to the set of 5 subjective listener aspects in ISO 3382, when respective JND's are taken into account. This means that the remaining 91% of the listeners in Vienna experiences noticeably different conditions than the average conditions. Further work showed that the reputation and quality rating of the hall could be better explained by the 5 parameters when accepting seats that varied noticeably from hall average.

2.2 Gade's 126 measurement points in 11 European halls

With the version 10, Odeon released geometric models and simulations corresponding to the 126 measurements by Gade in 11 European Halls in 1989 [4]. This was a convenient opportunity to do a number of studies on prediction and measurements of room acoustical parameters in performance spaces.

In 2010 it was demonstrated how the 4 parameters corresponding to the listener aspects Level, Reverberance, Clarity and Listener Envelopment can be predicted from RT, with the so-called TVR-predictor, where T is reverberation time, V is room volume, and R is source-receiver distance[2]. The TVR-predictor is mainly based on results from Barron's Revised Theory[11].

Further, since 10 of the 11 halls also are included in Beranek's subjective rank-ordering of 58 halls, the opportunity was taken to perform as study on correlation between objective data based on listening conditions at listeners' ears, and subjective preference data. There 10 halls have 116 parameter data sets.

A method for testing relevance of different suggested parameter-sets was presented (ICA 2010) [14].

Among the first results reported was that correlation increased about 0.7 to 0.9 when omitting one of the ten halls from the analysis (Skålevik 2010)[1]. This was interpreted as an indication that the set of five parameters may lead to misprediction of one out of ten halls.

However, the fact that very few listeners actually experience conditions corresponding to hall-average parameter values, does not by itself imply that subjective hall preference can be predicted from the average values. But it does make preference more difficult to explain. Though explanation usually includes prediction, prediction does not depend on explanation. On the other hand, explainability tends to strengthen the belief in the prediction results.

In this paper, correlation between subjective and objective data will be presented, testing the predictability potential of average data as well as point data.

3 OBTAINING "OCCUPIED" DATA

Data for the occupied condition in all 116 source-receiver combination was obtained in six different ways. Methods 1,3 and 4 use measured unoccupied LF-data, 2 use simulated Odeon data, while the four other parameters in 1 thru 4 were calculated as follows: 1) TVR-prediction using occupied reverberation T and volume V mainly from Beranek, partly from Barron, and source-receiver distances R from the Odeon models. 2) Same as 1) but T calculated in Odeon. 3) Measured values corrected by differences calculated with TVR, T from Beranek (and Barron); 4) Same as 3) but T calculated in Odeon. 5) Measured data corrected for occupancy by calculated increments in Odeon; 6) All values simulated measurements in Odeon 10. These form the six objective data sets that will be used below.

While #1 is a set for analyzing explanability, #2 and #6 are data sets for analyzing predictiability from scratch. #3, #4 and #5 can provide partly explanation, partly prediction of smaller changes.

Data sets #1, #2 and #6 are considered the more important in this study.

4 OBTAINING OBJECTIVE SINGLE RATING NUMBER

In order to adapt objective data that can be compared directly with Beranek's rank-ordering, it is necessary to come up with an algorithm that computes a single-number value from the large amount of data measured or simulated in the many source-receiver combinations of each halls. Each receiver combination has five parameters with usually 6-8 octave bands each. While frequency averaging is computed according to ISO3382, different methods have been used for converting five parameter values to one, and converting all the measurement points into one value representing the hall.

4.1 Objective Seat Rank

Each measurement position is treated as representing a seat with a listener. If all parameters at this position satisfies their respective criteria, its Seat Rank number is 1. For each parameter that fails to meet its criterion, the seat rank is reduced by one. If n parameters fail to meet their criteria, the Seat Rank is 1+n. As a starting point of an iteration process, an average value from high ranked halls are used as a center value m, defining a qualifying interval of [m-x,m+x] where x is the chosen tolerance x from the center value. In the correlation analysis m and x is adjusted by trial and error until the highest correlation (Pearson R square) is obtained. x is usually in the order of 1-2 jnd's (Table 1).

Parameter	EDT (s)	G(dB)	C(dB)	LF(1)	GL(dB)
Criterion, center value	2,0	4,0	0,8	0,15	0,0
Tolerance(x=1.2 JND)	0,11	1,1	0,9	0,06	1,2
Data to be assessed	**1,7**	**3,8**	**1,1**	**0,18**	**0,0**
Qualified	0	1	1	1	1

Table 1 Example of objective data to be converted into a single rating value. Since the number of disqualified parameter values is n=1, Seat Rank is 1+n=2

4.2 Objective Hall Rank

In the correlation analysis presented in this paper, Objective Hall Rank have been obtained in two different ways.

4.2.1 Hall ranking from average of computed seat rank

Method 1. Objective rank-ordering ready for correlation with Beraneks subjective rank-ordering can be obtained simply by using the average subjective Seat Rank value.
Note the difference between averaging assessed data, and assessing average data.

4.2.2 Hall ranking computed from hall average

Method 2. Instead of letting the hall rank value be the average of seat rank values, the hall rank value is obtained from the average parameter-values in the hall. By using the same method as in 4.1 for converting a set of five parameter values into a single rank value, the Hall Rank is simply obtained similar to Seat Rank in Table 1, letting "Data to be assessed" be the five hall average values.

5 CORRELATION ANALYSIS OF OBJECTIVE AND SUBJECTIVE RANKINGS

1) First, one objective value per hall is obtained, according to 4.2.2.
2) From these values the objective rank-ordering of the halls are obtained and correlation with Beranek's subjective rank-ordering is computed.
3) With output from 2), correlation A is calculated by using Pearson's R square and criteria intervals [m-x, m + x], as in 4.1, are varied by trial and error until the highest possible correlation is found.
4) The criteria interval coming out from the iteration process in 3) now defines the criteria for the calculation of seat rank from the five parameters in each of the 116 measurement configuration,
5) obtaining Hall Rank equal to average Seat Rank, according to procedure described in 4.2.1.
6) with output from 5), correlation B, with Hall Rank by method 2 is calculated
7) The percentage of seats in each hall satisfying criteria [m-x,m+x], see 3), is calculated.
8) With output from 5), the average seat rank is calculated for three groups of halls commented by Beranek as being significantly different in quality. Vienna, Amsterdam and Cardiff are in Group 1, Gothenburg and Gasteig Munich are in Group 2, while the five others are in Group 3. Correlation C between average seat rank and subjective ranking of group 1, 2 and 3 is calculated.

9) 5% significance test is performed.

Now, in order to weigh correlation A for its explanation value it is multiplied by the percentage of seats satisfying criteria (7), and optimised by repeating trial and error in 3). Results are presented below.

6 RESULTS

Correlations A, B and C according to Section 5 above is presented in the Table 2, and Figure 1 below.

Data set #	**#1**	**#2**	#3	#4	#5	**#6**	Ref
A. Hall-rank from data-average	**0,91**	**0,88**	0,85	0,78	0,78	**0,68**	3)
B. Average Seat Rank	**0,88**	**0,85**	0,85	0,80	0,80	**0,70**	5)
C. Three Beranek Groups, avr. Seat Rank	**0,92**	**0,85**	0,88	0,73	0,80	**0,71**	8)
Parameter criteria tolerance ”x” in JND	**2,0**	**1,1**	1,2	1,1	1,1	**1,0**	3)
Seat percentage within criteria [m-x,m+x]	**29 %**	**6 %**	0 %	1 %	0 %	**2 %**	7)
Group Significance (5% conf)	**yes**	**yes**	No	no	no	**no**	9)

Table 2 Results of correlation analysis described in Section 5 (reference in Ref column), of the 6 data sets in 3. #1 is explainability based on measured TVR and LF. #2 is predictability based on occupied T from Odeon, measured V, R and LF. #6 is based on Odeon-simulations.

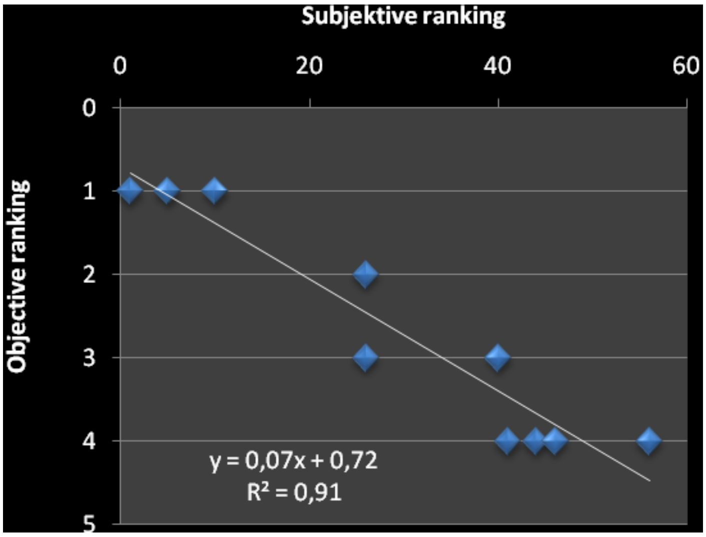


Figure 1 Diagram illustrating correlation between objective rank-ordering of 10 halls and subjective rank-ordering of 58 halls (Beranek). Objective hall-rank calculated from measured hall-average values of reverberation time, volume, source-receiver distance and LF, data set #1.

7 CONCLUSION AND FURTHER WORK

High correlation (r^2=0.91) is found between subjective hall-ranking based on 10 hall-averages of measured occupied reverberation time and measured LF, and Beraneks subjective Rank-ordering of 58 halls. This is interpreted as high explainability by the actual set of 5 listeners' aspects and corresponding parameters. Hall rank calculated from average Seat Rank (assessment in individual

points - at listeners ears) also results in quite high (r^2=0.88) correlation with subjective hall rank, indicating that hall preference can be explained by conditions at listeners' ears. Merely 29% of the seats actually satisfy the parameter criteria. The set of five parameters proves to be able to distinguish significantly (5% confidence) between the three groups of high, medium and low subjective preference reported by Beranek. Predictability is almost as good as explainability referred to above. 32% of seats satisfying parameter criteria is a marginal improvement, but still quite unsettling, and so is the rather low predictability of Odeon.
In further work, it will be investigated other sets of parameters that can provide reliable predictions by available prediction tools. Brief testing without LF showed that the remaining four parameters showed interesting results, e.g. with improved results for Odeon simulations. Possible improved explainability will be pursued. More halls will be added to the analysis.

8 REFERENCES

[1] M Skålevik, "Room acoustical parameter values at the listener's ears – can preferred concert hall acoustics be predicted and explained?", Proceedings of 20th International Congress on Acoustics, ICA 2010, Sydney, Australia

[2] M. Skålevik, "Reverberation Time, the mother of all acoustical parameters", Proceedings of ICA 2010
http://akutek.info/Papers/MS_reverberationtime_BNAM2010.pdf

[3] L. Beranek, "Subjective rank-orderings for concert halls", Acta Acoustica u w Acoustica Vol 89 (2003)

[4] A. C. Gade, "Acoustical Survey of Eleven European Concert Halls", DTU Report No.44, 1989, ISSN 0105-3027

[5] Hiroyoshi Shiokawa and Jens Holger Rindel, "Comparisons between Computer Simulations of Room Acoustical Parameters and Those Measured in Concert Halls", Report of the Research Institute of Industrial Technology, Nihon University Number 89, 2007, ISSN 0386-1678

[6] M. Skålevik, "Room acoustic parameters and their distribution over concert hall seats", Proceedings of Auditorium Acoustics 2008, Institue of Acoustics, Vol.30. PT.3. 2008, ISSN 1478-6095, http://www.akutek.info/Papers/MS_Parameters_Distribution.pdf

[7] M. Skålevik, "Room acoustic parameters and their distribution over concert hall seats", Conference presentation, Auditorium Acoustics 2008, Oslo 2008.
http://www.akutek.info/Presentations/MS_Parameters_Distribution_Pres.pdf

[8] ISO 3382, ''Acoustics — Measurement of the reverberation time of rooms with reference to other acoustic parameters'' (1997): Annex A of later revisions.

[9] L.Beranek, Concert Hall Acoustics—2008, J. Audio Eng. Soc., Vol. 56, No. 7/8, 2008 July/August
http://www.leoberanek.com/pages/concerthalls2008.pdf

[10] L. Beranek: Concert Halls and Opera Houses, second edition, Springer, 2003

[11] M. Barron, Auditorium Acoustics and Architectural Design (E & FN Spon, London, 1993).

[12] M. Barron, Using the standard on objective measures for concert auditoria, ISO 3382, to give reliable results, Acoust. Sci. & Tech. 26, 2 (2005)

[13] M. Barron, "Objective assessment of concert hall acoustics", Proceedings of Auditorium Acoustics 2008, Institue of Acoustics, Vol.30. PT.3. 2008, ISSN 1478-6095
http://www.akutek.info/Papers/MB_Objective_Assessment.pdf

[14] M. Skålevik, http://www.akutek.info/Presentations/MS_ParametersRelevanceTest_Pres.pdf

9 ANNEX

9.1 The five listener aspects and parameters in this study

Note that the parameter chosen to describe Listener envelopment LEV is the late Sound Level G_{late}, in contrast to Late Lateral Sound Level LG in ISO 3382-1

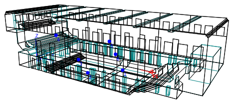
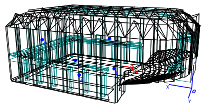
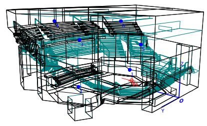
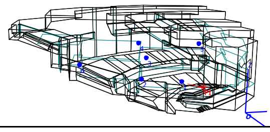
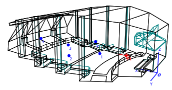
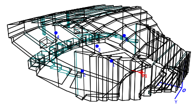
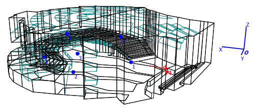
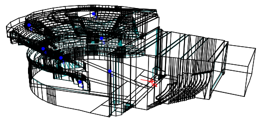
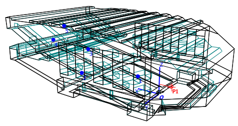
Subjective listener aspect	**Acoustic quantity**	**Just Noticeable Difference (JND)**
Subjective level of sound (SOUND LEVEL)	Sound Strength G, in dB	1dB
Perceived reverberance (REVERBERANCE)	Early Decay Time, EDT, in s	5%
Perceived clarity of sound (CLARITY)	Clarity, C80, in dB	1 dB
Apparent source width, ASW	Early Lateral Energy Fraction, LF	0.05
Listener envelopment LEV	Late Sound Level, G_{late} , in dB	1 dB

9.2 The Ten Halls

Table 3. The ten halls

Rank	Concert hall	Volume m^3	RT occ (s)	Beranek Ranking
1	Musikverein, Vienna	15000	2,0	1
2	Concertgebouw, Amsterdam	19000	2,0	5
3	St David, Cardiff	22000	2,0	10
4	Gasteig, Munich	30000	1,9	19-39
4	Konserthus, Gøteborg	12000	1,6	19-39
6	Festspielhaus, Salzburg	15500	1,5	40
7	Liederhalle, Stuttgart	16000	1,6	41
8	Usher, Edinburg	16000	1,3	44
9	Royal Festival Hall, London	22000	1,5	46
10	Barbican, London	18000	1,7	56

9.3 Hall models

Concert hall	Odeon Model
Musikverein, Vienna	
Concertgebouw, Amsterdam	
St David, Cardiff	
Gasteig, Munich	
Konserthus, Gøteborg	
Festspielhaus, Salzburg	
Liederhalle, Stuttgart	
Usher Hall, Edinburg	
Royal Festival Hall, London	
Barbican, London