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Subjective Rank-Orderings and Acoustical Measurements for Fifty-Eight Concert Halls

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Summary
A rank-ordering of fifty-eight concert halls according to their acoustical quality is presented, based on interviews of conductors, music critics and well-traveled music aficionados. For a large percentage of these halls, objective measurements of the acoustical attributes are presented. These objective data are compared to the subjective rank orderings in a series of charts. The acoustical attributes considered are reverberation time RT, early decay time EDT, Binaural Quality Index BQI (proposed name for the quantity [1–$IACC_{E3}$], where the measured quantity is the interaural cross-correlation coefficient, integrated over 0 to 80 ms and averaged for the three octave bands, 500, 1k and 2k Hz bands), initial-time-delay gap ITDG, bass ratio BR, strength factor G at mid-frequencies (average of 500 and 1k octave bands), strength factor G_{125} at 125 Hz, lateral fraction LF_E (both the average of LF_E in the 125, 250, 500 and 1k Hz bands and in the 500, 1k and 2k bands, where "E" indicates integration over 0 to 80 ms), surface diffusivity index (visual) SDI, and support factor ST1. The objective quantities that correlate best with the subjective rank orderings are BQI, EDT_{mid}, G_{125}, SDI and ITDG, in that order. The possible use of the characteristics "texture" and "late lateral strength factor" are discussed.

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1. Introduction

The acoustical problems with the Philharmonic Hall that opened in 1962 in New York City startled the acoustical world. Because many concert halls were being planned in several countries during the next decades, more needed to be known about the acoustics of concert halls. Government-sponsored and private research was conducted at the University of Goettingen, the Technical University of Berlin, the Technical University of Copenhagen, at various laboratories in England, the University of Kobe and the Takenaka Research and Development Institute in Japan, Bolt Beranek and Newman in the USA, and the National Research Council of Canada, the Technical University of Delft, Netherlands, and other places.

In several of those studies, listeners, often students, were situated in laboratories and, by means of loudspeakers or earphones, they listened to orchestral sounds recorded binaurally in various halls (unoccupied). The subjects were asked to judge the acoustical quality of each. Acoustical measurements were made in those halls (unoccupied) and by factor analysis the measurements were compared with the listeners' subjective judgments. A number of orthogonal acoustical parameters came out of those studies that are largely the basis of the measurements presented in this paper.

Today, the measurements in concert halls are usually made with a dodecahedral (non-directional) loudspeaker on stage, emitting pulsed sounds, and the receivers are either a non-directional microphone used in combination with a figure-8 microphone or two microphones at the entrance to the ear canals of a person or a dummy. The room impulse responses are recorded and analyzed in the laboratory. The designation "E" on the data means integration of the room impulse response in the time period from 0 to 80 ms. The measurements that are commonly made are: RT (the reverberation time RT quoted in this paper is for occupied halls, although it is more easily measured in halls unoccupied); BR (the bass ratio is always taken from reverberation times measured in occupied halls); Binaural Quality Index BQI (it, [1–$IACC_{E3}$], can be measured in either occupied or unoccupied halls, the results are nearly the same); EDT (the measured early decay times recorded here are for unoccupied halls); $C_{80,3}$ (the clarity factor is usually measured unoccupied, although it is more meaningful measured occupied); LF_E (the lateral fraction is usually measured unoccupied and is so reported here); G_E (the strength index is measured unoccupied); ITDG (the initial-time-delay gap is reported in this paper for one position near the center of the main floor and can be determined from architectural drawings or from reflection patterns at this location with the room either occupied or unoccupied); SDI, (the surface diffusivity index is determined visually, using the guidelines of Haan and Fricke [1]); ST1 (the stage support factor can be measured in either occupied or unoccupied hall, using the proce-

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dure of Gade [2]). Most of the formulas or definitions for these quantities are listed in International Standard ISO 3382 or are given in Appendix A1. (References: Books: [3, 4, 5, 6, 7, 8, 9, 10]. Papers: [11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 8, 28, 29, 30].

2. Subjective judgments of the acoustical quality of fifty-eight concert halls

A list of halls that are rank-ordered according to their subjective acoustical quality is an essential ingredient in choosing which objective acoustical measurements are best suited to aid in evaluating the acoustics of a hall. The author, over a period of 40 years (1960–2000), has conducted interviews and made questionnaire surveys of over 150 conductors, music critics and (a few well traveled) aficionados of concert and opera music. About half were conductors. The process was easier when there were fewer halls, because most halls were well known by many of the persons contacted. A plethora of halls has been built since 1980, and the subjective assessment of their relative acoustical quality has become ever more difficult. It is believed that the early interviews are still valid on those halls that have not been renovated, because the symphonic repertoire has not changed significantly in this period. Only about 80 of the interviews were judged useful in this study because the other interviewees either knew too few halls well enough to comment or actually never seemed to have thought much about the acoustics.

One problem is that no person interviewed is well acquainted with more than one- third of the 65 or so concert halls that I have recently asked about, so each person's ratings are for only part of them. I am well aware that the combination of their remarks, each on a limited number of halls, and my interpretation of how they should be combined, or overlapped, does not constitute a scientific canvass of expert opinions. Written questionnaires would seem to be an alternate. Questionnaires are successful for a limited number of halls, say 25 or less, that have been in existence for many years. Such a questionnaire study has been reported recently for opera houses [25]. But a questionnaire with over 100 halls on it, of which the recipient is familiar with only a fraction, would probably not even be acknowledged.

The procedure that was followed in developing the relative rankings of the 58 halls of this paper is generally called "non-parametric" (Webster definition: Estimates of quantities determined from observations). As an example, Table I illustrates this procedure for 17 conductors and 20 halls. The letters "A" to "Q" represent names of conductors. The numbers in the table are replacements for the names of the halls. In the process, both during interviewing and analysis, no numbers were used, only the names of the halls. The conductors' names are not disclosed here because of confidential agreements with them, many signed. Conductor A ranked only seven halls. After this ranking, he was asked how much lower in acoustical quality was hall 18 than hall 3 (only hall names were used). He felt 18 was of much lower quality, and he made remarks about the relative acoustical qualities of the other five halls. The author spaced these out as shown based on his remarks, although the same results would be obtained from this table by not spacing out the responses. Conductor F felt confident in rating 19 halls and the order of the halls shown were his ranking. To illustrate the difference in judgments of different halls, note that five of seven conductors placed hall 20 at the bottom of their list, while two placed it in the middle.

To get the final ranking shown in Column 1, one connects together across the page, the name of each hall. It is easy to see that the hall now numbered "1" easily ranks highest. This procedure was followed for each of the halls (on separate sheets) of Table I. Of course, some halls have nearly the same visual ranking, but the "across the page" bouncing lines for the different halls move down the page. This process leads to the ranking of the halls in the left column (the names are now replaced by the rank order numbers). The names in the entire table are replaced by the numbers in the first column. The reason for not showing the hall names is that this is an illustrative table and is not the one used for the 58 halls and 80 interviewees. Also, with the replacement of names with numbers, one can see how each conductor's rank ordering correlates with the overall rank ordering.

The final ranking of the 58 halls used in the study that follows is shown in Table II[1]. The top 20 halls could be ranked with reasonable confidence by this non-parametric method. The bottom 19 halls were not hard to rank. But the intervening halls could not be ranked with sufficient certainty, and their hidden ranking, shown by numbers 21 to 39, is based on the ratings of the dozen or so conductors that I felt spoke most clearly about their choices. As will be seen later, the uncertainty of the ranking of these middle 19 halls does not affect the conclusions of this paper. One should carefully note that although halls 21 through 39 were not judged as good as the top 20, they are all successful venues for symphonic concerts and the audiences in them are generally satisfied with their acoustics.

Of the bottom 19 halls, the fifteen lowest (except for two, TK, which is very large and Manchester MN, which has been replaced) were judged by their owners to be so deficient acoustically that they have been extensively renovated to affect improvement. All data and interviews

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[1] The ranking of TN, Tokyo Opera City Concert Hall, for which the author was the acoustical consultant, was not obtained from interviews. Rather written comments made to the owners after its opening were surprisingly specific in ranking it among the world's best halls. The written comments are available for inspection. Artists included Yo Yo Ma, Michael Tilson Thomas, Andras Schiff, Hasafumi Hori (Concertmaster of NHK Symphony Orchestra). Peter Serkin, Kent Nagano, Bill Douglas (Pianist), Marie- Claire Alain (Organist) and Nobuaki Tanaka (chorus conductor). A lengthy article about it, that appeared in The New York Times, April 18, 2000, was headed: "Art + Physics = Beautiful Music." There were no negative comments. The reason for including this hall is to show that if all the findings in this paper are adopted in design, a hall can be successful. It seats 1632. This design would be equally successful if its capacity did not exceed about 2200 seats, i.e., if its width and length did not become too large.

Table I. Illustration of the non-parametric method used in establishing the rank orders given in the following table. The letters "A" to "G" are conductors (names withheld by request, usually written), and the numbers are replacements for the names of halls. The numbers were chosen after the rank ordering took place to facilitate easier understanding of how individual conductors rank ordered in comparison with the overall non-parametric rank ordering.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	0	P	Q
1	3	1	5	1	1	1		2	1		1					10	1
2				3		2	2	3		3		2		9			2
3				5	3	3	3	4	3	8		3					
4	4	3		4	8	5	4	5	4	10		4	8	4			
5		5		7		4			5			8	9	11	6		
6		7	3	6	4	11			6			5		8	7		6
7		8	4		6	14			8	4	16	7		12	8	2	
8	9	9	6	8	9	20	8	6	12	6	4	12	6	10		5	
9		13	8	10	10	6	20			9	14	14	7	3	9		
10			9	11	12	8	10			13	3	17			10	8	
11			15	12	13	9	14	10	17				4			9	
12	12	6		13	14	10	18	12	13			9					12
13		18		15	16	12	16	13	14	11	8	10	12				
14	13	4		18	17	13	9	14	16	12		15	14	14			
15	15	12	12		19	15	7	16		14	6	16	16	15			
16		14	14			16	5		15				19	16			
17		15	16	14		17	19		10	20				19			
18		16	17	17		18	12										
19	18	19	18			19	11					19					
20	7		12		20 14			10	20 14	11	7	14	9	11	20 6	5	5 20
		15	-	15		19	15										

on these halls were taken *before* the renovations and are marked (br) to make it clear that the ratings shown do not apply to their present state.

It is interesting to see that five halls, Chicago's Orchestra Hall, Cleveland's Severance Hall, Vienna's Konzerthaus, Toronto's Roy Thompson Hall, and Washington D.C.'s JFK Concert Hall were ranked in the middle group by those interviewed, yet their owners have made extensive renovations to improve their acoustics. Of course, there is some truth to the occasional statement that, "The best halls are those with the best orchestras," which may indicate, at least partially, why those halls were ranked in the middle group instead of among the bottom fifteen where "(br)" would indicate they should be ranked.

Finally, the interviews showed that halls that are ranked adjacent to each other could be interchanged. For example, the two halls that are frequently described as the world's best, Boston's Symphony Hall and Vienna's Musikvereinssaal are oppositely ranked by a number of conductors. It is the author's opinion, that any two or, in some cases, three halls in sequence in the table might be interchanged. This is an indication of the accuracy of the rankings.

3. Comparison of the objective measurements with the subjective judgments

In the following sections, ten objective acoustical parameters are plotted against the subjective ratings of Table II. The number of halls shown on the abscissas of the following graphs depend on the valid data available. As an example of rejected data, the interviews that helped rank Carnegie Hall were made before recent renovations in the hall and the measured data were taken after the renovations. No data were left off to make the graphs look better. The objective data are taken from Appendix 4 of [9] or from data obtained from well known laboratories since 1995. Where data from several laboratories were obtained on the same hall, the data were averaged as shown in [9]. More data will be available in Appendix 2 of a forthcoming book [10]. For 42 halls only reverberation times are available, and were either measured when the halls were occupied (from stop chords) or when unoccupied (impulse source on stage).

3.1. The frequency range important to determining acoustical quality

It is generally agreed that in the best halls, a sound source on the stage seems broadened, owing to early lateral reflections from the sidewalls. This is the explanation why the majority of the halls in the top group of Table II are rectangular, which is the easiest shape for the production of lateral reflections. The phenomenon of source broadening is often called "auditory spaciousness AS" or "apparent source width ASW." Blauert *et al.* [31] set up an experiment to determine the frequency range that contributes most to "auditory spaciousness AS" as judged by students. Their results are shown in Figure 1, along with the well-researched, psychoacoustic, speech-articulation-index, cumulative-AI curve. (The AI for syllables is attributed to French and Steinberg [32] and that for running conversation is attributed to Studebaker *et al.* [33]). The cumulative AI curve lays one octave to the right of the cumulative-AS curve, because speech intelligibility depends heavily on consonant sounds, while music depends

Table II. Rank Ordering of Concert Halls According to Acoustical Quality in Audience Areas. The rank ordering presented here is based on interviews and questionnaires involving conductors, music critics and (a few well-traveled) concert aficionados. No one interviewed expressed opinions on more than 20 halls, and most knew well no more than 10 to 15. The list is compiled by overlapping these subjective judgments using a non-parametric method. Note that (br) indicates that both the interviews and measurements were made before recently planned or completed renovations. The list is only made to assist in judging the efficiancy of the different objective measures of the sound fields in the halls. All of the halls are regularly used for concerts and today the audiences are generally satisfied (after the renovations marked (br) were completed) with their acoustics.
Perception of acoustical quality differs from one person to another and different parts of a hall may have different acoustics. The author does not recommend the use of this list by any party for purposes of comparing halls other than for research, or listing any hall as superior or inferior to any other. Further, the author does not claim that the results below are the same as those that would be obtained by a scientifically rigid procedure.
The halls 21 to 39 were judged to lie below the first 20 halls in acoustical quality, but were not clearly separated from each other by those questioned. They were judged superior to those after No. 39. An alphabetical list of the halls in that group is given in the table.

Table II. Continuation.

VM	Vienna, Grosser Musikvereinssaal
BO	Boston, Symphony Hall
BA	Buenos Aires, Teatro Colon (Concert Shell)
BZ	Berlin, Konzerthaus (Schauspiethaus)
AM	Amsterdam, Concertgebouw
TN	Tokyo, Tokyo Opera City TOC Concert Hall
ZT	Zurich, Grosser Tonhallesaal
NY	New York, Carnegie Hall
BC	Basel, Stadt-Casino
CW	Cardiff, St. David's Hall
DA	Dallas, McDermott/Meyerson Hall
BN	Bristol, Colston Hall
SO	Lenox, Seiji Ozawa Hall (Rear Door Open)
CM	Costa Mesa, Segerstrom Hall
SL	Salt Lake City, Abravanel Symphony Hall
BP	Berlin, Phiiharmonie
TS	Tokyo, Suntory Hall
TB	Tokyo, Bunka Kaikan (Orchestra Shell)
BR	Brussels, Palais des Beaux Arts (Renovated)
BM	Baltimore, Meyerhoff Symphony Hall
21 to 39	*Bonn, Beethovenhalle*
	Chicago, Civic Center
	Chicago, Orchestra Hall (br)
	Christchurch, Town Hall
	Cleveland, Severance Hall (br)
	Gothenburg, Konserthus
	Jerusalem, Binyanei Ha'Oomah
	Kyoto, Concert Hall
	Leipzig, Gewandhaus
	Lenox, Tanglewood Music Shed
	Munich, Phitharmonie Am Gasteig
	Osaka, Symphony Hall
	Rotterdam, De Doelen Concertgebouw
	Tokyo, Metropolitan Art Space
	Tokyo, Orchard Hall, Bunkamura
	Toronto, Roy Thompson Hall (br),
	Vienna, Konzerthaus (br)
	Washington, JFK Concert Hall (br)
	Washington, JFK Opera House (set)
SA	Salzburg, Festspielhaus
ST	Stuttgart, Liederhalle, Grosser Saal
AF	New York, Avery Fisher Hall
CR	Copenhagen, Radiohuset, Studio I
EB	Edinburgh, Usher Hall (br)
GL	Glasgow, Royal Concert Hall (br)
LF	London, Royal Festival Hall (br)
LV	Liverpool, Philharmonic Hall (br)
MA	Manchester, Free Trade Hall (Replaced)
PP	Paris, Salle Pléyel (br)
ED	Edmonton, No. Alberta Jubilee Auditorium (br)
MP	Montreal, Salle Wilfrid-Pelletier (br)
TK	Tokyo, NHK Hall (3677 Seats)
SH	Sydney,Opera House Concert Hall (br)
SF	San Francisco, Davies Symphony Hall (br)
TE	Tel Aviv, Fredric R. Mann Auditorium (br)
LB	London, Barbican, Large Concert Hall (br)
BU	Buffalo, Kieinhans Music Hall (br)
LA	London, Royal Albert Hall (5080 Seats) (br)

for its quality on a range of frequencies extending to lower frequencies. If the two curves were not parallel, a completely different hearing mechanism for spaciousness than for speech intelligibility would be indicated, which is not the case. Potter *et al.* [23, Figure 10] performed various experiments that show that the 500 and 1000 Hz octave bands are the strongest contributors to spaciousness. The AS curve would seem to indicate that frequencies below about 177 Hz are not very important. But the bass frequencies are important–it is their level that is important. Bass strength has been shown to add appreciably to spaciousness [34]. Okano *et al.* [27] found that "the strength of the bass in the 125 and 250 Hz bands, and probably lower, measured in decibels must be adequately great for a hall to receive a high subjective acoustical rating"

3.2. The binaural quality index, BQI

The Binaural Quality Index BQI equals the quantity $[1-\mathrm{IACC}_{\mathrm{E3}}]$ (see definition of IACC, the interaural cross-correlation coefficient, in ISO 3382). To explain IACC, note that when a lateral reflection reaches a listener, it impinges on the closest ear without change. After it travels around the head, it will be decreased in amplitude and will be delayed in time. The IACC takes into account all of the lateral reflections impinging on both sides of the head within a stated time, including the differences in their amplitudes and time differences at the two ears. A monaural measurement of the strength of lateral reflections (figure-8 microphone) only measures their combined mean square magnitude.

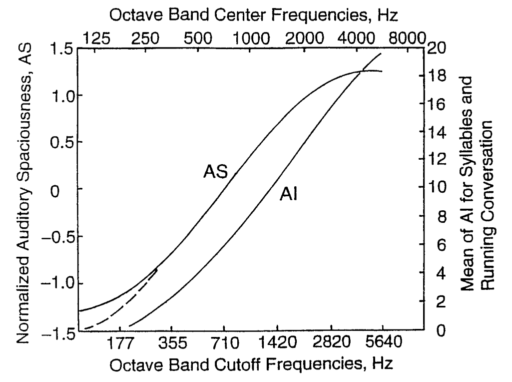

Figure 1. Plots of cumulative auditory spaciousness and cumulative articulation index vs. frequency [31, 37].

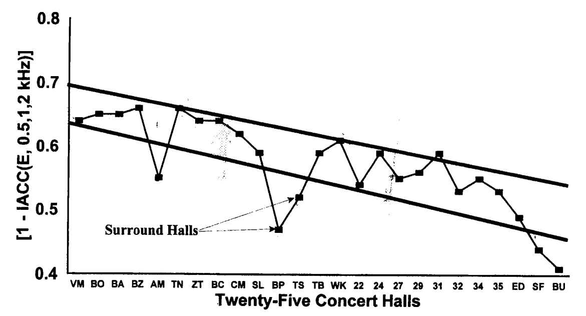

Figure 2. Binaural Quality Index BQI for 25 concert halls, measured when unoccupied, plotted versus the subjective rank orderings of acoustical quality listed in Table II. Average standard deviation 0.11, courtesy Noriko Nishihara.

Gottlob [11], Siebrasse [13] and Schroeder *et al.* [12] found the interaural cross-correlation coefficient to correlate positively with the subjective judgments of acoustical quality by their subjects. Also, IACC was later advocated by Ando, based on the judgments of synthetically generated sound fields [4]. Hidaka *et al.* [24] and Okano *et al.* [27] found that [one minus] the interaural cross-correlation coefficient $\mathrm{IACC}_{\mathrm{E3}}$, when combined with the low-frequency sound strength $\mathrm{G}_{\mathrm{Elow}}$, was "the best measure of ASW." The "E" means integration of the impulse response from 0 to 80 ms, "3" means the sum of the IACC's in the three octave bands 500, 1k and 2 kHz, and "low" means the average of the levels in the 125 and 250 Hz octave bands. Bilsen [35] and Bilsen and Berg [36] report linear relations between spaciousness and [one minus] the interaural cross-correlation coefficient (BQI). Since BQI involves three bands (0.5, 1 and 2 kHz) of which 0.5 and 1 kHz are two it might be expected to correlate highly with spaciousness. However, BQI is not necessarily only measuring spaciousness, but will be shown shortly to be correlating well with the larger concept of overall subjective acoustical quality.

Potter *et al.* [22] showed that there is a psycho-physical basis for BQI and the correlation of [1–CMC] with [1–IACC] is high, where the psycho-physical quantity CMC means "central modulation coefficient."

The 250 Hz band of Figure 1 is not used for determining BQI because, in a binaural cross-correlation measurement, the wavelength at 250 Hz is so long compared to the acoustic distance between the two ears that the correlation of the sounds at the two ears is almost perfect, regardless of the hall in which it is measured. As will be shown in Section "J" below, the ratio of the energy from lateral reflections to the total energy (ratio averaged over a number of seats in real halls) is nearly the same in all frequency bands. Hence, measurements in the higher frequency bands alone appear to be sufficient for measuring ASW. The value of BQI will increase somewhat as the strength of the direct sound is decreased relative to the strengths of the lateral reflections, because there is less correlation of the sounds at the two ears. A decrease in the strength of the direct sound may occur when the source is located in the pit of an opera house while there may not be a corresponding decrease in the strength of the lateral reflections. To determine the magnitude of this BQI increase, recorded data for two halls was used and the direct sound alone was decreased by amounts from 1 to 5 decibels. The result for a decrease of 5 decibels was an average increase in BQI of about 15 percent.

To determine to what extent BQI is related to the overall acoustic quality of a concert hall, a plot of BQI is presented in Figure 2 (for all concert halls for which pertinent data are available) vs. the hall-ranking scale of Table II. The values of BQI shown on the ordinate are the averages of the BQI's at 8 to 16 positions throughout the halls. For the halls where the audience surrounds the stage, the quality of the sound varies greatly with position because at many seats there are few lateral reflections within 80 msec because there are no nearby surfaces to reflect the sound, except from overhead. In Figure 2, the spread of the BQI is 0.07, or about 10 percent at the left end of the graph and about 15% at the right end. Clearly, it separates the bottom six halls in the lower group in Table I, from the top 9, halls except for the Amsterdam (AM) hall which is very wide and where the orchestra is surrounded by a sizeable portion of the audience.

An important advantage of BQI for estimating acoustical quality is that it is almost the same whether the hall is occupied or unoccupied (See Figure 3).

3.3. Reverberation time RT (occupied halls)

Composers have created compositions with certain performance spaces in mind. The characteristic of the performance space that interacts with their music is its reverberation time RT. The music of Bach and the early composers sounds best in halls with moderate reverberation times. The late music of Beethoven and the music of Mahler and Bruckner, for example, sound best in halls with relatively high reverberation times [9, 10, Chap.1]. All of the concert halls in Table II are used for performances of music spanning these two extremes. The question arises, how has the

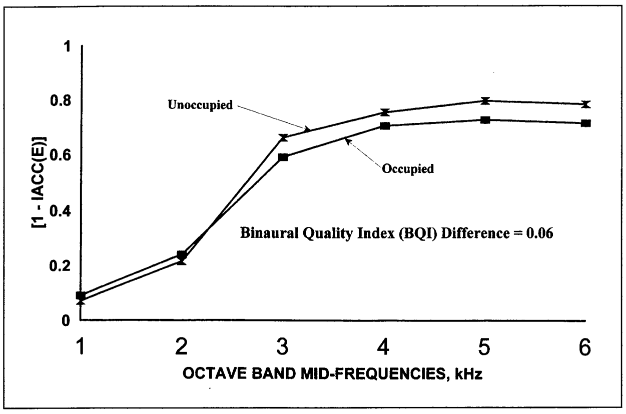

Figure 3. Plots of the Binaural Quality Index BQI versus frequency for occupied and unoccupied concert halls. Data are available for only six halls.

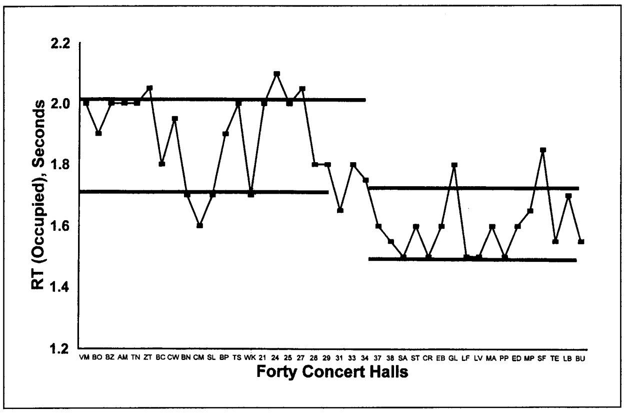

Figure 4. Mid-frequency reverberation times for 40 concert halls, measured with full occupancy, plotted versus the subjective rank orderings of acoustical quality listed in Table II. Average standard deviation, measured with loudspeakers on stage 0.05 sec; from stop-chords 0.11 sec, courtesy Noriko Nishihara.

reverberation time of a hall affected its acoustical ranking by conductors and music critics?

The RT_{mid}'s of occupied halls, averaged in the middle 500 and 1k octave bands, are plotted against the rank orderings in Figure 4. In the top half of the rated halls the reverberation times fall between 1.7 and 2.0 seconds, with the top six halls having reverberation times of about 2.0 seconds. In the bottom group of halls, the RT_{mid} lies between 1.5 and 1.7 seconds. It is apparent that the conductors and music critics prefer a hall with a reverberation time approaching 2.0 seconds and are less enamored with those halls that have reverberation times less than 1.7 seconds.

At low frequencies, the reverberation time is not as important as is the level of the sound in decibels as we shall show later.

3.4. Early decay times EDT (unoccupied halls)

Because successive notes in most symphonic compositions follow one another rapidly (except when there are stop chords), only the early 10 decibels of the sound decay is heard most of the time. Of course, when there is a slow passage or a stop chord, a greater part of the decay or the full RT is heard. The early decay time $EDT_{unoccup}$ is easier to measure than the RT_{occup} and it is interesting to investigate whether this attribute is better than RT_{occup} for judging the acoustical quality of a hall. A plot of $EDT_{mid,unoccup}$ is shown in Figure 5. Except for the two halls with lightly-upholstered chairs, part of which are completely un-upholstered, the $EDT_{unoccup}$'s seem a better indication for how the rank orders of halls in Table II came about than RT_{occup}. It should be noted that the EDT's of a hall are less affected by occupancy than the RT's, except in halls with very lightly upholstered seats.

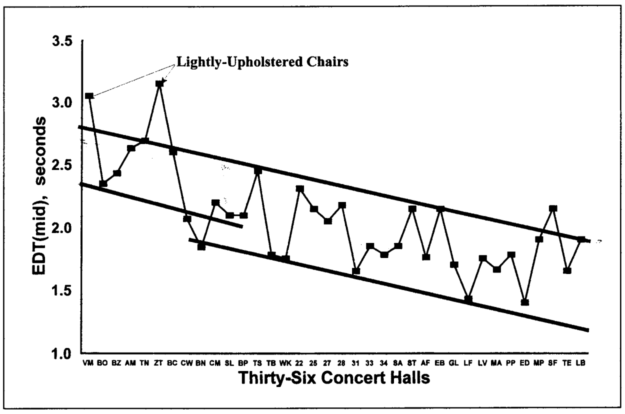

Figure 5. Early decay times EDT for 36 concert halls, measured without audience, plotted versus the subjective rank orderings of acoustical quality listed in Table II. Average standard deviation 0.18 sec, courtesy Noriko Nishihara.

3.5. Strength factor G_{mid} as a function of EDT_{mid}/V

The loudness of music in a concert hall is related in large part to the strength factor at mid-frequencies because the ear is most sensitive in this region. In Appendix A2, it is shown that in a concert hall where the audience absorption is 70 to 85% of the total sound absorption at mid-frequencies, the strength factor $G_{mid} \approx 10 \log K[EDT_{mid}/V]$ [9, pp.437, 449]. Both G and EDT are for unoccupied halls. The results are shown in Figures 6 and 7. The data for Figure 6 were taken by the Takenaka Research and Development Institute of Chiba, Japan. The data for Figure 7 were taken by laboratories in five other countries. Presumably because the calibrations of the sources are different, the G's in the two charts differ by 1.2 dB. The data closely fit the two lines that are drawn with a slope of 3 dB for each doubling of [EDT / V]. The scatter in the points, which are the averages at 8 to 20 positions in each hall, is due, in part by the validity of the assumption above and in part by how many points are taken under balconies or in remote parts of a hall. The strength G_{mid} can decrease by 6 or so dB from front to back of a hall and several more decibels under balconies. Since loudness is important to all listeners, it appears that in the best halls, the hall-average G_{mid} factor falls between 4 and 8 dB for measurements made by Takenaka (Figure 6), or 3

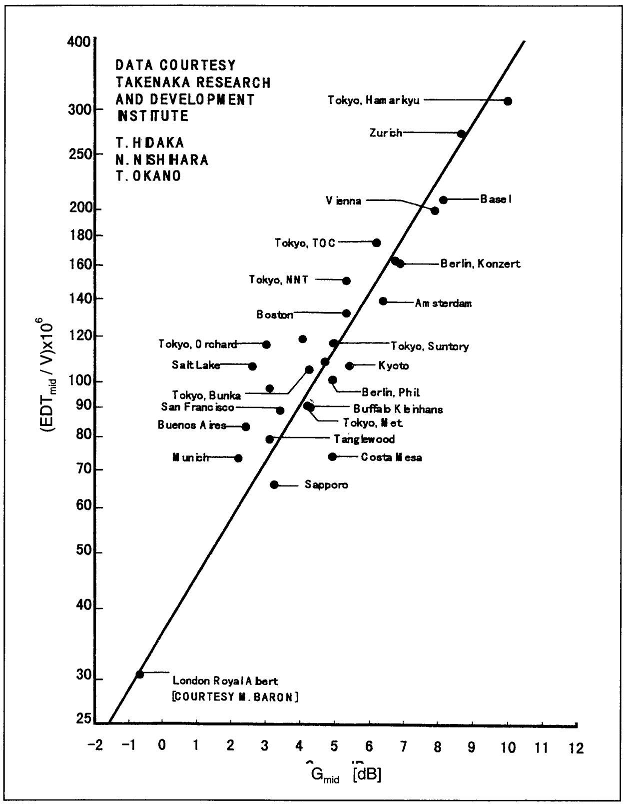

Figure 6. Measurements of the strength of the sound at mid-frequencies Gmid versus the ratio EDT/V, where both Gmid and EDT were determined in unoccupied halls. All data were taken by Takenaka Research and Development Institute. The definition of the reference for G (i.e., G = 0) is the sound pressure measured at a point 10 meters from the center of a non-directional sound source located in an anechoic chamber with input power equal to that in hall The sound source used was a regular dodecahedral "box" with a cone loudspeaker in each of its 12 faces. The halls that deviate most from the 3 decibels per doubling of the ordinate values have architectural features that either heavily concentrate the early sound energy on the main floor (i.e., there is less energy in the reverberant sound, as in Costa Mesa) or the opposite (as in Tokyo, Orchard Hall). Average standard deviation 1.7 dB, courtesy Noriko Nishihara.

to 7 dB for measurements made in other countries (Figure 7). Any hall in which the hall-averaged level G_{mid} is less than 1 dB (European calibration) is likely to be unsatisfactory. When one considers that doubling the size of an orchestra would only increase G by 3 dB, this range of 4 dB is large. The halls on these graphs have seating capacities ranging from 600 to 5000, volumes from 11,000 to 96,000 m^3 and EDT_{mid}'s from 1.7 to 3 seconds.

The difference in the values of G_{mid} for seven occupied and unoccupied halls for which data are available is presented in Figure 8. It is seen that the difference, which is independent of the calibration of the source, is about 1.0 dB in the two low frequency bands and the highest band and 1.5 dB in the three middle bands.

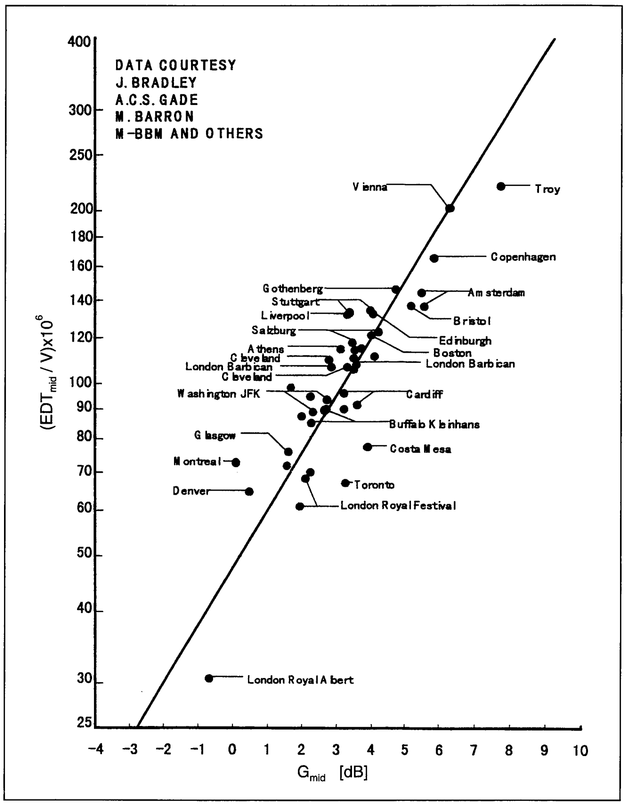

Figure 7. Same as Figure 6 except the data were obtained by researchers in other countries. The stated difference of 1.2 dB between the two graphs is based on the difference between measurements made by the two different parties in the same halls.

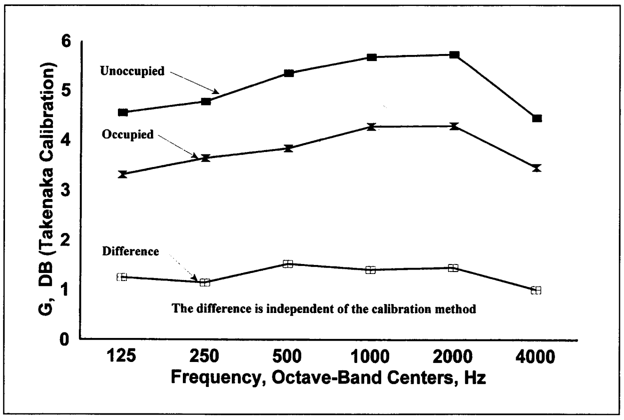

Figure 8. The difference in the strength of the sound G between unoccupied and occupied halls as a function of frequency. Data are available for only seven halls. This difference is independent of the calibration method.

3.6. Bass ratio BR (occupied halls) and G_{125}, (unoccupied halls)

In large halls, adequate strength of the bass sounds is difficult to achieve because it depends on the materials used in the construction of the walls, ceiling and floor, on the thickness of the upholstering on the chairs, on carpets or other sound absorbing materials used for echo control, and on ventilation and lighting fixtures and other openings.

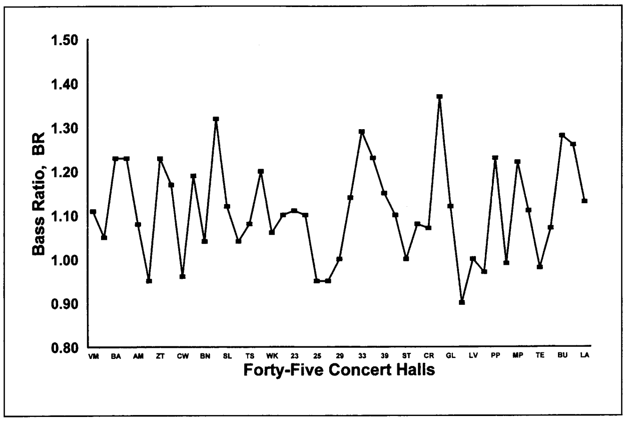

Figure 9. Bass ratio for 45 concert halls, measured in occupied halls. Average standard deviation measured with loudspeaker on stage, 0.09 sec; measured from stop chords 0.2 sec.

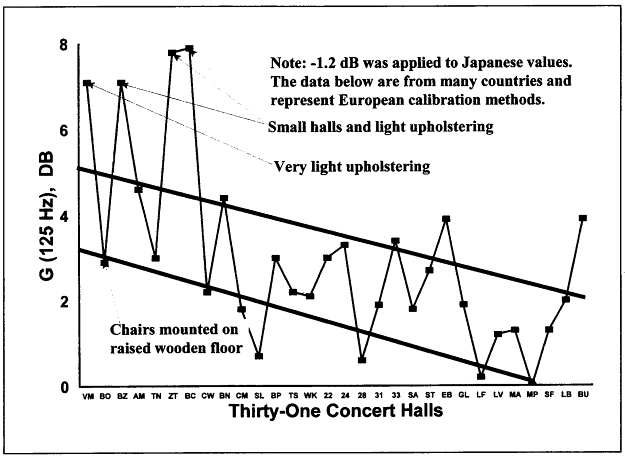

Figure 10. Strength G at 125 Hz for 31 concert halls. Measured with halls unoccupied. G_{125} is larger in small halls, and in halls with light upholstering.

In the past, (based, in part, on early studies in the Technical University of Berlin [3]) the quantity usually used for judging whether the bass is satisfactory is the bass ratio BR, obtained from the reverberation times vs. frequency curve measured in occupied halls. BR equals the sum of the RT's in the 125 and 250 Hz bands divided by the sum in the 500 and 1000 Hz bands.

Bradley and Soulodre [38] (also Bradley [39]) have found in the laboratory, that when the RT's are held constant at frequencies above 333 Hz, laboratory subjects find that the quality of the sound in a concert hall is influenced hardly at all by large variations in BR. They found instead that the quality of sound is strongly related to the *absolute sound levels in the two lowest bands, especially the 125 Hz band.*

The two measurements, BR and G_{125}, plotted against the subjective rankings of the halls are shown in Figures 9 and 10. As found by Bradley and Soulodre, the bass ratio BR is not related to subjective acoustical quality. However, except in halls with seats that are very lightly upholstered, G_{125} dB does relate reasonably well to the subjective quality. The difference between the "excellent" halls and the halls at the lowest end of the ranking scale is about 4 dB. (Note the remark above about doubling the size of an orchestra).

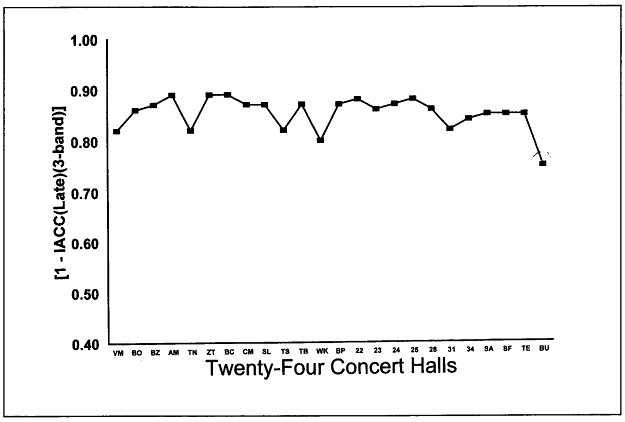

Figure 11. Plot of the late (after 80 msec) quantity [1–$IACC_{L3}$] against 24 rated concert halls.

3.7. Surface diffusivity index, SDI

Every successful concert hall appears to have an abundance of surface irregularities. These irregularities diffuse the acoustical energy in the room and lend a smooth, homogenized feeling to the early sound and the late decaying sound. These often take the form of coffers in the ceiling, and niches, statues and baroque decorations on the sidewalls. Personally, I have listened to music in only one hall that had no irregularities on any surface. That was the ill-fated Philharmonic Hall in New York City [7, Chap.15], for which the planned surface irregularities were eliminated in a cost-saving move just as the hall was being finished. The sound in that hall was "glassy", "hard" and very disturbing. The owners of the hall attempted to hide the lack of irregularities by hiring an interior decorator who prescribed dark-blue paint on the walls and blue lighting. It is my opinion that the lack of irregularities was more responsible for the unsatisfactory sound in Philharmonic Hall than any other factor.

As of this writing, there is available no agreed-on instrumental means for measuring the degree of surface irregularity. One possibility was tried, namely, the interaural cross-correlation coefficient, which was determined for an integration of the impulse response from 80 ms to 1 sec and averaged over the seating areas. A plot of [1–$IACC_{L3}$] is shown in Figure 11. It reveals that this quantity does not correlate well with the rank-orderings of the concert halls for which measurements are available. Only the BU hall, which has nearly smooth walls, has a value for this quantity that is noticeably different.

Haan and Fricke [1] found that the highest correlation between a) architectural features in a hall (length, width, height and their ratios, and splay of the side walls, etc.), and b) subjective acoustical quality, is the degree of surface irregularities. They devised a visual means for rating surface irregularity on a scale from 0 to 1.0 obtained during visits to a hall or by inspection of photographs. Their

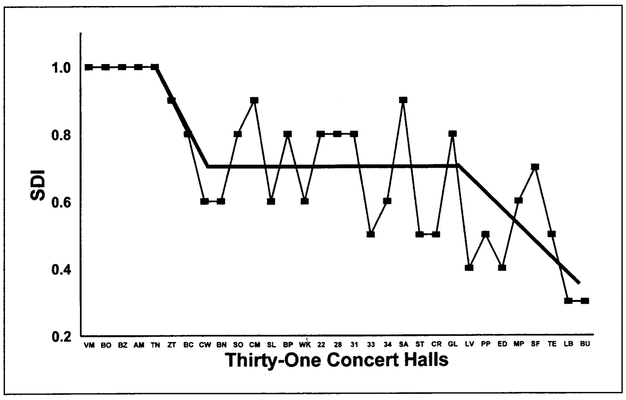

Figure 12. The surface diffusivity index SDI as determined from visual inspections of photographs or visits to 31 concert halls. The highest rated halls have SDI's of 1.0, while those of the lowest rated halls fall in the range of 0.3 to 0.7. The intermediate halls have SDI's of the order of 0.7 + 0.1.

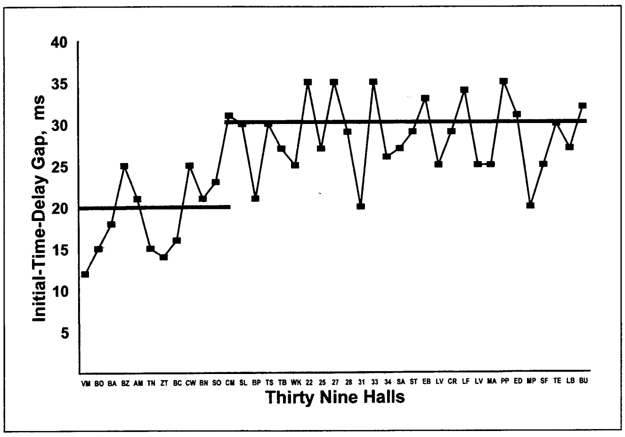

Figure 13. Plot of ITDG for 39 concert halls. Of the top 14 halls, only two have ITDG's greater than 25 msec.

visual rating involves only the side walls and the ceiling–the front and rear ends of the hall are disregarded. The procedure they advocate was applied to 31 halls in this study and the results, called *surface diffusivity index* SDI, are shown in Figure 12. The highest rated halls have many observable irregularities, in the form of statues, niches, baroque ornamentation, and coffered ceilings and are rated near unity. On average, the middle group falls in the 0.5 to 0.8 range, while the lowest rated halls have SDI's in the 0.3 to 0.6 range.

3.8. Initial-time-delay gap ITDG–Intimacy

The subjective impression of listening to music in a large room and its sounding as though the room were small is one definition of intimacy. A deaf person can sense the size of a room by listening to the sound while standing in the center of the main floor. It seems obvious, that a room will sound large if the time difference between the arrival of the direct sound and the first reflection is large (near-middle of the room). Hence, the ITDG is defined, for that position, as the length of time, in msec, between the arrival of the direct sound and the arrival of the first reflection.

It is generally believed that the time separating the early sound from the reverberant sound in a concert hall is about 80 msec after arrival of the direct sound and that the early sound is heavily responsible for setting the acoustical quality. If we accept this belief, then the ITDG should be short so as to allow time for a significant number of early sound reflections to reach the listener between the first reflection and 80 msec, measured from the time of arrival of the direct sound.

In this text the initial-time-delay gap is given only for one position near the center of the main floor, about halfway between the stage and the first balcony front and about one meter off the centerline. This position eliminates positions where there is the possibility of reflections from nearby walls or other surfaces, which would give short ITDG's. A long ITDG at this position is encountered in a hall that is very wide or is fan shaped and has a high ceiling and no suspended reflecting panels.

The center-hall initial-time-delay gaps for thirty-nine halls are shown in Figure 13. In most of the highest rated halls, the ITDG is 25 msec or less. Amsterdam (AM) is a wide hall. It is famous for its long and enveloping reverberation time, which tends to mask the longer initial-time-delay gap. In most of the other halls the average ITDG is about 30 msec. No hall among the thirty-nine in Figure 13 is a poor hall. In a very large hall, which is a "poor" venue for symphonic music, the initial-time-delay gap may be of the order of 50 msec or more. One conclusion to draw from this graph is that it is not too difficult to obtain a reasonable ITDG in a hall that is not too large, provided it is not fan shaped. Hidaka and Beranek [25] found for opera houses, that the best have ITDG's of 20 msec or less, and the lowest ranked of 21 houses has an ITDG of 40 msec.

3.9. Texture

Texture has been defined as "the subjective impression the listeners derive from the patterns in which the sequence of early sound reflections arrive at their ears." In an excellent hall those reflections that arrive soon after the direct sound follow in a more-or-less uniform sequence. In other halls there may be a considerable interval between the first and the following reflections. Good texture requires a large number of early reflections, uniformly but not precisely spaced apart, and with no single reflection dominating the others in amplitude" [9, p.25].

The only way to determine the "quality" of texture at a seat in a hall is by analysis of a reflectogram, i.e., the sound amplitude vs. time of the impulse response. In principle, rectifying and smoothing the reflectogram should facilitate this procedure, but visual determination of the number of reflections in the early sound is usually inaccurate. One way to eliminate the uncertainty in the count is to introduce a mathematically well-defined procedure to the reflectogram, namely to form its "Envelop Function, EF" [40]. Hidaka and Nishihara [41] have studied this problem and advocate using a band width extending from 353 Hz to 2.8 kHz for determining EF and the usual monaural impulse response. Also, they recommend the range of 0 to

−25 dB. They applied this method to the opera houses where the rank ordering was the result of a questionnaire study [25], as mentioned above. They found that the most highly rated houses had more than 17 reflection peaks, a middle group, 10 to 16 peaks, and the lowest group, less than 10 (near center position on main floor). This method has not been tried on the concert halls in this study, but there is no reason why it should be less effective. It could possibly be added as a component of a future single- number rating of acoustical quality of a concert hall provided it is found to be orthogonal to the other objective characteristics.

3.10. Lateral fraction LF_{E4} and LF_{E3}

Meyer and Kuhl attempted in 1952 (See [3, p.113]) to improve the projection of sound to the audience in the Opera House in Hamburg, Germany, by placing large reflectors at both audience-sides of the proscenium. They observed that the sound source seemed to expand laterally, without losing its localization. Other than making this observation, they carried the experience no further, nor did anyone else at that time. This widening effect is now called "spaciousness" and was discussed earlier.

Marshall [19] advanced the concept that the famous old shoebox concert halls were so successful because the most influential of the early reflections in them come from lateral directions, i.e., from the sidewalls and side-balcony fronts.

Baron and Marshall [18], in a limited laboratory experiment, used six to eight subjects who were asked to make judgments of "spatial effect" and "enveloped by the sound" (the subjects gave the same results for both questions). Musical motifs were radiated to a seated subject from loudspeakers located in a circle around the subject at various lateral angles and delayed by 0 to 100 ms and at various sound levels. Simultaneously the same motif was presented from a loudspeaker directly in front of the subject. From the experiments, Barron and Marshall concluded, in part: 1) The degree of spatial impression [they determined the "apparent source width ASW"] is directly related to the ratio of the lateral early reflection energy to the total early reflection energy, both summed over the first 80 ms after arrival of the direct sound. 2) Frequencies above 1500 Hz do not contribute significantly to spatial impression (compare with Figure 1). 3) The degree of spatial impression is a function of overall listening level.

They devised a method that is widely used in halls for measuring the relative strength of lateral reflections. A non-directional source is placed on the stage (or in the pit) that radiates successive sound impulses. Two microphones are employed, 1) a figure-eight microphone, with its null facing the source and 2) a non-directional microphone. After squaring the outputs and integrating the result from the time of arrival of the direct sound to 80 msec after, 1) is divided by 2) and is named the lateral fraction LF_E. They derive a single number by averaging the LF_E in the 125, 250, 500 and 1000 Hz bands, and designated it LF_{E4}.

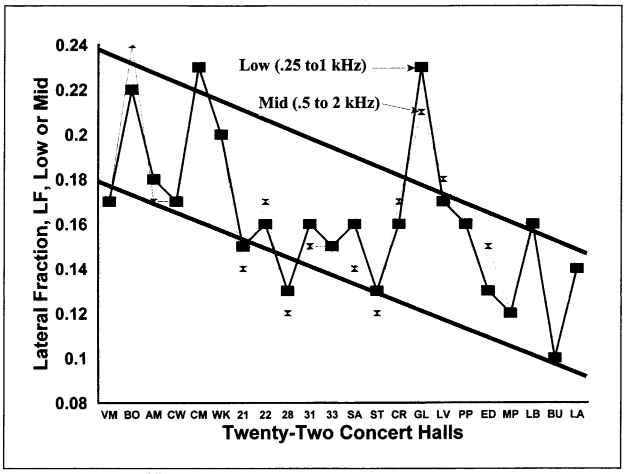

Figure 14. Plot of the early lateral fraction LFE vs. the quality ratings of 22 unoccupied concert halls. The LE was measured in two ways, "low" the average of the values in the four lowest bands, and "mid" the average in the 500, 1000 and 2000 Hz bands. There is no significant difference. All LFE data were taken by those who contributed to Figure 7. Average standard deviation 0.08, courtesy Noriko Nishihara.

Because it is a ratio, 1) to 2) above, partial shielding, or absorption of the direct sound during measurement can increase the value of LF, because the direct-sound energy appears in the denominator. For example, a source placed in the pit may radiate less direct sound into an auditorium, without obstructing lateral reflections. To determine the magnitude of this LF_{E4} increase, recorded data for the same two halls as in "A" above was used and the direct sound alone was decreased by amounts from 1 to 5 decibels. The result for a decrease of 5 decibels was an average increase in LF_{E4} of about 30 percent.

Marshall and Barron [20] now show some reservation in applying LF as the principal measure of acoustical quality in particular halls. As examples, they find that Usher Hall, in Edinburgh, with one of the highest LF_{E4} measured values, namely 27, has a reasonable acoustical reputation, but not among the best. St. David's hall in Cardiff, Wales, has the best reputation of all of UK's halls, but has low LF_{E4} values in many of the seats, with an average value of 17. The Kammermusiksaal in Berlin, they report, has few lateral reflections, but this has not done great damage to this hall's reputation.

Marshall and Barron state that LF_{E4} is a good measure of spaciousness because it is determined by lateral reflections in the low frequency bands, and that any measure which obtains its values from measurements at middle frequencies is not as effective a measure. Let us define LF_{E3} as the lateral fraction determined for the average of LF_E in the 500, 1000 and 2000 Hz bands. The plot of LF_{E4} and LF_{E3} given in Figure 14 clearly shows that there is no difference in the values of the two different LF's in real halls, hence, LF_E measured at 125 Hz is nearly the same as LF_E measured in all the higher frequency bands. Hidaka *et al.* [24] reported the same result.

From Figure 14, the usefulness of the $\mathrm{LF}_{\mathrm{E4}}$ as a measure of concert hall sound quality is shown. The spread of the two sloping lines, which equals 0.06, indicates that it is at best a crude measure. A spread of 0.06 varies from 26% of the mean value at the left end of the graph to 60% at the right end. Further, it is inconceivable that $\mathrm{LF}_{\mathrm{E4}}$ acting as a measure of acoustical quality for London's Barbican (before recent renovations) should be nearly the same as for Christchurch's Town Hall (one of the best of the middle group).

3.11. Stage support factor ST1

The stage support factor ST1 [2] measures the degree to which a lone musician's sound is reflected by surfaces around the stage back to him/her. Figure 15 indicates this factor does not influence the quality of the acoustics in the auditorium, because the rank-ordering scale (abscissa) is for the audience areas. Of the top 8 halls, only in the Berlin Konzerthaus (BR), the Amsterdam Concertgebouw, and the Cardiff St. David's Hall is the ST1 lower than −15 dB. In all three of these halls, no nearby sound reflecting surfaces surround or are located above the performers. In Hall 28, at the request of the musicians, a canopy over the stage has been added since these data were taken. The presence of nearby reflecting surfaces has always been believed to be of importance to the musicians. One is surprised that the famous Amsterdam Concertgebouw has an ST1 as low as −18 dB, Two conductors have expressed their dissatisfaction with this hall on stage. Eugene Ormandy, interviewed by me in 1960, said that after conducting many concerts there, "There is a jumble in the sound and poor orchestral balance." Bernard Haitink, who was music director of the Concertgebouw Orchestra for many years, interviewed by the music critic of the Boston Globe (August 12, 2001) said, "In Amsterdam musicians can hear only themselves, and it is very difficult to hear the other players..."

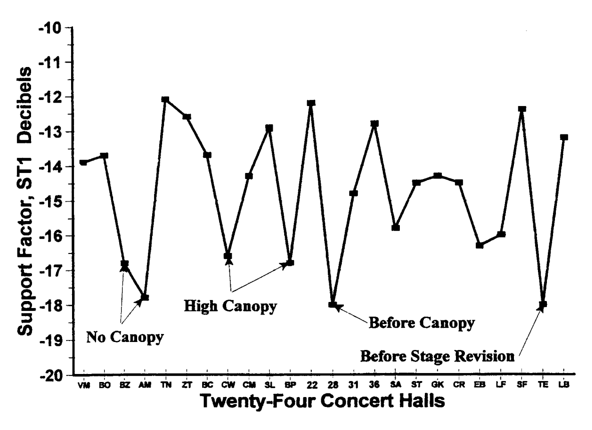

Figure 15. The stage support factor ST1 plotted against the subjective ranking for 24 concert halls. The method of determining it is described in Appendix A1. Generally speaking, halls with high ceilings and no canopy make it more difficult for an orchestra to play in good ensemble. It is seen that even in several halls, there is no canopy, the usual reason for not installing one is that it is unsightly. A desirable range of −12 to −14.4 dB for ST1 is indicated. Average standard deviation, 1.6 dB, courtesy Noriko Nishihara.

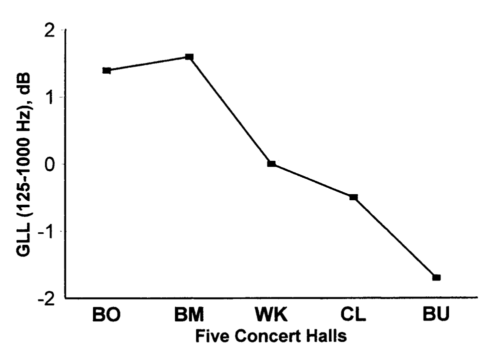

Figure 16. Plot of late lateral strength GLL, as measured by Bradley [39] for five of the halls listed in Table II.

3.12. Late Lateral Strength Factor G_{LL} – Listener Envelopment

One factor that makes Boston Symphony Hall have great sound is that the sidewalls, rear-wall, and the front of the hall, are all reflective and have large areas (between the upper balcony and the ceiling) so that the sound waves travel freely to and from all parts of the room. Thus, the listeners are "enveloped" in the reverberant sound field, that is to say, it arrives at their ears from all directions. In many halls of lesser quality, especially where there is a balcony that nearly covers the rear wall, the reverberation seems to arrive only from the front of the hall, and these halls are usually not rated as high.

Extensive studies of how the reverberant sound field affects listeners' judgment of acoustical quality are currently being made in several laboratories [38, 39, 42]. One objective measure has followed from those studies that shows promise of high correlation with the subjective attribute "listener envelopment." This quantity is the late lateral strength factor G_{LL}, defined as the ratio, expressed in decibels, of (a) the output of a figure-8 microphone (with its null direction aimed at an omnidirectional source on stage) in the time range of 80 ms to 2 s after arrival of the direct sound at a listener's position in a hall, to (b) the total output of a non-directional microphone. The reference level of the non-directional microphone (0 decibels) was determined in an anechoic chamber at a distance of 10 m from the acoustical center of the same omnidirectional source operating at the same acoustical power output as was used for determining (a), [39]. The figure-8 microphone has the same calibration at the peak of its directional pattern as that of the non-directional microphone.

Bradley [39, Figure 21] has measured this quantity, averaged over the frequency bands 125–1000 Hz, in 16 halls and has plotted the hall-averaged values versus the names of the halls. Only five of the halls for which he has data are among the halls rank ordered for acoustical quality in this paper. The results for those five halls are shown in Figure 16, where the abscissa is in accordance with the rank orderings of Table II.

Bradley shows that this measure is higher in rectangular "shoebox" halls than in other shapes, particularly fan shapes. Also, higher reverberation times mean higher values for G_{LL}.

The measure G_{LL} shows promise and certainly should be part of future sets of measurements made in concert halls. Just as for "texture" it possibly may be used as a component in an overall single-number rating for concert halls if it is shown to be orthogonal to the other objective attributes.

4. Orthogonality of the objective acoustical attributes

Any list of acoustical parameters based on physical measurements that purport to be of assistance in judgments of concert hall quality must be independent of each other. In Table III the correlations for the results of the physical measurements in 42 halls are portrayed. These results do not conflict with other correlations reported in the literature. All measurements were performed in unoccupied halls. It is seen that there are high correlations among reverberation time RT, early decay time EDT and the clarity coefficient C_{80}, so that only one of the three can be used in comparisons with subjective quality. We found from Figure 5 that EDT is the most useful of the three in comparisons with subjective judgments. There is a partial correlation between BQI and LF_{E4}, as one would expect, because both are responsive primarily to sound reflections from lateral directions and both measure the sound in the first 80 msec after arrival of the direct sound.

5. Precision of the subjective and measured data

The precision of the measured acoustical data has been reported by the Takenaka Research and Development Institute. Their data were used in 30 concert halls and opera houses of this book and are given in the captions to the graphs. Only measurements by qualified laboratories were used in this text, and the precision of their data should be nearly the same. Some differences among data of different groups (Appendix 4 of [9] and Appendix 2 of [10]) occur because of number of and different locations (averaged) in any given hall. In 26 halls, only the reverberation times were available, often measured by stop-chords at a limited number of positions.

An independent investigation of the precision of separating the rank-orderings of Table II into three groups was made by Takayuki Hidaka and is presented in Appendix A3.

6. Conclusions

The results of this study clearly show that the more important of the measured acoustical parameters in a concert hall are Binaural Quality Index BQI, early decay time EDT_{mid}, strength factor at mid-frequencies G_{mid}, strength factor at 125 Hz G_{125}, surface diffusivity index SDI, and initial-time-delay gap ITDG, in that order. Because these factors are orthogonal, they should be able to be combined in some way to obtain a single rating number for the halls, as suggested in [9]. An improvement in that endeavor is beyond the scope of this paper. It is possible that the charismatic "texture," and the "late lateral strength factor" will fit into this sequence, provided it is shown that they are orthogonal to the other parameters.

Appendix

A1. Equations for acoustical attributes

The Strength Factor G, measured at a particular location in a concert hall, is

$$G = SPL - PWL + 31\,dB, \qquad (A1)$$

where the sound source radiates an impulse, SPL is the sound pressure level in dB measured at that location, and PWL is the sound power level of a non-directional source in dB measured in a reverberation chamber according to ISO 3741 procedure. If PWL is measured in an anechoic chamber, the same value will be obtained if the sound source is truly non-directional, the electrical input to the source is the same as in the reverberation chamber, and if the measurements are made at a number of points on a spherical surface whose origin is the acoustical center of the source.

The Late Lateral Strength Factor, measured at a particular location in a concert hall, is

$$G_{LL} = \int_{0.08}^{\infty} p_8^2(t)\,dt \Big/ \int_0^{\infty} p_A^2(t)\,dt \quad dB, \qquad (A2)$$

where $p_8(t)$ is the response of a pressure-gradient microphone in the hall, with its null axis pointed toward the non-directional impulse source located on the stage, and $p_A(t)$ is the reference pressure for the same source, set at the same electrical input, measured at 10 m in an anechoic chamber. The figure-eight microphone must be properly calibrated.

The Support Factor is

$$ST1 = 10\log\left[\int_{0.02}^{0.1} p^2(t)\,dt \Big/ \int_0^{0.01} p^2(t)\,dt\right] \quad dB, (A3)$$

where $p(t)$ is the pressure response of a non-directional microphone located at a distance of 1 m from a non-directional impulse source located on the stage. Generally, nearby music stands and chairs are removed during the measurement.

Table III. Correlations among physical quantities measured in 42 concert halls. Correlations greater than 0.6 are listed in bold type. A low correlation means the two parameters are independent of each other. Table courtesy Takenaka R&D Institute.

	RT_{mid}	EDT_{mid}	$C_{80,3}$	G	BQI	LF_{E4}	BR	ITDG
RT_{mid}	–							
EDT_{mid}	**0.99**	–						
$C_{80,3}$	**-0.84**	**-0.88**	–		Bold: > 0.6			
G	0.29	0.27	-0.30	–				
BQI	0.15	0.17	-0.33	0.49	–			
LF_{E4}	0.23	0.25	-0.27	0.33	**0.71**	–		
BR	0.08	0.04	0.03	0.05	-0.13	-0.38	–	
ITDG	-0.48	-0.50	0.57	-0.43	-0.12	-0.20	-0.04	

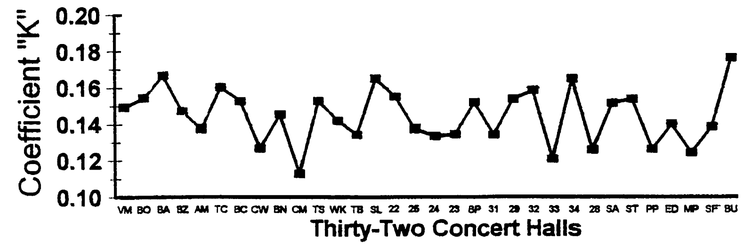

Figure A1. Value of "K" in equation (A4) of Appendix A2 as measured in thirty-two occupied concert halls.

A2.

The approximate reverberation time, detemined from V and S_T, useful in the early stages of the design of a concert hall.

$$RT_{occup} = K(V/S_T) \approx 0.145(V/S_T) \quad \text{sec.} \quad (A4)$$

Sabine's formula is $RT_{occup} = 0.16[V/(S_R\alpha_R + S_T\alpha_T)]$, where "R" indicates all areas in a hall and their average absorption coefficient, excluding those areas occupied by the audience and the orchestra (if present), and "T" indicates the same for the audience seating areas with edge corrections plus the actual area occupied by the orchestra (if present). It is assumed that there is negligible air absorption at these frequencies. In equation (A4), V = hall volume, m^3; S_T = audience seating area with edge corrections plus actual orchestra area, m^2. The assumptions are: (1) Average of quantities at mid-frequencies (500 Hz, 1000 Hz); (2) The audience absorption coefficient at mid-frequencies = 0.83 [29, Fig.7, p.3175]; and (3) the audience accounts for 75% of total sound absorption in hall at mid-frequencies.

The value of K that is calculated from V, RT and S_T for 32 halls is shown in Figure A1. The halls that deviate the most from K = 0.145 are those that differ appreciably in shape from the standard shoebox-shaped concert hall and/or from the 75% assumption. Some part of the deviations are due to measurement inaccuracies.

The approximate strength factor determined from V and $EDT_{unoccup}$

$$G_{mid} \approx 10 \log \left[A(EDT_{unoccup}/V)\right] \quad \text{dB}, \quad (A5)$$

where A is a constant, EDT is the early decay time measured in the unoccupied hall in seconds, and V is the volume in m^3. The equation is from Sabine's work, wherein, $p^2 \approx RT_{occup}/V$. It is assumed that $EDT_{unoccup} = 1.15RT_{occup}$.

A3. Statistical examination of classification of physical parameters

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The objective acoustical data assembled for this paper are plotted against the subjective ratings of Table II in Figures 2 through 15. The subjective ratings are assembled in three groups, Group 1: VM through WK; Group 2: 21 through 39; and Group 3: SA through LA. The purpose of this Appendix is to examine statistically whether each physical parameter, e.g., $[1\text{–}IACC_{E3}]$, RT, LF_{E4}, etc., can properly be classified into three groups. For this purpose, a "one-way analysis of variation" as described by Guttman and Wilks [43, Chap.16] was applied. By this method, a "variance ratio" and a "boundary value of F-distribution" are obtained for the three groups of each graph. If the "variance ratio" is larger than the "boundary value of F-distribution" this is proof of the validity of dividing the ratings into three categories. The larger the ratio, the more definite is the proof. If the opposite is true, the ratings cannot validly be so divided. The method leads to a boundary value "p" (in percent) of the significant level for each parameter as follows:

Figure 2, BQI = $[1\text{–}IACC_{E3}]$ = 0.008%
Figure 4, RT = 0.02%
Figure 5, EDT = 0.02%
Figure 9, BR = 75%
Figure 10, G_{125} = 3.2%

Figure 11, $[1\text{–IACC}_{L3}] = 0.5\%$
Figure 12, SDI = 0.3%
Figure 13, ITDG = 1.8%
Figure 14, $\text{LF}_{E4} = 1.4\%$
Figure 15, ST1 = 98%

From this tabulation, one may conclude that BQI, $[1\text{–IACC}_{L3}]$, RT, EDT and SDI are classified into three groups with high probability. Certainly, BR and ST1 cannot be so classified. For LF_{E4}, ITDG and G_{125}, the boundary value "p" is not low enough to eliminate ambiguity. To illustrate the fragility of separating Group A from Group B for the parameter LF_{E4}, the lowest hall in Group A was transferred to Group B and the calculations repeated. The value of "p" rose to 7.3%. Such a transfer for BQI made negligible difference; hence, one may say that BQI is more robust.

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