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COMPARISON BETWEEN SUBJECTIVE JUDGMENTS OF CONCERT HALL QUALITY AND OBJECTIVE MEASUREMENTS OF ACOUSTICAL ATTRIBUTES[1]

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Thanks Prof. Lara Sáenz. It has been a great pleasure to be in Spain again. I am very pleased to see so many attendees at this historical meeting, the twenty fith anniversary of the Spanich Acoustical Society and of course I bring the greetings of the American Acoustical Society to you on this great occasion.

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[1] From *"How They Sound-Concert and Opera Halls"*, In Press. Publisher: Acoustical Society of America, 500 Sunnyside Blvd., NY 11797 (January 1996, 635 pages).

l. Introduction

This study compares the results of a survey of the subjective judgments of acoustical quality of forty well known concert halls of the world with some of the modern acoustical measurements made in those halls. A large part of the material in this paper is a cooperative effort by Hidaka, Beranek and Okano (1995).

2. The Subjective Rank Orderings.

The Interview Method for ranking the acoustical quality of occupied concert halls that was utilized in the present study is similar to that reported in Music, Acoustics and Architecture (Beranek, 1962). Musicians, music critics and those who listen often to symphonic music in many halls, including acoustical consultants and selected listeners, were used as subjects. Examples of their responses are found in the above reference.

There is no question but that this procedure produces a ranking that would not be agreed to by everybody, but it uses subjects who are older and more sophisticated, musically, than subjects generally used in university experiments. Also, the author was reminded by two music critics that a person's perception of a musical event cannot be transmitted to another person unless (s)he has experienced the same event. For this reason this author has attended concerts in all but three of the halls in this paper with the intent that he could better understand the responses of the interviewees.

Based on the interviews, a rank-ordering is made in Table 1 of 40 halls, out of a total of 66 concert halls that were included in the study, for which considerable modern acoustical data exist. Six rating categories were used, A+, A, B+, B, C+, and C. No attempt is made to rank-order the halls within each category. Rather, they are listed alphabetically by city.

Those halls in the two end groupings (A+,A) and (B,C+,C) were sufficiently separated by the interviews so that there is no doubt that they belong in different classes. Those in the large group of 21 halls that constitute Category B+ were the recipients of mixed judgments. Some persons rated some of those halls in the A category and others rated the same halls in the B category. Others simply said they knew they were not in the A category. Thus a few halls may belong in a category above or below those indicated.

It must be emphasized that the B+ group includes good halls, used in most cases as home bases by excellent orchestras. And, in general, their reputations among local concert goers are excellent. The study does not include any bad halls.

3. The objective measurements.

The objective measurements consisted of (i) reverberation time RT, both occupied and unoccupied; (ii) early decay time EDT; (iii) inter-aural cross-correlation coefficient IACC; (iv) lateral fraction LF, (v) early/reverberant sound energy ratio C80; (vi) bass ratio BR, which equals the ratio of (a) the average of the reverberation times at 250 and 500 Hz to (b) the average of the occupied hall reverberation times at 500 and 1000 Hz, both for occupied conditions; (vii) the initial-timedelay gap tl, determined only at the center of the main floor; and (viii) the strength factor G, taken separately for low and middle frequencies. All quantities other than RT and BR were measured in unoccupied halls.

4. [1 - $IACC_{E3}$] and LF_{E4} as measures of apparent source width ASW [2]

It is shown in the literature and a recent paper (Hidaka, et al., 1995) that both [1 - $IACC_{E3}$] and LF_{E4} are measures of that aspect of subjective spaciousness called apparent source width ASW. The further object of this paper, and a book (Beranek, 1996), is to determine whether objectively measured acoustical attributes in unoccupied halls can serve to predict the acoustical quality of occupied halls during regular concerts. The data available for doing this is taken from Tables 1 and 2.

The first tests were to determine whether either LF or IACC, or both, are suitable candidates for separating halls into different categories for comparison with subjective ratings.

The music from a performing body on stage in a concert hall seems to expand in width and take on body and fullness both due to the presence of lateral sound reflections and increased loudness. For lateral reflections, the sound will be different at the two ears, while the direct sound and reflections from overhead will reach the two ears alike. The interaural crosscorrelation function is a measure of the degree of coherence of sound at the two ears, at frequencies above about 350 Hz,

$$IACF_t(\tau) = \left[\int_{t_1}^{t_2} p_L(t)\, p_R(t+\tau)\, dt\right] \Big/ \left[\int_{t_1}^{t_2} p_L^{\,2}(t)\, dt \int_{t_1}^{t_2} p_R^{\,2}(t)\, dt\right]^{1/2} \qquad (1)$$

where, L and R designate the entrances to the left and right ears, respectively. The maximum possible value of Eq. (1) is unity.

The transit time from one side of the head to the other for a sound wave is about 1 ms, so that it is customary to vary *t* over the range -1 to +1 ms. To obtain a single number that measures the maximum similarity of all waves arriving at the two ears within the integration limits and the range of 1, the maximum value of Eq. (1) is selected and called the interaural cross-correlation coefficient,

$$IACC_t = \left|IACF_t(\tau)\right|_{max}, \qquad for\ -1 < \tau < + \qquad (2)$$

$IACC_A$ is defined for integration limits of $t_1 = 0$ and $t_2 = 3500$ ms; $IACC_E$ for 0 to 80 ms; and $IACC_L$ for 80 to 3500 ms. Hidaka *et al*. show that IACC is most sensiti ve to differences in musical levels at the two ears if it is measured in octave bands and the average is taken of the

[2] All of the LF data in Fig. 1(a) were obtained by The Acoustical Laboratory of The National Research Council of Canada, with John Bradley as head. Bradley, Anders C, Gade, Michael Barron and Sandy Brown, Assoc. supplied the data on British concert halls. The IACC data in Fig. 1(b) were taken by the Takenaka Research Institute in Chiba, Japan. The IACC and other data taken by two groups were found to be in good agreement wher both measured the same halls. Many scientists and consultants in a number of countries supplied additional acoustical and architectural data, and are duly thanked.

values in the 500,1000 and 2000 Hz bands to yield $IACC_{E3}$ and $IACC_{L3}$. Finally, $[1 - IACC_{E3}]$ has been shown to be directly related to ASW and to have a psycho-physical basis (Potter 1993).

The lateral fraction LF is measured by placing two microphones at a seat location, one with a figure-8 directivity pattern and the other omni-directional. The ratio of their outputs, respectively, is LF. It has similarly been demonstrated that averaging of its values in the 125, 250, 500 and 1000 Hz bands yields the most sensitive values. Its value is usually determined from the first 80 ms of the impulse response.

To determine which is better suited to separating the impulse responses of sound transmission in a concert hall, a statistical "t" test at the 95% confidence level was performed on numbers obtained in unoccupied concert halls by the two methods as shown in Fig. 1 (a) and (b). For

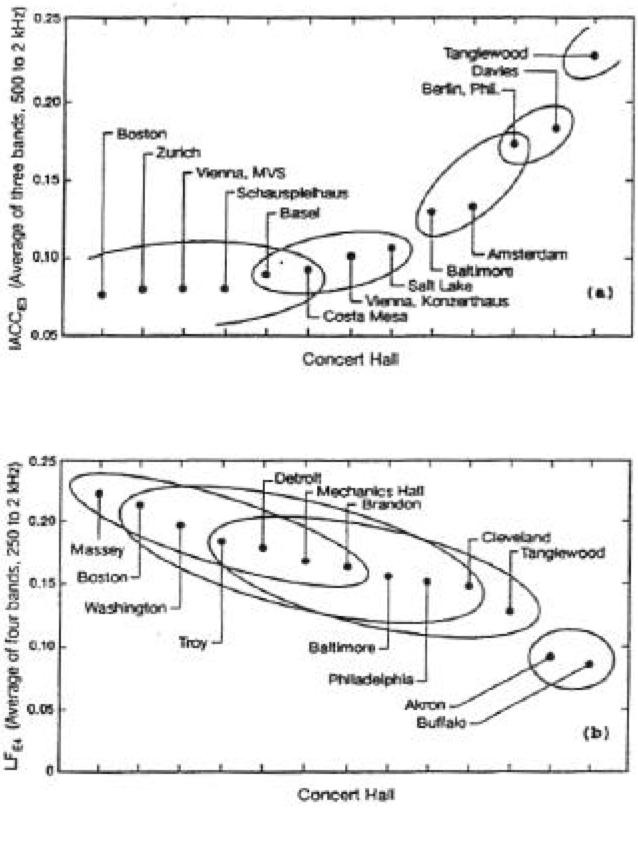
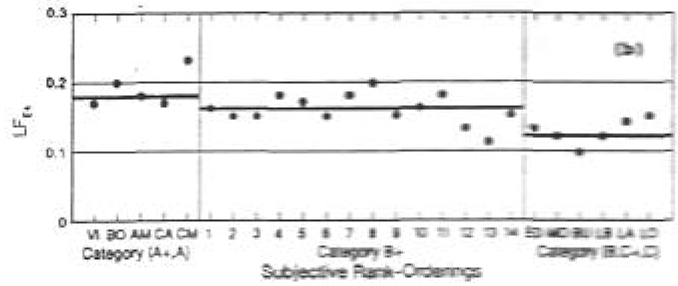


Figure 1. (a) Ovals showing statistical 95% confidence levels for Interaural Cross-Correlation Coefficient for 13 halls. Halls within the same oval have equal values statistically (averages of 8 to 15 seats in each hall and usually 3 source positions). The six halls that are in one oval are among the top ten world-wide according to the subjective evaluations by conductorss music critics, musicians and informed listeners. Particularly important is the separation of the ovals. Tanglewood Music Shed is a special case because optimum values of the other acoustical attributes raise its overall rating to be equivalent to Salt Lake and Baltimore. (b) Ovals showing statistical 95% confidence levels for Lateral Fraction for 13 concert halls. Halls within the same oval have equal values statistically (averages of about 8 seats per hall.) Eleven of the 13 halls are in one oval and include halls of every ranking among the subjective evaluations by conductors music critics, musicians and informed listeners. (Hidaka et al.. 1995).

LF_{E4} the ovals overlap by large amounts and eleven of the 13 halls shown fall within the same oval, which means that all halls within the same oval should have ratings that statistically are equivalent. For $IACC_{E3}$ the "t" test at 95% confidence level show a large difference in its values and the ovals hardly overlap.

5. Correction of IACC data when taken in halls with unupholstered chairs.

Sound traveling over rows of chairs will reach the measuring Positions differentlY if the seats are not upholstered (or lightly upholstered) or fully upholstered. The direct wave in non-upholstered seating area is augmented more strongly by diffracted waves from the chairs surrounding the measurement position than would be the case in halls with upholstered chairs. This direct-sound augmentation causes larger values of IACC. In this study halls with unupholstered or lightly upholstered chairs are Vienna, Boston, Amsterdam, Basel, Zurich and Berlin's Konzerthaus [formerly Schauspielhaus]. Because it is desired to develop a



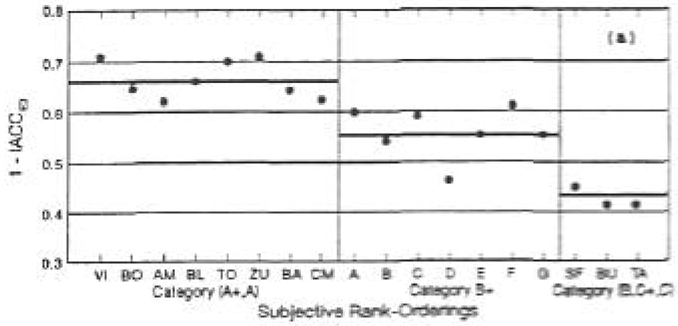


Figure 2. (a) [1 - $IACC_{E3}$] plotted vs. name of hall: In sequence, Vienna, Boston, Amsterdam, Berlin (Konzerthall), Tokyo, Zurich, Basel, Costa Mesa, Cleveland, Baltimore, Salt Lake, Berlin (Philharmonie), Jerusalem, Washington,D.C., Worcester, San Francisco, Buffalo and Tel Aviv.
(b) LF_{E4} plotted vs. name of hall: In sequence, Vienna, Boston, Amsterdam, Cardiff, Costa Mesa, Cleveland, Christchurch, Baltimore, Bristol, Liverpool, Toronto, Wash:.ıgton,DC, Worcester, Salzburg, Copenhagen, London (Festival), Munich (Gasteig), Stuttgart, Paris (Pleyel), Edmonton, Montreal, Buffalo, London (Barbican), London (Albert).

method for use in judging the musical quality of occupied halls, all IACC data must be corrected as though they were taken in the same halls but with upholstered chairs. The method of correction was given in Hidaka *et al.* (1995) and amounts to increases in [1 - $IACC_{E3}$] for the six halls above of +0.07, 0, +0.08, +0.02, +0.07, and +0.02, respectivelv .

6. Comparison of [1 - $IACC_{E3}$] and LF_{E4} in judging acoustical quality of occupied concert halls.

Comparison of [1 - $IACC_{E3}$] with the subjective judgments for which data are available is shown in Fig. 2(a). The measurements were made at 8 to 16 positions and one to three source positions in thirteen well known concert halls. A real or a dummy head with two microphones at the two ear canals was used to feed binaural data into a DAT recorder from which impulse responses were obtained. Comparison for the 24 halls for which LF data were available are shown in Fig. 2(b). The letters are related to the names of the halls in Table 1. The data are further summarized in Table 3.

The range of median values of [1 - $IACC_{E3}$] is from 0.41 to 0.71, a difference of 0.3, while LF ranges from 0.10 to 0.23, a difference of only 0.13. Because the standard deviations of the measurements of LF in each hall are about 50% of the mean values, there are a sizeable number of overlaps among the values in the three groups as seen in both Fig. 2(b) and Table 3. However, for [1 - $IACC_{E3}$], there are no overlaps among the groups.

It is concluded that LF measured in unoccupied halls is not an adequate acoustical attribute to be used in calculations of occupied concert hall quality.

7. Selection of other measured acoustical attributes for use in rank ordering concert halls.

From Table 1 the median reverberation times (occupied halls) for the three groups are 2.0, 1.7 and 1.5. If the values of EDT for halls with unupholstered seats (Amsterdam, Boston, Vienna, Basel, Berlin, and Zurich) are eliminated, the difference between EDT (unoccupied and RT is about 0.2 sec in all three groups. Hence, for these six halls, it can be assumed that, if they had upholstered seats, EDT would equal measured RT plus 0.2 sec. Thus, either RT or EDT can be used in an overall computation scheme for estimating concert hall acoustical quality.

From Table 2, we see a good separation of values of the initial-time-delay gap t_I in these three groups, 17, 27 and 29 ms, respectively. Because no bad halls are included no large values of t_I were measured. Thus t_I should be one of the components in a scheme for estimating acoustical quality.

The values of G_{mid} in the three groups are 5.6, 3.8 and 2.4 dB, respectively, indicating that the strength factor is important in judging acoustical quality.

The bass ratio BR is indeterminate. The three A+ halls have BR's between 1.03 and 1.11. These low values of BR are permissible probably because of the optimum values of the three previously discussed attributes. The Tanglewood Music Shed, which was rated subjectively as

A in the front half of the hall, has optimum values of G_{mid} and t_I and a bass ratio of 1.44, three factors which seem to compensate for the low value of $[1 - IACC_{E3}]$. But some of the lowest rated halls have BR's in excess of 1.20. Perhaps, part of this conundrum is due to the difficulty of making adequate RT measurements at low frequencies in occupied halls using musical stop chords. This subject needs further study.

$C_{80}(3)$ seems not to be a usable acoustical attribute in concert hall calculations. Its high negative values are only in halls with unupholstered seats. Otherwise its median values are about -0.3. It is also highly correlated obversely with EDT. Its principal value is for subjective judgment of the clarity of musical sound, but it adds nothing to a calculation scheme dependent on orthogonal attributes.

8. Toward a calculation scheme for estimating acoustical quality.

In my upcoming book I explore a method of calculation using the orthogonal parameters EDT, $[1\text{-}IACC_{E3}]$, t_I, G_{mid}, BR, plus one more. The sixth acoustical attribute is diffusivity which is related to the irregularities on the side walls and ceiling of a hall. I am exploring the use of SDI, surface diffusivity index, based on visual inspection of sound diffusing surfaces in concert halls, after Haan and Fricke (1944).

9. Acknowledgments

The author is deeply appreciative of those who supplied acoustical data for this study and to N. Nishihara, K. Suzuki and S. Tanabe of Takenaka Research Institute for their assistance in data analysis. I wish especially to thank John Bradley and Gilbert Soulodre of the NRC Canada for their help. The NRC data were partly sponsored by the Concert Hall Research Group, a consortium of acoustical practicians.

Table 1. Listing of concert halls for which modern acoustical data are available into categories of acoustical quality based on intewiews and questionaires. Note: Within categories, the halls are not rank-ordered. They are listed alphabetically, by city.

	Seats	Vol.	RT oc.	EDT unoc.
	No.	m³	s.	s.
Category A+: Not rank-ordered				
Amsterdam, Concertgebouw	2037	18,780	2.0	2.6
Boston, Symphony Hall	2625	18,750	1.85	2.4
Vienna, Grosser Musikvereinssaal	1680	15,000	2.0	3.0
Category A: Not rank-ordered				
Basel, Stadt-Casino	1448	10,500	1.8	2.2
Berlin, Konzerthaus [Schauspielhaus]	1575	15,000	2.05	2.4
Cardiff, Wales, St. David's Hall	1955	22,000	1.95	2.1
New York, Carnegie Hall	2804	24,270	1.8	
Tokyo, Hamarikyo Asahi	552	5,800	1.7	1.8
Zurich, Grosser Tonhallesaal	1546	11,400	2.05	3.1
Median values of Categories A+ & A	**1680**	**15,000**	**2.0**	**2.4**
Category B+: Not rank-ordered				
Baltimore, Meyerhoff Hall*	2467	21,520	2.0	2.3
Berlin, Philharmonie	2325	26,000	1.95	2.1
Christchurch, N.Z., Town Hall	2662	20,500	2.1	2.4
Bristol, Colston Hall	2121	13,450	1.7	1.85
Cleveland, Severance Hall	2101	15,690	1.5	1.7
Copenhagen, Radiohuset, Studio I	1081	11,900	1.5	2.0
Costa Mesa, Segerstrom Hall	2903	27,800	1.6	2.2
Glasgow, Royal Concert Hall	2459	28,700	1.75	1.7
Jerusalem, Binyanei Ha'Oomah	3142	24,700	1.75	1.85
Liverpool, Philharmonic Hall*	1824	13,560	1.5	1.8
London, Royal Festival Hall[Assist. Res. on]	2901	21,950	1.5	1.65
Munich, Philharmonie Am Gasteig	2487	29,700	1.95	2.1
New York, Avery Fisher Hall	2742	20,400	1.75	1.95
Paris, Salle Pleyel*	2386	15,500	1.5	1.8
Rotterdam, De Doelen Concert Hall	2242	27,070	2.05	2.3
Salt Lake, Utah, Symphony Hall	2812	19,500	1.7	2.1
Salzburg, Festspielhaus	2158	15,500	1.5	1.85
Stuttgart, Liederhalle, Grosser Salle	2000	16,000	1.6	2.1
Toronto, Roy Thompson Hall	2812	28,300	1.8	1.9
Washington, Kennedy Concert Hall	2759	19,300	1.85	1.75
Worcester, MA, Mechanics Hall	1343	10,760	1.55	2.15
Medianvalues B+:	**2459**	**20,400**	**1.7**	**1.9**
Category B: Not rank-ordered				
Chicago, Orchestra Hall*	2585	18,000	1.2	
Edmonton, Alberta Jubilee Hall	2678	21,500	1.4	1.45
Montreal, Salle Wilfrid-Pelletier*	2998	26,500	1.65	1.9
San Francisco, Davies Hall*	2743	24,070	1.85	2.15
Tel Aviv, Mann Auditorium	2715	21,240	1.55	1.7
Category C+: Not rank-ordered				
Bloomington, Univ. Auditorium	3760	26,900	1.4	
Buffalo, Kleinhans Music Hall*	2839	18,240	1.3	1.6
London, Barbican Concert Hall*	2026	17,750	1.75	1.9
Median values B & C+:	**2730**	**21,370**	**1.5**	**1.8**
Category C:				
London, Royal Albert Hall	5080	86,650	2.4	2.6

**Before renovations either recently completed, underway or in planning, designed to improve the acoustics.*

Semi-Outdoor Concert Facility					
A-Rating	Lenox, Tanglewood Music Shed	5121	42,480	1,9	3.3

Table2. Listing of measured acoustical atributes fo rhalls that have been classified into categories of acoustical quality based on interviews

City and name of Hall or House	1-IACC(E3) 0.5,1, 2kHz + correct. Unoccupied	LF(E4) 125-1kHz Unoccup.	t(I) ms Unocc.	G(mid) dB Unocc.	BR 125/250 bands Occup.	C(80)(3 0.5-2kHz Unocc.
Category A+ "Superior"						
Amsterdam, Concertgebouw	0.62	0.18	21	4.3	1.08	-3.3
Boston, Symphony Hall	0.65	0.20	15	4.8	1.03	-2.7
Vienna, Grosser Musikvereinssaal	0.71	0.17	12	5.5	1.11	-3.7
Category A "Excellent"						
Basel, Stadt-Casino	0.64	-	16	6.6	1.17	-2.3
Berlin, Konzerthaus [Schauspielhaus]	0.66	-	25	5.5	1.23	-2.5
Cardiff, Wales, St. David's Hall	-	0.17	25	3.8	0.96	-0.9
New York, Carnegie Hall			23	-	1.14	-
Tokyo, Hamarikyo Asahi	0.70	-	16	9.3	0.94	-0.2
Zurich, Grosser Tonhallesaal	0.71	-	14	6.7	1.23	-3.6
Median (A+ , A)	**0.66**	**0.18**	**16**	**5.5**	**1.11**	**-2.6**
Average (A+ , A)	**0.67**	**0.18**	**18**	**5.8**	**1.10**	**-2.4**
Category B+ "Good to excellent"	1-IACC(E3)	LF(E4)	No. of	No. of	No. of	No. of
0	if exists	if exists	Halls	Halls	Halls	Halls
Number of halls	7	15	21	21	21	21
Range of values	0.46 - 0.61	0.11-0.20	11-35	2. -5.8	0.93-1.32	-2.8-1.7
Median value (B+)	**0.55**	**0.16**	**28**	**3.9**	**1.07**	**-0.3**
Average value (B+)	**0.56**	**0.16**	**26**	**3.8**	**1.09**	**-0.4**
Category B: "Good"						
Chicago, Orchestra Hall	-	-	36	-	1.15	-
Edmonton, Alberta Jubilee Hall	-	0.13	31	0.4	0.99	4.1
Montreal, Salle Wilfrid-Pelletier	-	0.12	20	0.8	1.21	-0.3
San Francisco, Davies Hall*	0.44	-	12	2.8	1.11	-0.9
Tel Aviv, Mann Auditorium	0.41	-	30	2.9	0.98	-0.4
Category C+: "Fair to good"						
Bloomington, Univ. Auditorium			40	-	1.12	-
Buffalo, Kleinhans Music Hall*	0.41	0.10	32	2.9	1.28	3.1
London, Barbican Lrg Concert Hall		0.12	27	3.6	1.07	-1.6
Category C: "Fair"						
London, Royal Albert Hall		0.14	15	-0.1	1.23	0.5
Median (B, C+, C)	**0.41**	**0.12**	**30**	**2.8**	**1.12**	**-0.3**
Average (B, C+, C)	**0.42**	**0.12**	**27**	**1.9**	**1.13**	**0.6**

Table 3. Relation between the subjective rating categories of the second parameter and the medians and ranges of the un-occuppied-hall values of [1-$IACC_{E3}$] and LF_{E4} for the concert halls for wich IACC and LF data are available.

	[1-$IACC_{E3}$]	**LF_{E4}**
Groups A+ , A Range:	**0.66** 0.62 to 0.71	**0.18** 0.17 to 0.23
Group B+ Range:	**0.55** 0.46 to 0.61	**0.16** 0.11 to 0.20
Groups B, C+ Range:	**0.41** 0.41 to 0.44	**0.12** 0.10 to 0.14

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