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PRESENTS

Concert Hall Parameters 2012 – a status report

by M Skålevik

SUMMARY

Since Wallace Sabine introduced the reverberation time as a critical measure of acoustical quality in concert halls some hundred years ago, it soon became evident that two halls having the same reverberation time could still be subjectively very different. During the 20th century, a great number of additional parameters were suggested in order to provide a complete objective characterization of concert halls for symphonic music, but ISO 3382 have reduced these to a set of five listener aspects with their corresponding objective parameters. However, it remains to prove that this set of parameters actually is capable of explaining the subjective preference of concert halls, and even more important – to prove critical enough to be able to predict the success or failure of new concert halls. Given the set of five parameters, an actually highly ranked hall and a bottom ranked hall would have been predicted to become equivalent medium ranked halls.

This paper is a status report on the search for a relevant set of parameters. Among the unsettling results found are the implications of multiple linear regression, the assumption of linear relationship between objective measures and subjective aspects, the assumption of orthogonal parameters, and the fact that the parameter values at listeners ears differ noticeably from the hall averages being used in characterization of a hall. A method for testing the relevance of added parameters, and for justifying the relevance of established parameters, has been presented.

From the results we conclude that it is easier to predict and explain preference for concert halls by hall-average quantities than by quantities at listeners' ears. However, this paradox calls for open-minded exploration of the link between physical stimulus and listeners' subjective response.

Concert Hall Parameters 2012 – a status report

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Since Wallace Sabine introduced the reverberation time as a critical measure of acoustical quality in concert halls some hundred years ago, it soon became evident that two halls having the same reverberation time could still be subjectively very different. During the 20th century, a great number of additional parameters were suggested in order to provide a complete objective characterization of concert halls for symphonic music, but ISO 3382 have reduced these to a set of five listener aspects with their corresponding objective parameters. However, it remains to prove that this set of parameters actually is capable of explaining the subjective preference of concert halls, and even more important – to prove critical enough to be able to predict the success or failure of new concert halls. Given the set of five parameters, an actually highly ranked hall and a bottom ranked hall would have been predicted to become equivalent medium ranked halls. This paper is a status report on the search for a relevant set of parameters. Among the unsettling results found are the implications of multiple linear regression, the assumption of linear relationship between objective measures and subjective aspects, the assumption of orthogonal parameters, and the fact that the parameter values at listeners ears differ noticeably from the hall averages being used in characterization of a hall. A method for testing the relevance of added parameters, and for justifying the relevance of established parameters, has been presented. From the results we conclude that it is easier to predict and explain preference for concert halls by hall-average quantities than by quantities at listeners' ears. However, this paradox calls for open-minded exploration of the link between physical stimulus and listeners' subjective response.

1 Introduction

Since Wallace Sabine introduced the reverberation time as a critical measure of acoustical quality in concert halls some hundred years ago, it soon became evident that two halls having the same reverberation time could still be subjectively very different. During the 20th century, a great number of additional parameters were suggested in order to provide a complete objective characterization of concert halls for symphonic music, but ISO 3382 have reduced these to a set of five listener aspects with their corresponding objective parameters, Table 1. However, it remains to prove that this set of parameters actually is capable of explaining the subjective preference of concert halls, and even more important – to prove critical enough to be able to predict the success or failure of new concert halls. Given the set of five parameters, an actually highly ranked hall and a bottom ranked hall would have been predicted to become equivalent medium ranked halls. This paper is a status report on the search for a relevant set of parameters, during investigation by this author, mainly in the period from 2008 up to present.

Table 1 Five subjective aspects with corresponding objective quantities (parameters)

Listener aspects in ISO 3382	**Quantity**	**(JND)**
SOUND LEVEL	G (dB)	1 dB
REVERBERANCE	EDT (s)	5%
CLARITY	C80 (dB)	1dB
APPARENT SOURCE WIDTH	LF (1)	0.05
ENVELOPMENT[1]	$G_{,late}$ (dB)	(1dB)

2 Previous work

Over the past century, many authors have addressed concert hall acoustics in terms of parameters [1,...,18]. As insufficiency became evident, many new parameters have been suggested along the way. Over the past decades, much effort has been put in to boil the abundance down to a set of few important parameters. Beranek in particular has been strongly advocating the search for orthogonal parameters, i.e. parameters that vary independently of each other, and the use of multiple linear regression in order to find formulae for predicting subjective preference for concert halls.

This author has approached the topic both as a consultant and as a researcher, using the experience from field measurements, computer simulations, and by applying the knowledge and empirical results from literature. The results this far are summarized in the following.

3 Work since 2008

3.1 Few listeners hear the average sound of a hall (IOA, Oslo 2008)

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) [8] reported results from a computer simulation study indicating that in the case of Musikverein 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.

Recent investigation by this author reveals that "occupied data" acquired by other methods than computer simulation results in less spatial deviation from hall averages in Musikverein: Results show that 58-67% of seats in Musikverein have conditions equal to its hall average, given the 5 parameters and JNDs in Table 1. See also Figure 3 in Annex.

Further research apparently showed that the reputation and quality rating of the hall could be better explained by the 5 parameters when assuming that listeners are less critical to differences from hall average. However, this seems to imply that the hall averages become less precise descriptors of concert hall acoustics and leaves the question: With greater uncertainty associated with hall averages, will it be possible to find significant correlation with subjective rank-orderings, e.g. the results from Beranek [4]?

[1] In ISO 3382 the suggested quantity is the late lateral energy LG. It is however evident [10] that late energy from all directions contributes more or less to envelopment, supporting that envelopment is best described by G_{late}.

3.2 Parameter values at listeners' ears in occupied hall condition

3.2.1 Acquiring occupied hall data

In order to better understand, explain and describe the actual listening conditions that affects the subjective preference for different halls, data from halls in their occupied condition are demanded. However such 'occupied data' are difficult to acquire, and no such set of parameter data is available to the extent necessary for this research. Hidaka et.al pursued the problem by investigating the relationship between occupied condition and unoccupied condition, suggested simple formulae for conversion from unoccupied hall average to occupied hall average for the following parameters: T, EDT, C, G and 1-IACC [18]. It is interesting to note that average 1-IACC in occupied condition differs little from average 1-IACC in unoccupied condition, indicating that ASW is not affected by the presence of the audience.

Since this author chose to investigate the variation in parameter values at listener's ears, having stated that these are noticeably different from hall averages, the Hidaka conversions could not serve the purpose of this investigation.

In order to acquire parameter values at listeners' ears, no less than six different methods were used, all leading to six "occupied data" sets. In five of these methods, the algorithms denoted TVr predictors were applied.

3.2.2 TVr predictors (BNAM 2010, Bergen)

Based on Barron Revised Theory, the Schroeder Curve and the energy parameters G, C and $G_{,late}$ can be predicted in the average hall with reverberation time T, volume V and at the average seat having source-receiver distance r. From the Schroeder Curve the EDT as originally suggested by Jordan (1980) can be computed. Moreover, the incremental differences in G, EDT, C and $G_{,late}$ due to difference between occupied T and unoccupied T can be predicted. This made it possible to convert measured parameter data at specific positions in unoccupied condition to "occupied parameter data" at the same positions.

3.2.3 Six sets of occupied data (ICA 2010, Sydney)

Given a set of data measured at specific positions in an empty hall, the six alternative methods for obtaining data in occupied condition is described in Table 1.

Table 2 Description of the six alternative methods for obtaining "occupied data"

#	EDT, G, C and G_{late}	LF
1	TVR-predicted values calculated from volume, global T and r. Occupied hall-average T from measurements.	Measured, empty hall
2	TVR-predicted values calculated from volume, global T and r. Occupied hall-average T predicted by ODEON.	Measured, empty hall
3	Measurements in empty hall are corrected by differences in TVr-predicted due to differences in **measured** hall-average T due to occupancy of hall. Measured occupied T and measured unoccupied T.	Measured, empty hall
4	Measurements in empty hall are corrected by differences in TVr-predicted due to differences in **predicted** hall-average T due to occupancy of hall. Occupied T and Unoccupied T both predicted in ODEON.	Measured, empty hall
5	Measurements in empty hall are corrected by differences calculated from computer-simulations in ODEON.	
6	Pure ODEON simulations, predicting occupied data from scratch	

3.2.4 Testing the TVr-predictors

Data sets #1 and #6 were tested by evaluating the difference relative to physical measurements in 126 specific positions in 11 unoccupied halls performed and reported by Gade [5]. With the release of ODEON 10, computer models and simulated data for the exact same positions in unoccupied conditions were available, providing the data set #6.

Comparison showed that data set #1 differed from measured data by 1.2 JND averaged over the four aspects G, EDT, C and $G_{,late}$, given the JNDs 1dB, 5%, 1dB and 1dB, respectively, while data set #6 differed by 1.6 JND. Keep in mind that the data in #6 are pure ODEON predictions [15]. In light of ODEON being a state of the art prediction tool, the

TVr-predictions proved to be very promising. One may argue that TVr-predictions and ODEON-predictions are not comparable since the TVr-predictions in set #1 take advantage of measured T, while ODEON predicts from scratch. However, the strength of the TVr-predictions were demonstrated by replacing measured T with T predicted in ODEON, i.e. data set #2, with almost the exact same result, only two hundreds of a JND less accurate.

In practice, this means that the safest predictions from scratch, of the parameters G, EDT, C and $G_{,late}$, are done by first predicting the global T in ODEON, and then use this T as input in the TVr-predictors. This result is quite surprising, given the simplicity of the TVr method.

Table 3 Results from testing two predictions methods by comparing predictions with physical measurements

Listener aspects	**Quantity**	**T,V,r – predictor re measured (JND)** **Data set #1**	**ODEON predictions re measured (JND)** **Data set #6**
SOUND LEVEL	G (dB)	1,6	2,3
REVERBERANCE	EDT (s)	0,78	1,1
CLARITY	C80 (dB)	1,4	1,8
ENVELOPMENT	G,late (dB)	0,81	1,3
AVERAGE OF 4 ASPECTS	**-**	**1,2**	**1,6**

3.2.5 Apparent Source Width is difficult to predict

There are two alternative physical quantities associated with the subjective aspect Apparent Source Width (ASW), namely the early energy lateral fraction (LF) and the $1\text{-}IACC_{early}$. While measurements of the two are quite straightforward, they are difficult to predict. ODEON may seem to predict LF quite well on average, and in the testing of data set #6 referred to above, ODEON predictions of LF were only 1.3 JND different from the 126 measurements. However, 1.3 JND can be quite an uncertainty, e.g. it equals the difference between the average LF in Musikverein (0.17) and the average LF of the halls with poorest values, LF=0.10-0.11. True 1-IACC measurements require two time-varying sound pressure signals and the technique is not implemented in common room acoustic prediction tools.

ASW has proved to be a critical aspect, and in some of the wide concert halls combined with low ceilings or canopies, ASW can be too weak. On the other hand, sufficient ASW is often associated with non-wide halls with rather high ceiling.

For these reasons, this author has looked in to the possibility of predicting ASW from the width-to-height ratio, W/H. In Beraneks data library the 22 halls with 1-IACC data showed that correlation between 1-IACC and W/H was r^2 =0.49. On the other hand, correlation between LF and H/W in 20 halls was as low as r^2 =0.06.

To exclude ASW due to the difficulties referred to above is not recommended. Even though most halls tend to have a geometry that provides sufficient ASW, history showed that sooner or later there will be planned halls were the opposite is the case. These cases should be avoided by taking ASW into account in any set of parameters applied in the prediction programme.

3.3 Subjective data vs Objective data - 116 points in 10 halls (Reported ICA 2010 in Sydney and IOA 2011 in Dublin)

Provided with 116 measurements by Gade in 10 halls (5.2 Ten Halls) that also are included in Beranek's rank ordering, this author tried to find an answer to the following question: Can subjective preference for concert halls be explained and predicted by objective data at listeners' ears? In science, prediction and explanation is usually closely related. Often, more insight and understanding is fruitful in order to predict outcomes of a process. However, prediction methods can be accurate, with high repeatability, without the mechanisms governing the outcome being fully understood. And insight is not necessary: "Light goes on" can be predicted and explained by "someone pushed the red switch" without any knowledge about electricity, and without understanding why light does not go on when pushing the green switch.

The main results of the analysis of the 10 halls are summarized as follows: High correlation between subjective evaluation and objective evaluation can only be seen if assuming that a low percentage of the listeners have acceptable parameter values [1] , or if assuming that listeners have a tolerance for parameter deviation in the order of 3-7JND, see Table 4, [2].

3.4 Musikverein-Concertgebouw criterion (Sydney results)

The subjective-objective analysis partly reported at ICA in Sydney in 2010 was based on the following objective quality criterion: Parameter values found in 12 points in Musikverein Vienna and 10 points in Concertgebouw Amsterdam are considered acceptable. This choice is discussed below.

If all five parameters are acceptable in a majority of seats, the hall would be given a subjective ranking equal to 1. If any single parameter fails to be acceptable in a majority of seats, the subjective rank is equal to 2, and so on. Seats are here represented by Gade's measurement points. A percentage X of least good seats are excluded, defining the majority by the percentage 100%-X.

Plots of subjective evaluation versus objective evaluation, based on Gade measurements and Beranek rank-ordering, are shown in Figure 1. Optimum correlation coincides when excluding 38% and 23% of the least good seats, respectively. The subjective evaluation is equal to 1 whenever all 5 parameters meet their respective criteria. Here, the criteria are the span of parameter values found in Musikverein Vienna and Concertgebouw Amsterdam. Criteria span in units of JND given in Table 4.

3.4.1 Mispredictions with 5 parameters, Musikverein-Concertgebouw criterion and Odeon

We demand from the chosen set of parameter, criteria and prediction methods, that the subjective quality of future concert halls can be predicted. The combination of parameters describing the 5 aspects in ISO 3382, the Musikverein-Concertgebouw criterion, and Odeon predictions, would lead to serious mispredictions. Two halls with very different subjective ranking in Beranek's rank-ordering, number 10 (Cardiff) and number 56 (Barbican hall) came out with the same objective ranking based on Odeon results ("Objective ranking = 3" in the plot to the right in Figure 1. In practice, one consequence of such mispredictions are that some good projects would never be reality, supported by science. Another consequence, given that the number 10 ranked hall already is built and turned out to be a success, why not build another one that is predicted with the same objective quality? Thus some halls with bad reputation may be built, with decisions supported by science.

One lesson learned from these results is that r^2=0.59 is not to be considered "good correlation".

3.4.2 Confusing LF-values

Though Apparent Source Width is established as a critical aspect, and LF is an accepted quantity for measuring this aspect, the use of LF has some confusing results. When the analysis above was repeated without the LF parameter, it was still possible to achieve correlation equal to r^2=0.72 with the 4-parameter set, but this time by using data set #2, [16]. A more detailed analysis reveals that Odeon in general seems to predict LF with twice as much scattering than measured in Musikverein and Concertgebouw, leading to a wide range of acceptable LF-values see Table 4. Thus Odeon is less able to distinguish between the good and the less good when it comes to LF than the other parameters. On the other hand, leaving out LF from Odeon predictions resulted in lower correlation between objective and subjective data. In the Dublin results, 3.7 below, LF is the parameter that prevents the subjectively bottom-ranked hall to be objectively bottom-ranked too.

3.4.3 Linear regression and orthogonal parameters

It has been demonstrated that the assumption that subjective preference for concert halls can be predicted by a formula with linear combinations of orthogonal parameters does not apply [2]. Linear regression can be used to deduce such a formula. However, subjective preference is not linear over a wide enough range of parameter values. On the contrary, most of the suggested parameters seem to have optimum values, e.g. too little is bad and too much may be worse. A linear expression may lead to the meaningless result, e.g. "a shorter EDT can be compensated by weaker $G_{,late}$". In such a formula there is no such thing as too much or too little – only "the more, the better". The concept of the formula is in conflict with common experience.

3.4.4 A new method for testing of parameter relevance

Instead of choosing parameter sets based on linear regression and the assumption of orthogonal parameters, discussed above, a new test method for testing the relevance of each parameter was presented [16]. The concept is basically two simple tests:

- any added parameter will have to be justified by improved r^2 correlation
- in a set of established parameters, any parameter should justify its membership by proving a decrease in r^2 correlation when removed from the analysis

A sufficiently varied and representative set of subjective and objective data must form the basis for the parameter test.

Note that even if this test is a test on dependency and independency, it does not assume a linear relationship between subjective and objective data, and does not require orthogonal variables in the common terms of linear algebra.

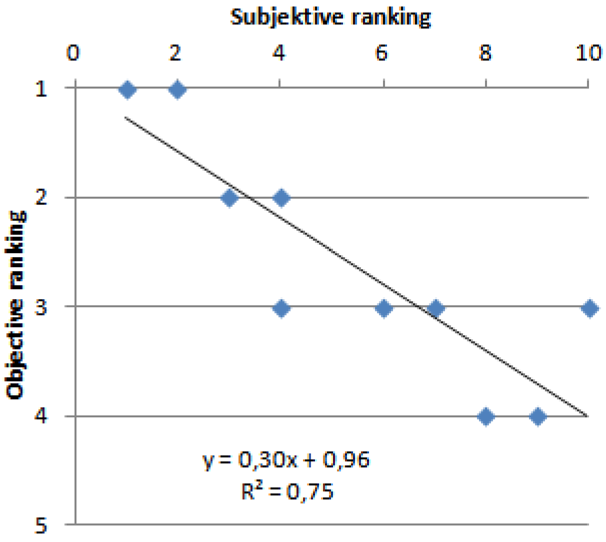
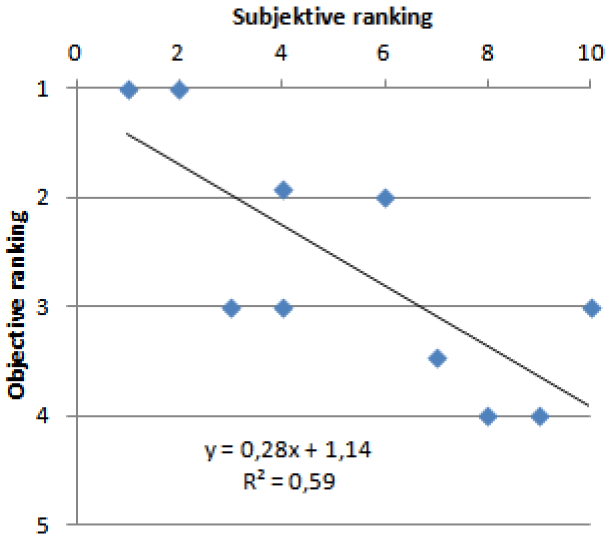
Data set #1, G, EDT, C and G,late from TVr, and measured LF; 38% least good seats excluded.	Data set #6, Odeon predictions "from scratch"; 23% least good seats excluded.
	

Figure 1 Plots of subjective evaluation versus objective evaluation, based on Gade measurements and Beranek rank-ordering. Parameter values found in 12 Musikverein points and 10 Concertgebouw points define the objective quality criterion. Maximum correlation coincides when excluding 38% and 23% of the least good seats, respectively.

Table 4 Span of variation in JNDs in parameter values found in the 12 Musikverein points and 10 Concertgebouw points that defines the objective quality criterion of the objective ranking, see Figure 1. Note that data sets #1 thru #6 have their individual acceptable variation.

ISO 3382 aspects	Quantity	#1	#2	#3	#4	#5	#6
REVERBERANCE	EDT	7	7	8	8	11	8
SOUND LEVEL	G	5	5	6	6	6	6
CLARITY	C	5	5	7	7	9	7
APPARENT SOURCE WIDTH	LF	3	3	3	3	4	6
ENVELOPMENT	GL	3	3	4	4	5	4

3.5 Musikverein criterion (Sydney revised)

It is natural to question the choice of using the span of values found in Musikverein and Concertgebouw as quality criteria in the basis of the Sydney results, see 3.4. One objection would be that it turns out the choice leads to a wide range of acceptable parameter-values, see Table 4, which seem to raise the risk for seats in bad halls to be judged good. However, this would be taken care of in the correlation assessment.

Another objection is that it had been better to start with the value range of Musikverein since this is the very top subjectively ranked hall. This objection has been pursued, presenting some key results here. Plots of subjective evaluation versus objective evaluation, based on Gade measurements and Beranek rank-ordering are shown in Figure 2. Parameter values found in 12 Musikverein points define the objective quality criterion. Optimum correlation coincides when excluding 49.9% and 23% of the least good seats, respectively. Criteria span in units of JND given in Table 6.

Compared to Sydney results, the change to a Musikverein criterion results in higher correlation with data set #1 (r^2 up from 0.72 to 0.79), but the percentage of seats excluded is up to X=50%. Also a slightly higher correlation in data set #2, from 0.72 to 0.74, but only with excluded seats increasing from 34 to 50%. Data set #2 is of particular interest since it can be predicted from scratch with a combination of TVr and Odeon. However, data set #6 shows very poor Odeon prediction with the Musikverein-criterion. The exclusion of 49.9% of the seats is associated with the fact that the Musikverein-criterion is a stricter one, having a narrower interval of acceptable parameter values than the combined Musikverein-Concertgebouw criterion in the Sydney results above. Thus fewer seats meet the criterion. These results are based on the better 50.1% of the seats in each hall, the smallest possible majority, which inevitably leaves the results less strong. See Figure 3, for an illustration of how values in 116 points deviate from Musikverein-average.

Data set #1, G, EDT, C and G,late from TVr, T and LF from Odeon; 49.9% least good seats excluded.	Data set #6, Odeon predictions “from scratch”; 23% least good seats excluded.

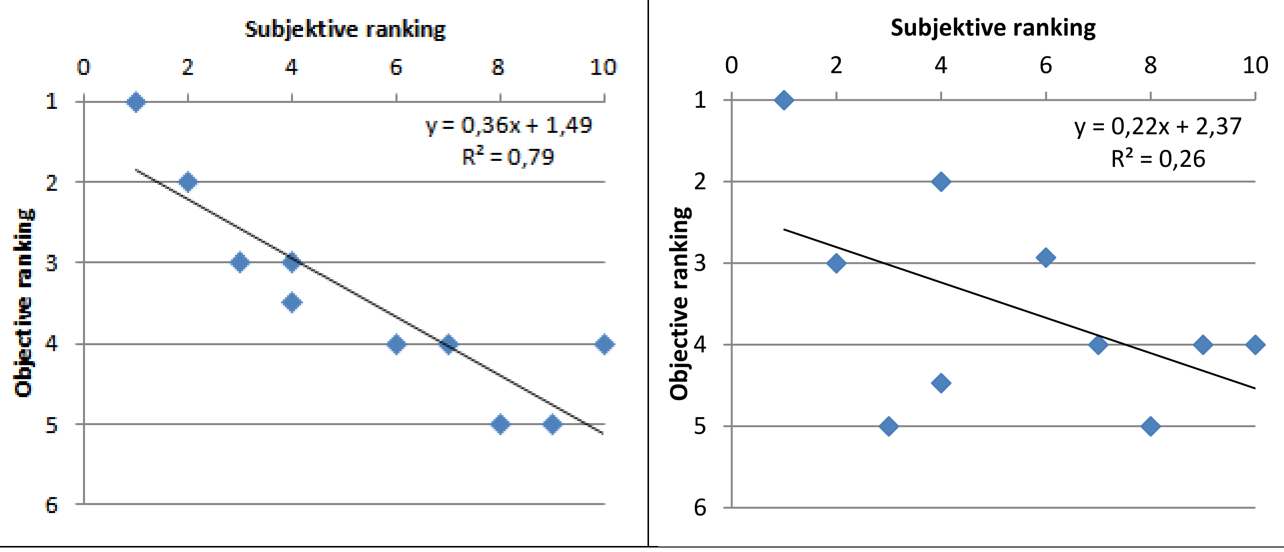


Figure 2 Plots of subjective evaluation versus objective evaluation, based on Gade measurements and Beranek rank-ordering. Parameter values found in 12 Musikverein points define the objective quality criterion. Maximum correlation coincides when excluding 8% and 23% of the least good seats, respectively.

Table 5 Variation span (in JNDs) in parameter values found in the 12 Musikverein points that defines the objective quality criterion of the objective ranking, see Figure 2. Note that data sets #1 thru #6 have their individual acceptable variation.

ISO 3382 aspects	Quantity	#1	#2	#3	#4	#5	#6
REVERBERANCE	EDT	3	3	5	5	8	5
SOUND LEVEL	G	4	4	5	5	5	5
CLARITY	C	3	3	7	7	9	7
APPARENT SOURCE WIDTH	LF	3	2	3	3	3	2
ENVELOPMENT	GL	2	2	3	3	3	2

3.6 Conclusions regarding Explainability, Understandability and Predictability

As mentioned in 3.3 above, variations in subjective response can be explained in scientific terms by variation in objective quantities, even if the mechanisms involved are fully understood. Such an explanation can be found in high correlation (here, Pearson's r^2). In our study, reported above, the correlation between objective quantities at listeners' ears and subjective ranking is not high. So we must conclude that this relationship is not yet explained, given the data available. Independently of this, the range of apparently acceptable parameter-values in Musikverein and Concertgebouw is very wide compared to established just noticeable difference limen (JND), and still the subjective qualities of the halls are widely recognised.

Regardless of the correlation mentioned, the subjective acceptance of the parameter deviation from hall average inside these halls remains a mystery, given the JNDs. Note that even if this is the same conclusion as in the Oslo report, 2, this conclusion is based on measurements while the Oslo report was based on Odeon-simulations.

With this conclusion, it was natural to pursue explainability (and predictability) based on correlation between hall average data in addition to position-specific data, since the former are much more available the latter. From this point we have two research fields, namely 1) the search for explainability and predictability and 2) the search for insight and understanding in the way listeners' subjectively judge the actual physical input at their ears.

Note that explanation can be provided without practical predictability. For example, explanation can be found in measured data with a given set of parameters and a given set of criteria, when correlation with subjective data is high. But the explanation is not valid when measured data is replaced by predicted data. True predictability is only achieved with high correlation between predicted data (data set #2 and #6) and subjective data, using the same prediction method, parameters and criteria throughout a large number of halls.

It is to be emphasised that parameter-criteria for evaluating predicted data in general have different set of values than those used to evaluate measured data. In our study this becomes evident by the substantial differences seen between the 6 data sets. Criteria-values valid for one set are not for a different set, if data are acquired by different methods.

3.7 Best fit hall-average criterion (Dublin results)

With the only priority to search for possible high correlation between objective and subjective data, it was chosen to use hall-averages computed from the same data as above, described in 3.2.3. By trial and error, the criterion value and a value for tolerance was varied systematically until the highest possible r^2 correlation was achieved for each of the 6 data sets. Since the Sydney results, a sixth parameter, G_{125}, was added, justified by the relevance test referred to above. This is the low frequency strength parameter defined by G in the 125Hz octave band, commonly referred to in the literature. The introduction of G_{125} seems to put Barbican (subjective rank 10) more in the right place.

Results from the process of maximising correlation by best fit hall-average criteria to each of the 6 data sets are presented in Table 6. The first row (a) in each block shows the plot of objective evaluation versus subjective evaluation, including the best fit line, its formula and the Pearson correlation r^2.

In second row (b) column diagrams shows the objective quality of the three groups of concert halls, A, B and C, in Beranek's ranking.

Each group is here represented by their quality average and their individual 5% confidence intervals (error bars), as a result of the parameter-criteria and tolerance (3 bottom rows in each block) associated with maximum correlation seen in row (a). Beranek commented to these groups that all halls in the A group were judged better than those in group B, and those in B better than those in C. Therefore, as a minimum requirement, we demand that the halls in A, B and C are forming significantly different from each other. As can be seen from the error bars, this requirement is only met with data sets #1 and #2.

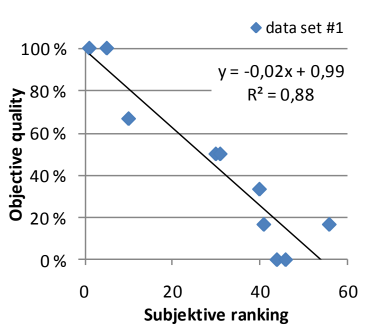
We conclude from these results, reported at IOA Auditorium Acoustics Conference in Dublin and therefore referred to as the Dublin results, as follows:

Only the criteria and tolerance valid for data sets #1 and #2 pass the significance test, while those of data sets #3 thru #6 fail the significance test. If #2 stands further testing, it could provide a possibility for predicting subjective quality of planned halls in the future. In that case, LF and global T will have to be computed in Odeon, and the five other parameters computed from TVr predictors based on global T from Odeon. In set #2, the hall-average parameter values are found in 17% of the seats in Musikverein, 10% of the seats in Concertgebouw, and in 8% of the seats in St David Hall. While these low percentages call for more insight and understanding, they do not reduce the explainability and predictability in the scientific sense, as discussed in 3.6 above.

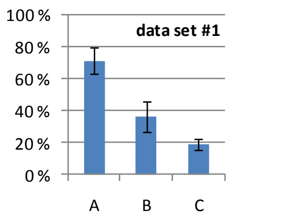
Table 6 Results after maximising correlation by best fit hall-average criteria to each of the 6 data sets. Row (a): Plots with regression line and correlation. Row (b): Objective quality, average and 5% confidence, in hall groups A, B and C; Note: significance in #1 and # only. Last rows: Parameters, best fit criteria value and accepted tolerance (±JND). See text.

Data set #1

(a)

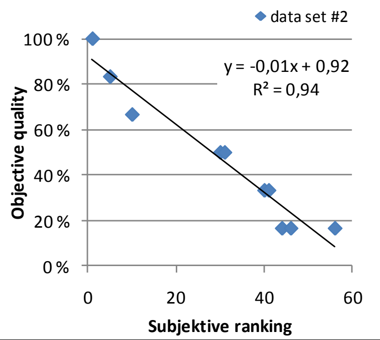


(b)

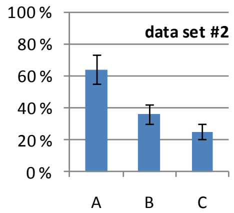


Data set #2

(a)

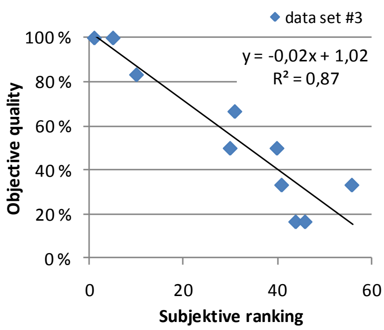


(b)

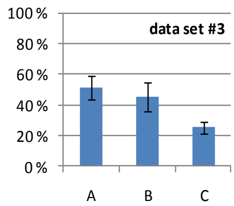


Data set #3

(a)



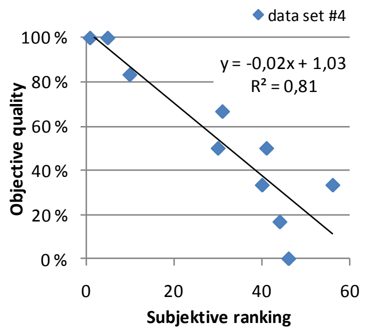
(b)



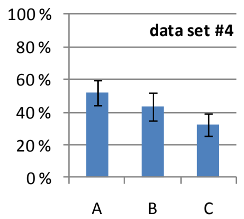
Param	EDT	G	C	LF	G_{late}	G_{125}	EDT	G	C	LF	G_{late}	G_{125}	EDT	G	C	LF	G_{late}	G_{125}
criteria	1,9	4,0	-0,3	0,16	1,5	4,6	2,0	4,3	-0,3	0,20	1,5	4,7	2,0	4,0	-1,2	0,16	1,0	4,4
± (jnd)	1,6	1,1	1,0	1,0	1,0	1,1	1,1	1,0	0,7	1,1	1,0	1,0	1,9	1,4	1,4	1,4	1,1	1,0

Data set #4

(a)

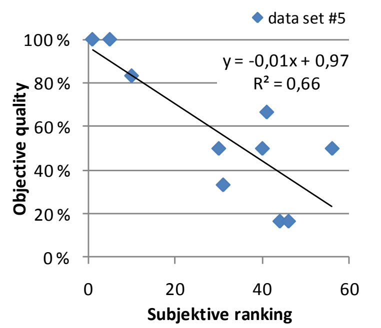


(b)

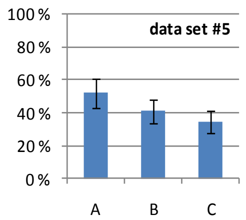


Data set #5

(a)

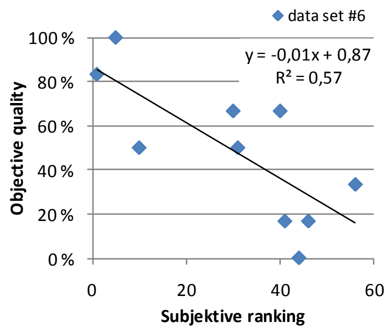


(b)

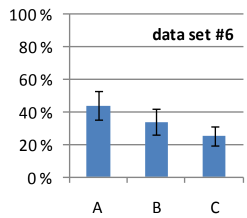


Data set #6

(a)



(b)



Param	EDT	G	C	LF	G_{late}	G_{125}	EDT	G	C	LF	G_{late}	G_{125}	EDT	G	C	LF	G_{late}	G_{125}
criteria	2,0	4,2	-1,3	0,16	1,6	4,7	2,0	3,0	-1,1	0,16	0,2	4,2	2,0	3,0	0,7	0,17	0,0	4,8
± (jnd)	1,5	1,0	1,4	1,4	1,0	1,0	1,9	1,0	1,3	1,4	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0

4 Conclusions and Further work

Based on 116 measurements in 10 halls, we have investigated parameter values at listeners' ears in order to find any explanation of subjective judgement of concert halls. As a part of this, six new methods for acquiring data in the "occupied condition" have been developed, resulting in six data sets, each requiring their individual quality criteria. The terms Explainability, Predictability and Understandability have been discussed. In particular, the distinction between explaining and understanding the subjective response to physical input has turned out to be important.

Three different parameter-criteria have been tested, one based on the range of values found in the two top-ranked halls, Musikverein and Concertgebouw. A second criteria based on Musikverein values only was tested. A third set of parameter-criteria came out of the process of trial and error until the maximum correlation between objective and subjective evaluation was found. This third attempt is referred to as the Dublin result, and it introduced the sixth parameter, G_{125}, in addition to those associated with the five ISO 3382 aspects included throughout this investigation. Dublin results show considerable improvement in terms of correlation and statistical significance. From the results we conclude that it is easier to predict and explain preference for concert halls by hall-average quantities than by quantities at listeners' ears. This paradox calls for open-minded exploration of the link between physical stimulus and listeners' subjective response.

Following the Dublin results, it is natural to extend the range of data to include more of the 58 halls in the Beranek ranking. From these halls, it is possible to obtain data set #1 from 56 halls. This extended analysis is in progress and results will be published in the near future. So far, the extension with more halls seems to bring lower correlation than the Dublin results. Other parameters will be tested for relevance according to the test procedure described in 3.4.4.

5 Annex

5.1 116 points in 10 halls - Deviations from Musikverein-average

Seat-to-seat variation in the ten halls is demonstrated in the plot in Figure 3. Each dot represents one of the 116 points in the 10 halls. Average deviation from hall-averages of the 5 parameters in Musikverein is plotted against the subjective quality of the hall to which the dot belongs. Note that single parameters deviates far more than the average parameter.

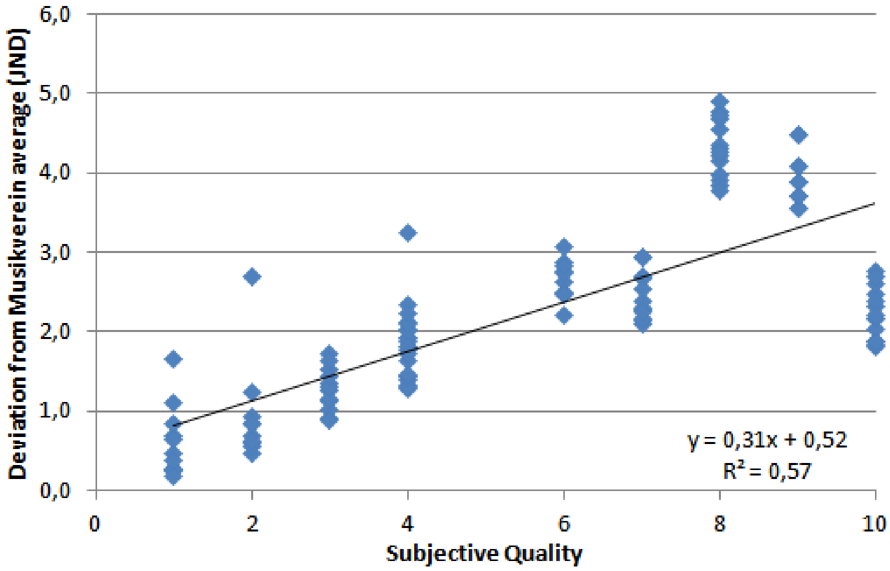
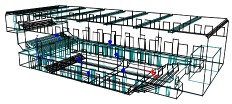
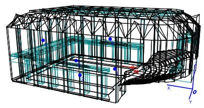
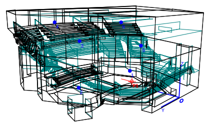
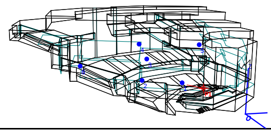
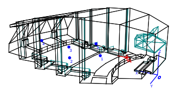
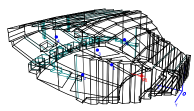
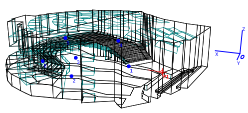
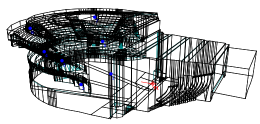
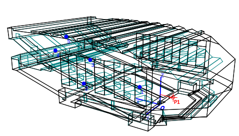
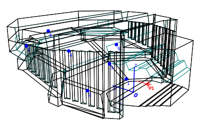


Figure 3. Average deviation (in JND) from hall-average in Musikverein, 5-parameter data set #1, 116 points in 10 halls; Leftmost points are the 12 points in Musikverein itself.

5.2 The ten halls

	Concert hall	Volume m^3	RT occ (s)	Beranek Ranking	Odeon Model
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	
5	Konserthus, Gøteborg	12000	1,6	19-39	
6	Festspielhaus, Salzburg	15500	1,5	40	
7	Liederhalle, Stuttgart	16000	1,6	41	
8	Usher Hall, Edinburg	16000	1,3	44	
9	Royal Festival Hall, London	22000	1,5	46	
10	Barbican, London	18000	1,7	56	

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