Objective and subjective evaluations of twenty-three opera houses in Europe, Japan, and the Americas

Takayuki Hidaka
Takenaka R&D Institute, 1-5-1, Otsuka, Inzai, Chiba 270-1395, Japan

Leo L. Beranek
975 Memorial Drive, #804, Cambridge, Massachusetts 02138

(Received 5 July 1999; revised 20 October 1999; accepted 21 October 1999)

The room acoustical parameters, reverberation time RT, early decay time EDT, clarity factor C_{80}, bass ratio BR, strength G, interaural cross-correlation coefficient IACC, and initial-time-delay gap ITDG [definitions in Hidaka *et al.*, J. Acoust. Soc. Am. **107**, 340–354 (2000) and Beranek, *Concert and Opera Halls: How They Sound* (Acoustical Society of America, New York, 1996)], were measured in 23 major opera houses under unoccupied conditions in 11 countries: Argentina, Austria, Czech, France, England, Germany, Hungary, Italy, Japan, The Netherlands, and the USA. Questionnaires containing rating scales on the acoustical quality of 24 opera houses were mailed to 67 conductors, 22 of whom responded. The objective measurements were analyzed for reliability and orthogonality, and were related to the subjective responses. Presented are (a) the rankings of 21 opera houses each rated by at least 6 conductors for acoustical quality as heard by them both in the audience areas and in the pit; (b) relations between objective room acoustical parameters and subjective ratings; (c) findings of the most important of the parameters for determining acoustical quality: RT (or EDT), G_M, ITDG, $[1-\mathrm{IACC}_{E3}]$, texture (appearance of reflectrograms in the first 80–100 ms after arrival of the direct sound), a lower limiting value for BR, and major concern for diffusion and avoidance of destructive characteristics (noise, vibration, echoes, focusing, etc.); (d) the differences between average audience levels with and without enclosed stage sets; and (e) the differences between average levels in audience areas for sounds from the stage and from the pit. [S0001-4966(00)06801-6]

PACS numbers: 43.55.Fw, 43.55.Hy, 43.55.Gx, 43.55.Mc [JDQ]

INTRODUCTION

For concert halls, measurements of current room acoustics parameters and their correlation with subjective ratings have been reported in Beranek (1996). There are only a few reported cases of similar studies for opera houses (Barron, 1993). It seems important to learn whether the acoustical parameters that correlate well with subjective ratings of concert halls are useful in evaluating opera houses, therefore a survey of a number of important opera houses is an obvious need. The purpose of this paper is (1) to assemble contemporary acoustical data for 23 houses used for opera; (2) to report on a survey of important opera conductors to learn their acoustical ratings on 24 well-known opera houses of the world; (3) to examine the ranges of various room acoustical parameters determined from the measurements; (4) to compare the subjective judgments by the conductors with the objective parameters; (5) to establish a framework for evaluating opera houses; and (6) to suggest guidelines for use in the acoustical design of new opera houses.

I. OBJECTIVE MEASUREMENTS

A. The halls surveyed

The opera houses to be investigated were selected from the standpoints: (1) they should be widely known as venues for classical opera; (2) their architectural characteristics should either be available in the literature or be determinable; and (3) they should supplement and extend the range of size and shape beyond information now existing in the acoustical literature.

We must emphasize that regular subscribers to performances in *all* of these houses spoke favorably of their acoustics.

Combining these guidelines with practical possibilities, measurements of the 22 opera houses listed in Table I were conducted by the staff of the Takenaka R. & D. Institute, and the data for an additional one were taken from Beranek (1996). Further information about the geometrical properties of the halls are available in that reference and other references (e.g., Beranek, 1962 and 1997; Cremer *et al.*, 1982; Veneklasen and Christoff, 1964; Schmidt, 1985; Moatti *et al.*, 1989; Beauvert, 1996). The seating numbers in these 23 opera houses vary from 1125 to 3816, while the volume and reverberation times (occupied) range from 7000 to 24 724 m^3 and 1.1 to 2.0 s, respectively.

B. Measurement procedures

The measurements were executed under the following conditions: (1) without audiences; (2) with fire and performing curtains open; (3) with major musical instruments and chairs in the orchestral pit (except for the Essen, the Tokyo New National Theater, and Seattle Opera House); and (4) with an orchestral enclosure at Rochester. (An example of the measuring positions is shown in Appendix A, Fig. A1.)

TABLE I. Opera houses for which objective measurements are available. Source at S_0. Listing is alphabetical. All except LO were measured by the Takenaka R. & D. Institute. LO was taken from Beranek (1996).

	Hall name	V m^3	N	V/S_T m	$RT_{occ,M}$ s	$EDT_{unocc,M}$ s	$BR_{occ.}$ -	$C_{80,3}$ dB	G_M dB	$1-IACC_{E3}$ -	ITDG ms	Stage set
AM	Amsterdam, Music Theater	10 000	1689	-	1.30	1.30	1.30	1.9	1.7	0.55	32	n
BD	Berlin, Deutscheoper	10 800	1900	7.5	1.36	1.60	1.30	0.7	1.2	0.39	33	n
BK	Berlin, Komischeoper	7000	1222	7.1	1.25	1.23	1.30	3.1	6.0	0.62	20	y
BE	Budapest, Erkel Theater	17 000	2340	-	1.30	1.40	1.14	3.8	3.3	0.45	17	y
BS	Budapest, Staatsoper	8900	1450	-	1.34	1.37	1.14	1.9	4.4	0.65	15	y
BA	Buenos Aires, Teatro Colón	20 570	2487	9.6	1.56	1.72	1.23	1.1	2.4	0.65	18	y
CC	Chicago, Civic Opera House	23 000	3563	9.1	1.51	1.49	1.32	2.1	0.3	0.53	41	n
DS	Dresden, Semperoper	12 480	1300	10.3	1.60	1.83	1.23	0.8	2.7	0.72	20	n
EO	Essen, Opera House	8800	1125	-	1.61	1.90	1.31	1.3	−0.4	0.54	16	n
HS	Hamburg, Staatsoper	11 000	1679	7.4	1.23	1.35	1.12	2.2	1.3	0.46	34	y
LO	London, Royal Opera House[a]	12 250	2120	7.7	1.10	1.04	1.07	4.5	0.7	0.53	18	n
MS	Milan, Teatro alla Scala	11 252	2289	6.9	1.24	1.14	1.26	3.6	−0.3	0.48	16	y
NM	N.Y., Metropolitan Opera	24 724	3816	9.1	1.47	1.62	1.07	1.7	0.5	0.62	18	n
PG	Paris, Opéra Garnier	10 000	2131	6.9	1.18	1.16	1.31	4.6	0.7	0.50	15	y[a]
PS	Prague, Staatsoper	8000	1554	-	1.23	1.17	1.29	3.1	2.2	0.64	16	y
RE	Rochester, Eastman Theater	23 970	3347	10.2	1.63	1.90	1.32	0.8	3.6	0.54	22	y
SF	Salzburg, Festspielhaus	14 020	2158	8.9	1.50	1.80	1.11	1.5	1.2	0.40	27	n
SO	Seattle, Opera House	22 000	3099	11.2	2.02	2.50	1.26	−0.4	2.7	0.48	25	n
TB	Tokyo, Bunka Kaikan	16 250	2303	9.8	1.51	1.75	1.18	1.1	0.3	0.56	14	n
TN	Tokyo, New National Theater	14 500	1810	9.9	1.49	1.70	1.07	1.6	1.7	0.65	20	n
NT	Tokyo, Nissei Theater	7500	1340	7.4	1.11	1.06	1.24	4.4	5.3	0.58	17	y
VS	Vienna, Staatsoper	10 665	1709	7.3	1.36	1.43	1.19	2.7	2.8	0.60	17	y
WJ	Washington, JFK Center, Opera House	13 027	2142	8.2	1.28	1.27	1.21	4.3	3.1	0.53	15	y

[a]Steel shutter behind main stage closed.

In some houses additional measurements were made with full occupancy and in others the occupied values were estimated using the procedures of Hidaka *et al.* (1998).

C. Measuring system

The block diagram of the measurement setup is shown in Fig. 1. The general outline for the measurements is in accordance with the ISO 3382 (1997), and has been described in more detail in Hidaka *et al.* (1998). A revised stretched impulse was radiated from a calibrated dodecahedral loudspeaker five to ten times, and recorded on DAT in the field. Subsequently, in the laboratory, the S/N ratio was improved from the multiple measurements using the synchronous summation method and later processing.

It is to be noted in the block diagram that a definite pre-triggering signal for the impulses is not used at the time of the field recordings. Such signals are usually employed to permit accurate sync summation subsequently. To eliminate the usual pre-triggering signal, one of the recorded signals, whose waveform was trimmed by a low-pass filter, is also used as the trigger signal for the sync summation. After passing through a digital delay unit, the recorded signals are digitally sampled. If the stretched impulse were to begin from a high frequency component, as is commonly specified (Aoshima, 1981), this sync summation method could not be utilized because of the waveform distortion at the pulse's beginning, which apparently is due to phase fluctuations that modulate the refraction index of the air. To accomplish this method, the revised signal using a lower frequency component [shown in Fig. B1(A) in Appendix B] was employed.

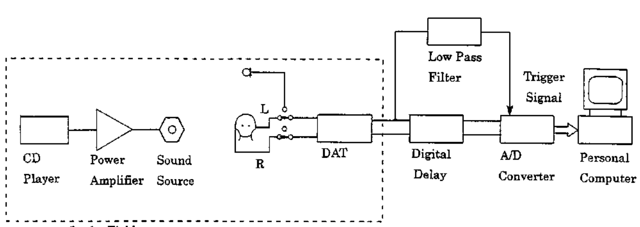

FIG. 1. Block diagram of the measuring system used by the Takenaka R. & D. Institute.

D. Source and receiver positions

Up to four on-stage source positions using the omnidirectional loudspeaker (height$=1.5$ m) were selected depending on the time available for measurement, where S_0 (3 m from the stage edge on the center line) was used in every hall. The source position, S_{pit}, near the conductor's position in the orchestra pit was used whenever possible. The number of receiving points (height$=1.1-1.2$ m) were distributed uniformly at 10–27 seats corresponding to the seating capacity of each (Fig. A1). The receivers were carefully placed at the position of a seated listener's ear position. The binaural measurements were made with tiny microphones taped to the outer ear canals of seated persons with DAT recorders held in their laps. The numbers of monaural and binaural measurements were almost the same.

The variations of objective parameters in the opera houses were of the same orders as for concert halls, the standard deviations (houses unoccupied) of RT_{low}, RT_{mid}, EDT_{mid}, $C_{80,3}$, G_{mid}, and $IACC_{E3}$, from source position S_0 (for NM which is the greatest in size) were 0.07 s, 0.04 s, 0.28 s, 1.3 dB, 1.4 dB, and 0.11, respectively. With the source in the pit at S_{pit}, these were 0.09 s, 0.05 s, 0.17 s, 2.9 dB, 1.8 dB, and 0.12, respectively.

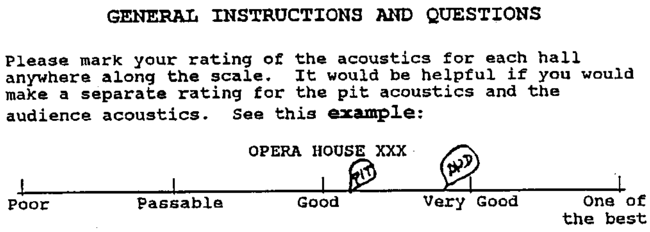

FIG. 2. The rating scale employed in the questionnaire for each of the opera houses, including general instructions for the conductors. The ''questions'' referred to are listed in the text.

II. SUBJECTIVE DETERMINATIONS

A. Questionnaires mailed to conductors

Questionnaires were mailed to 67 important opera conductors and 22 responded, with one response not usable. They were asked for ratings of the acoustics of the opera halls that they knew well on scales that had five steps: *Poor*, *Passable*, *Good*, *Very Good*, and *One of the Best*, which were assigned the numbers 1 to 5 (Fig. 2). Because 13 of the respondents preferred to remain anonymous, all names have been withheld in this paper.

The 24 halls that were included in the questionnaire are those in Table I plus some additions and eliminations. Inclusions were Munich Bayerische Staatsoper, Naples Teatro di San Carlo, Rome Opera da Roma, San Francisco War Memorial, Paris Opera Bastille, Amsterdam Stadtsschouwburg, and Tokyo NHK Hall, for which we have no acoustical data. Not included on the questionnaire were Budapest Erkel Theater, Rochester Eastman Theater, Washington JFK Opera House, Tokyo Bunka Kaikan, Tokyo NNT, and the Seattle Opera House, for which there are data.

The conductors' responses for 21 halls are given in Fig. 3. Four of the 24 halls were rated by fewer than 6 conductors and were not included in Fig. 3; added, as explained later, is Tokyo NNT. Nine halls received ten or more ratings. Note that higher ratings for the acoustics of the pits were made for three halls, NS, PS, and NM.

The standard deviations for the ratings for the audience areas ranged from 0.4 to 1.3 with the median at 0.8. The largest s.d.'s (0.9 to 1.0) were for New York NM, Naples NS, Paris Bastille PB, Chicago CC, and San Francisco SO; and Tokyo NHK Hall TK at 1.3. The smallest s.d.'s (0.4 to 0.6) were Berlin Komische BK, Rome RO, and Vienna VS.

Comments

New York NM (13 conductors) and Naples NS (10 conductors) are two of the three halls in which the pit ratings were significantly higher than the audience ratings. The houses TK, NM, SO, CC, and PB have large seating capacities. Houses BK, RO, and VS have low seating capacities. Thus the most obvious correlations with the magnitudes of the s.d.'s are (1) the seating capacities of the houses and (2) the magnitude of the differences between the pit and audience ratings.

Another factor of the rating system was that some conductors (3) used the full range of 1–5 for their ratings, while some others (3) used a range as little as 2–4. The main group used 2–5. If there was some way to justify expanding or contracting the breadth of the scales of the ratings so that they all covered the same range, the s.d.'s might be reduced, but this manipulation of the data seemed precarious because all conductors did not make the same choice of halls.

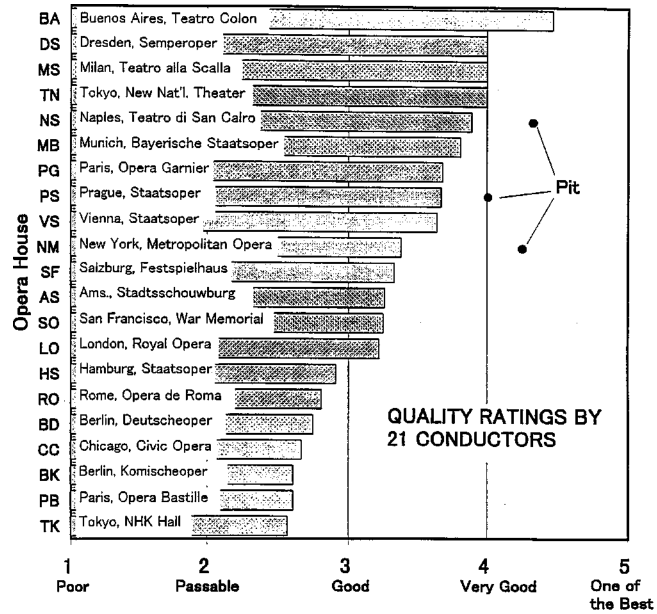

FIG. 3. Acoustical quality ratings in the audience areas of 21 opera houses by 21 opera conductors. The rating sheets contained scales for 24 houses. Only houses that received six or more ratings are included in this figure. All conductors rated the acoustics of the pits as well, but for only three houses were their ratings significantly different (higher) than the ratings for the audience areas, as shown by the large dots. A nonparametric rank ordering, without reference to the rating numbers yields nearly the same sequence—the differences are only among those with almost the same numerical ratings. The rating for TN, which opened in October 1997, was obtained from two opera conductors, two opera singers, two opera directors, two visiting listeners, and four music critics, all with world opera experience. The standard deviations are discussed in the text.

Finally, a nonparametric rank-order comparison of the houses, disregarding the numerical ratings given them by the conductors, was made. The halls fell into the following order: BA, DS, MS, MB, NS, PG, PS, VS, SF, NM, AS, LO, SO, HS, RO, BD, CC, PB, TK, BK. Although there are some reversals from the numerical ordering of Fig. 3, they do not affect the conclusions that are given in this paper because they are for houses with almost the same numerical ratings.

B. Comments by respondents to questionnaires

The two questions below were included in the letter in an attempt to find the keys to which objective parameters might be dominant. A summary of their responses is:

Question 1: ''What mostly makes you judge the sound in some opera houses better than in others?''

This question was answered by 10 of 12 respondents. Typical responses are the following (edited for uniformity of language):

- Can singers project without forcing? Are there dead spots on stage? Does the pit have warmth, but also clarity? Is the pit large enough to place horns and brass together?
- The singers must be clearly heard.
- There must be clarity of texture and richness in the sound.

- There must be presence and beauty of the sound.
- There must be early reflection['s?] and no echo and fast transport of tone.
- It is important that there be adequate resonance and warmth of blend between orchestra and singer while allowing absolute clarity to the sung text.
- One conductor wrote, Kangverhaltniss Buhne-Orch. Mischungsverhaltniss des OrchesterKlangs. Klarheit und Raumlichkeit. [Translation: Acoustical balance stage-orchestra. Ensemble balance among orchestra sounds. Clarity and spaciousness.]
- Depends on what piece was performed. Vienna is excellent in the balance between orchestra and singers. Of course, particular performance of the singers and the orchestra create different impressions of sound quality—that is, eternal issue.

From these comments, we can conclude that good opera houses should satisfy four fundamental demands, assuming no harmful factors: (1) hall support for singers; (2) uniformity of singer projection from a wide area on the stage; (3) good balance between orchestra and singer; and (4) clarity and richness of the orchestral and singing tones.

Question 2: ''Which halls on the list do you enjoy the most and why?''

This question was answered by 10 of 21 respondents. The halls which were nominated by more than two respondents were; Milan (4), Dresden (3), Naples (3), NY (3), Tokyo NNT (3), and Garnier (3). One stated strongly, ''Buenos Aires is extraordinary, as is Dresden. In Paris, I like the Garnier very much and the Bastille not. A basic problem, as ever, is clarity versus liveness. Houses like London (Royal Opera House before 1999 reconstruction) and Amsterdam are simply too dry.'' Another world famous conductor said that the New York Metropolitan Opera House should be ranked equal to the Dresden Semperoper in spite of the fact that only the most experienced and powerful voices can successfully perform in the Met because of its huge size (3816 seats vs 1300). A famous Austrian conductor wrote, ''The National Theater Opera House [TN, Tokyo] is absolutely 'One of the Best.' ''

One world famous conductor, who was not counted in the respondents above, wrote ''There is only one opera house existing which is excellent on all counts and which has never been able to be imitated by anyone, and that is Bayreuth.'' In part, this reflects the difficulty in choosing the best opera acoustics because the reputation of a house is influenced by the performing styles commonly presented and by the backgrounds and personal preferences of its principal conductors. Opera has a longer history than most orchestral music and the beauty of an operatic performance depends on a number of factors in addition to acoustics—the voice and personality (including acting styles) of the singers, the beauty of the orchestral music, the costume and scenery design, and the view of the stage. Opera is truly a composite art.

Parenthetically, it is common consensus that the Bayreuth Festspielhaus is especially suited to the performance of Wagner's compositions—particularly his *Parsifal*.

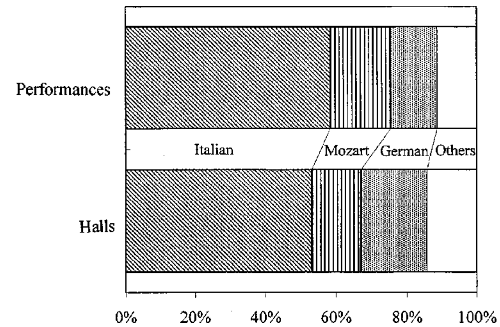

FIG. 4. Statistics of opera performances at 32 opera houses in the 1997–98 seasons taken from *Music and Opera*.

It is generally not believed suitable for Italian opera. The authors analyzed the statistics of opera performances in the 1997–98 seasons at 32 major opera houses around the world (*Music & Opera*, 1997–1998), where opera types, each of which was performed at more than ten halls, were classified into Italian, German, Mozart, and others. The result in Fig. 4 shows that Italian and Mozart type operas are dominant. For them intimacy and clarity are vital because the orchestras are usually not large, and the singers/orchestra together often include delicate ensembles and there are recitatives requiring understandable speech. This information seems to be one reason why horse-shoe halls of compact size have predominated throughout much of operatic history.

III. FINDINGS FROM THE OBJECTIVE MEASUREMENTS AND RELATIONS TO QUESTIONNAIRES

A. Introduction

A complete set of measurements of RT, EDT, C_{80}, G, IACC, and ITDG [definitions in Hidaka *et al.* (2000) and Beranek (1996)] was made in each of the 23 opera houses and is listed in Table I. The IACC_{E3}'s were measured for the 500 to 2000 Hz bands, since they have little meaning at lower frequencies. Only the IACC_{E3} data for the London Royal Opera House LO were converted from LF_{E4} values (Okano *et al.*, 1998). All the acoustical parameters were derived from measurements made with the omnidirectional source located at position S_0, except where indicated otherwise. The correlation matrix for these objective measures are given in Table II, where the suffix ''L,'' ''M,'' and ''3'' mean the average over 125 and 250 Hz, 500 and 1000 Hz, and 500, 1000, and 2000 Hz, respectively. The correlation matrix was calculated for unoccupied values except for BR which was taken from RTs for occupied halls. The correlation, not shown here, between RT for unoccupied and occupied halls is in the high 90's. It is seen that relatively low correlations exist among RT_M, G_L, G_M, IACC_{E3}, BR, and ITDG, while the correlations are high among RT_M, EDT_M and $C_{80,3}$. The correlation matrix for six octave bands is attached in Table AI of Appendix A.

B. Effect of source position on-stage and in pit

In the Tokyo New National Theater TN, on stage, each acoustical parameter was measured for three source posi-

TABLE II. Correlation coefficients among objective acoustical factors calculated from the results of measurements in 23 opera houses listed in Table I. The subscript "L," "M," and "3" mean, respectively, that the octave band average is for 125 and 250 Hz, 500 and 1000 Hz, and 500, 1000, and 2000 Hz. The significant correlations are in **bold** type.

	RT_M	EDT_M	$C_{80,3}$	G_L	G_M	$IACC_{E3}$	BR	ITDG	V	N
RT_M	-									
EDT_M	**0.98**	-								
$C_{80,3}$	**−0.86**	**−0.88**	-							
G_L	−0.02	−0.06	0.02	-			**Bold**: >0.6			
G_M	−0.11	−0.12	0.14	**0.89**	-					
$IACC_{E3}$	−0.05	0.04	0.06	−0.37	−0.34	-				
BR	0.13	0.05	−0.09	0.30	0.08	0.07	-			
ITDG	0.18	0.17	−0.35	−0.17	−0.20	0.42	0.19	-		
V	**0.63**	0.58	−0.46	−0.19	−0.21	0.05	−0.12	0.23	-	
N	0.42	0.35	−0.24	−0.29	−0.30	0.22	−0.06	0.25	**0.92**	-

tions. In the orchestra pit, measurements were made for four distributed positions (see Fig. A1). Both cases were with and without audience. As shown in Table III, the differences in the values of the parameters measured on average in the audience for the different source positions is within a tolerably small range. Similar measurements for various source positions on stage were executed at Berlin Komischeoper BK, Dresden DS, and Milan MS, with the same results for the latter two. We can say that in most houses, e.g., TN, DS, and MS, the different source positions on stage have little influence on the measurements in the audience as long as they are not extremely far from the singer's main position, S_0. The effect of stage position on the sound distribution in Berlin BK will be discussed later. The same conclusion holds for different source positions in the pit. Therefore two source positions, S_0 and S_{pit}, which are often selected in this paper, appear sufficiently reliable for our purposes.

The sound from the orchestra pit is of primary importance, so each acoustical parameter for it was measured in the audience areas of 13 opera houses as shown in Table IV. $RT_{M,occ}$ and BR_{occ} had nearly the same values as listed in Table I whether the source was on stage or in the pit. With the source in the pit, $C_{80,3}$, G_M, and $[1-IACC_{E3}]$ change their values from those for the sound source on stage because of weakened direct sound and the different paths for early reflections. An interesting finding is that the values of $C_{80,3}$ and G_M are similar from hall to hall, except for Vienna VS where G_M is 4 dB for the pit source, which also means that $C_{80,3}$ is small.

The question is, "Why is G_{pit} for VS so large?" Beranek has sat in the Vienna pit (second violin position at the rail) during an opera performance and saw and heard nothing unusual. The answer is that the ceiling, particularly above the pit, is shaped to reflect pit sounds to the main floor. The singers' voices are reflected to the rear of the main floor and to the higher boxes and balconies. There is recent indication that the opera producers in Vienna are aware of this unusual difference, because for two operas, *I Puritani* and *Les Contes D'Hoffman*, produced in late March 1999, stage sets were employed that were nearly closed, both ceiling and side walls, even for outdoor scenes. Also, any important singer's passage was performed very near stage center at the plane of the proscenium. With these arrangements, the singers had no apparent difficulty in making themselves heard above the orchestra. The acoustical consequences of closed sets are discussed shortly.

C. Applicability of the simplified Sabine equation for calculations

The volumes and areas of the different surfaces for the halls that are tabulated in the various tables are for the audience chamber only, as though the stage house was bounded at the proscenium by a wall with an appropriate absorption coefficient. In *Concert and Opera Halls: How They Sound* (C&OH) by Beranek, p. 437, it was shown that for concert halls, in which the sound absorption at mid frequencies of the audience is about 0.85 and the average absorption of all other surfaces in the room is about 0.1, the Sabine equation becomes, approximately, $RT_M = 0.14(V/S_T)$, where V is the volume in m^3 and S_T is the acoustical area of the audience and the proscenium, if open (plus that of the pit if the players

TABLE III. Range of objective parameters measured for three source positions on the stage and four in the orchestra pit under unoccupied and occupied conditions at Tokyo New National Theater Opera House TN.

	RT_L s	RT_M s	EDT_L s	EDT_M s	$C_{80,3}$ dB	G_L dB	G_M dB	$IACC_{E3}$ -
Unoccupied								
Stage	1.6–1.7	1.8	1.5–1.6	1.6	1.7–2.7	−1.7–−0.2	0.3–1.7	0.37–0.43
Pit	1.6–1.7	1.8	1.6–1.8	1.7–1.8	−2.6–0.3	−2.0–1.0	1.7–2.9	0.31–0.44
Occupied								
Stage	1.6	1.5	1.5–1.6	1.3–1.4	3.3–3.9	−1.1–−0.2	−0.4–0.4	0.42–0.51
Pit	1.5–1.6	1.4–1.5	1.5–1.6	1.3–1.4	0.1–1.6	−2.6–−0.5	−1.9–0.0	0.39–0.40

TABLE IV. Measurements made in audience areas of 13 opera houses with sound source in orchestra pit. There were no musical instruments or chairs in the pits at Essen and Tokyo TN. The sequence of the first nine houses is by conductors' ratings. The remaining four (''b'') were not rated. Note that for the source in the pit the clarity in the audience is often negative, good for orchestral music.

	Hall name	$RT_{M,occ}$ s	BR_{occ} -	$C_{80,3}$ dB	G_M dB	$1-IACC_{E3}$ -
BA	Buenos Aires, Teatro Colón	1.53	1.19	−2.6	1.9	0.66
TN	Tokyo, New National Theater[a]	1.49	1.03	−2.3	1.8	0.68
PG	Paris, Opéra Garnier	1.15	1.19	0.3	0.1	0.65
PS	Prague, Staatsoper	1.21	1.28	−0.4	2.5	0.67
VS	Vienna, Staatsoper	1.35	1.12	−0.5	4.0	0.65
NM	NY, Metropolitan Opera	1.48	1.07	−2.3	0.2	0.63
HS	Hamburg, Staatsoper	1.23	1.09	−0.7	1.4	0.57
BD	Berlin, Deutscheoper	1.32	1.28	−1.4	1.0	0.54
CC	Chicago, Civic Opera House	1.52	1.26	−0.2	−2.1	0.66
AM	Amsterdam, Music Theater[b]	1.29	1.20	−1.4	0.3	0.61
EO	Essen, Opera House[a,b]	1.46	1.25	−0.6	−0.1	0.71
TB	Tokyo, Bunka Kaikan[b]	1.49	1.15	−0.5	-	0.58
WJ	Washington, JFK Center, Opera House[b]	1.25	1.13	2.1	1.3	0.58

[a]No musical instruments or chairs in pit.
[b]Not rated by conductors.

are present during the measurements) in m^2. Note that in concert halls the reverberation times (occupied) range from 1.6 to 2.2 s.

We have only one opera house, the Tokyo New National Theater (TN), where we have measured *separately* the acoustic absorption of (1) the audience area, both occupied and unoccupied, (2) the remaining areas of the hall (residual absorption), and (3) the proscenium, with the results shown in Table V (Beranek and Hidaka, 1998). The walls of the stage house (fly-tower) of TN are highly absorbent.

The absorption of sound by a proscenium is a matter of how it is measured and of what conditions exist in the stage house. In the Tokyo NNT Opera House, the omnidirectional loudspeaker was placed either at position S_0 with the proscenium open, or moved forward so that a heavy fire curtain could be dropped behind it. The RTs were then measured for the two cases at seats throughout the opera house and averaged. From those data we could calculate the absorption of the open proscenium, as given in Table V, which, in the middle four bands, is about 1.5 times its area, i.e., 302 vs 205 m^2. This increase in absorption is possibly explained by coupled room theory, but the authors have not attempted verification. The same experimental result was obtained in the 10:1 wooden model. In a contiguous drama theater with 55% of the cubic volume and a highly absorbent stage house, the same measurement was made and the absorption was about 1.23 times the area of the proscenium. We would suppose that in a small theater where the stage house has hard walls, and only a limited amount of hung scenery, the absorption coefficient for the proscenium in those four bands might be near 1.0. We used 1.0 in another case with such a

TABLE V. Calculation of the reverberation times for the Tokyo, New National Theater Opera House TN with proscenium curtain open, a highly absorbent fly (scenery) tower and no stage set. The Sabine equation, $RT = 0.161V/(A_{total}+4\,mV)$, was used for the calculations. The absorption coefficients for the residual surfaces and the occupied chairs were determined from the reverberation times measured before and after installation of the chairs. The mid-frequency audience absorption (0.61) in this opera house is lower than that in most houses (0.80), because of the characteristics of the audience chairs which are similar to those in the TOC Concert Hall (see Beranek and Hidaka, Fig. 6, 1998). A photograph of the chair is in Beranek *et al.*, Fig. 9 (2000). Volume, $V = 14\,500$ m^3; Pit area, $S_0 = 102$ m^2; Audience area with edge correction, $S_A = 1153$ m^2; Proscenium opening, $S_p = 205$ m^2; Residual wall and ceiling areas, $S_R = 4206$ m^2. Total residual area without orchestra, $S'_R = S_R + S_0 = 4308$ m^2.

	Frequency, Hz					
Calculations:	125	250	500	1000	2000	4000
Alpha (R), residual absorption	0.17	0.16	0.13	0.11	0.11	0.10
$A_R = 4308 \times$ Alpha (R)	732	689	560	474	474	431
Alpha's, S_A, occupied,	0.39	0.44	0.60	0.62	0.65	0.54
$A_T = 1153 \times$ Alpha (S_A)	445	503	692	711	747	623
$A_R + A_T$, m^2	1177	1192	1252	1185	1221	1053
Proscenium absorption (Approx)	220	302	302	302	302	378
A_{total} = total absorption	1397	1494	1554	1487	1523	1391
4 mV, Air absorption	0	16	41	76	138	349
$RT = 0.161 \times 14\,500/(A_{total}+4\,mV)$	1.67	1.55	1.46	1.49	1.41	1.34
Measured RT, Occup., 2/15/97	1.62	1.59	1.49	1.49	1.42	1.32

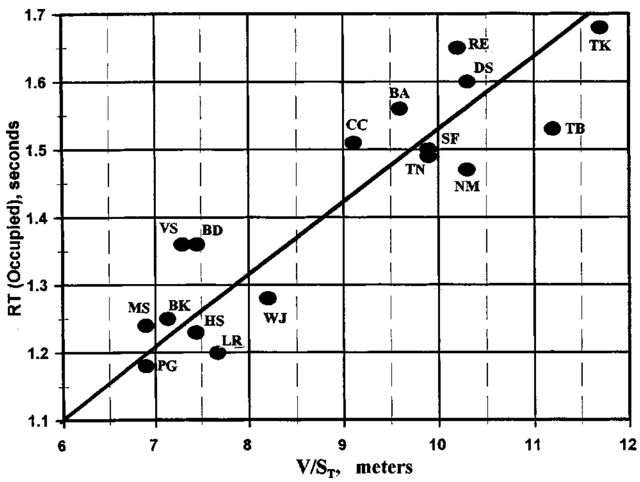

FIG. 5. Plot of the reverberation times for occupied opera houses versus the volume divided by the acoustical area of the audience. The text discusses how the RTs (occupied) were derived from the RTs (unoccupied) where they were not directly measured. The simplified Sabine equation is RT $=KV/S_T$. The mid-value of K for opera houses is 0.16, for the lower group 0.17 and for the upper group 0.15. For concert halls with larger RTs, $K=0.14$.

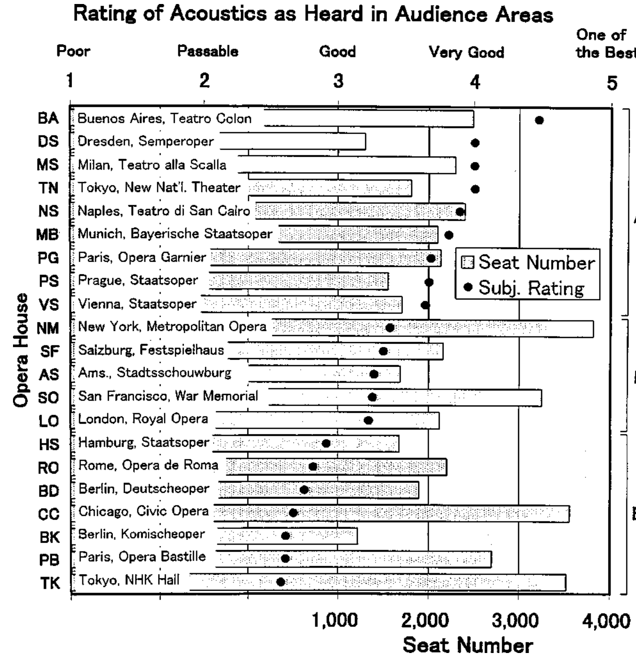

FIG. 6. Conductors' ratings of the acoustics in the audience areas compared to seating capacity. The opera houses are sequenced along the Y axis according to Fig. 3, with the rating shown by the solid points according to the scale on the upper X axis. The seating capacities are shown by the horizontal bars according to the scale on the lower X axis.

stage house and obtained reverberation times equal to those measured.

The RT_M's for 17 houses for which full-occupancy data are available are plotted as a function of V/S_T in Fig. 5. Because S_T is the acoustical audience area (''acoustical area'' means the area over which the audience sits plus edge corrections and plus the area of the proscenium when it is open), the abscissa is approximately equivalent to determining RT as a function of the volume assigned to the acoustical area over which each person sits, i.e., $(V/N)/(S_T/N)$. For estimating reverberation times during early design, the simplified Sabine equation with a suitably selected value of K would seem to provide sufficient accuracy. As discussed above, the RT of an opera house is a function of what is behind the proscenium. If the stage house is heavily sound absorbent (very low RT, say, 0.5 s) and the audience area with the proscenium closed off has a much higher RT (say, 1.7 s), opening the proscenium wall reduces RT in the audience area much more than if the two RTs are nearly alike. This says that the ''sound absorption coefficient'' for the proscenium opening is a variable depending on the stage-house condition.

There is another problem in calculation created by the boxes in a vertical, horseshoe-shaped ''wall'' whose surface is less than 50% perforated for the box openings, e.g., Milan La Scala 43%. Thus the RT in the main-floor audience chamber of such a house will be higher than in a house like the Philadelphia Academy of Music where there is no wall in front of the boxes, only balcony fronts, and no separating walls between the boxes. Depending on which architecture is being evaluated, the volume in the Sabine formula for La Scala should probably only be that of the main floor audience room, while the volume for Philadelphia should include the volume of the open boxes. In the former case, the absorption of the ''wall'' is that of the box openings, while in Philadelphia, the absorption is that of the audience area inside the ''boxes.''

Despite the fact that all types of architecture and stage acoustics are involved, the mean line of Fig. 5 is usually within 0.1 s of the measured values. One should note that the reverberation times for occupied houses that are reported in the literature generally were measured with a few stop chords at only one or two seats, and thus are expected to be off by ± 0.1 s, and if the decay curves are not properly evaluated (Hidaka *et al.*, 1998), even more.

D. Room volume V, shape, and number of seats N

The volumes of the halls of Table I range from 7000 to 24 724 m^3 and S_T from 980 to 2718. Newly built opera houses have not merely a variety of shapes, but also the acoustical area per seat S_T/N is generally larger than in the traditional horseshoe ones. From Fig. 6 it is seen that none of the houses with large seating capacities (above 2500 as shown on the lower scale), rank subjectively above the value of 3.6 on the five-point rating scale of the upper abscissa. With a large volume, assuming evenly distributed sound, there is less soloist energy per square meter of audience space. For the architect, a large house with modern seats occupying larger area per person, necessitates special construction around the proscenium to fully project voices to the audience areas.

Of the top nine houses, only one, TN, is not horseshoe shaped (see Fig. A1). The measured acoustical data also indicate that the horseshoe shape is not necessary to obtain a good opera house acoustically. Visual factors certainly have entered into the decisions to build horseshoe-shaped houses. In those houses, the distance of most of the listeners is

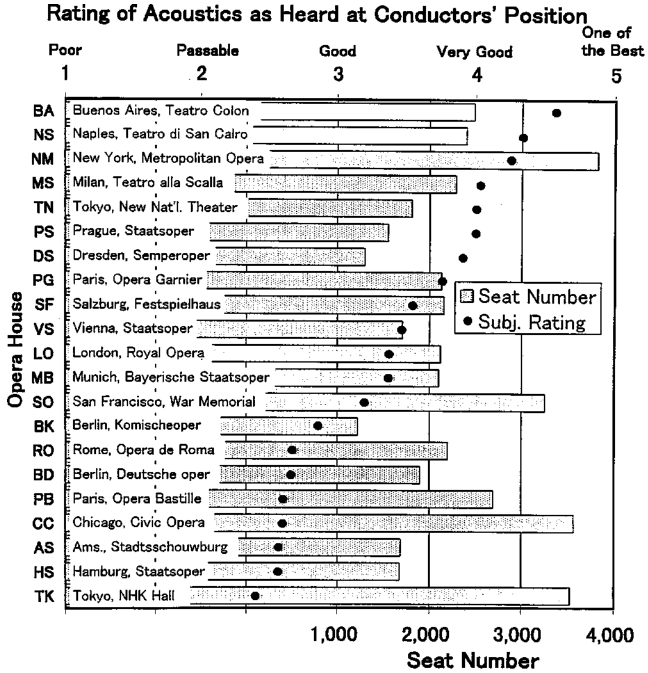

FIG. 7. Same as Fig. 6, except the conductor's ratings are for the acoustics of the pits.

shorter than in conventional auditoriums. Further, in the old houses, the percentage of seats on the main floor is less than in modern houses and the halls are narrower, which makes them more intimate, a fact confirmed shortly by the ITDG data. From Fig. 7 we see that the acoustical conditions around the proscenium and in the pit can increase the conductor's rating of the sound heard in the pit for a large hall, particularly in the case of the New York Metropolitan Opera House NM.

E. Occupied RT obtained from unoccupied RT

An empirical method (Hidaka *et al.*, 1998) for calculating occupied RTs at all six frequencies from unoccupied RTs produced many of the values of $\mathrm{RT_{occ}}$ in Table I. The others were determined from analysis of chords recorded during concerts. The accuracy of the empirical method can be illustrated by comparing calculations and measured $\mathrm{RT_{occ}}$'s at the New National Theater, Tokyo. They were, respectively, 1.49 and 1.51 s. The correlation matrix of Table II is the same for the occupied condition because the empirical equation is a linear transformation.

EDT_M has high correlations with both RT_M ($r=0.98$) and $C_{80,3}$ ($r=-0.88$). Hence, the subjective meaning of reverberance in opera houses may be explained by any one of RT, EDT, or $C_{80,3}$. When selecting reverberation times during design, acoustical clarity $C_{80,3}$ may be more meaningful to laymen than RT, because, in fact, the selection of RT is based on rendering singers' voices adequately articulate.

F. Bass ratio BR

The bass ratio for occupied houses (Table I) is distributed from 1.07 to 1.32, which is a narrower range than that of the concert halls, 0.92 to 1.45.

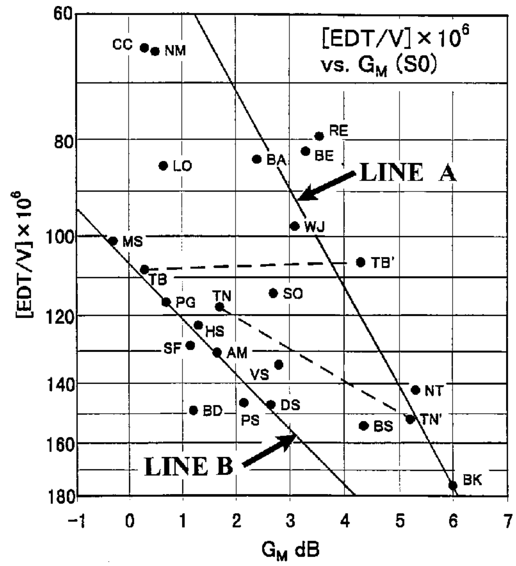

FIG. 8. The early decay time EDT_M divided by the volume V is plotted against the strength factor G_M, both quantities for unoccupied houses with the source at S_0. The measurements were the average of the positions throughout the audience areas. The houses divide into two groups, with four houses falling between. Line A is taken from Beranek (1996, p. 445) and is for opera houses that, during the measurements, had an orchestra enclosure in place, or a stage set that represented a closed room (with ceiling), or a stage house (fly-tower) that was highly reverberant. Line B is for houses with highly absorbent stage houses and either no stage set or a stage set that allowed free acoustical communication between the stage house and the audience auditorium. The letters TB' and TN' are for measurements made in houses TB and TN with silicated-calcium-board fire curtains down.

G. Strength factor *G*

The strength factor G_M (average sound pressure level in dB for 500 and 1000 Hz bands) is important because it is a means for estimating the strength of the singing voice located at the position S_0 on the stage. It has been found that when the Sabine equation is valid, G_M is proportional to RT and inversely proportional to V (C & OH, p. 444). Because the ratio of $\mathrm{EDT_{unocc}}$ to $\mathrm{RT_{occ}}$ is approximately 1.1 for the halls in this study, and assuming as before that the acoustic audience absorption is not less than 75% of the total room absorption with the proscenium closed off, we find that we should have the logarithmic relation shown by Line A in Fig. 8, where the omnidirectional source is at S_0 and the values of EDT_M and G_M are averaged over the audience areas.

Line A in Fig. 8 is the same as that for concert halls (C & OH, p. 445). It is valid for those houses that had, at the time of measurement, either (a) substantial stage sets (i.e., returning most of the energy from the back side of the omnidirectional source to the hall), or (b) either highly reverberant stage houses (fly-towers) or orchestra enclosures on stage. Line B was determined by those halls for which the absorption in the stage house was high and, for that condition, either there was no orchestra enclosure on stage or the stage set was sparse. The separation between the two lines illustrates clearly the approximate increase in the singer's voice that occurs when a roomlike stage set is used instead of a sparse set that opens into a dead stage house. The difference between A and B is 2–4 dB.

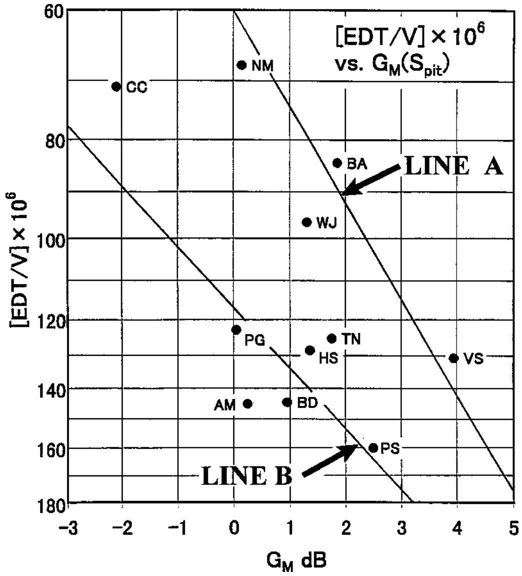

FIG. 9. Same as preceding figure, except the EDT_M and G_M figures are for the source at the position S_{pit}.

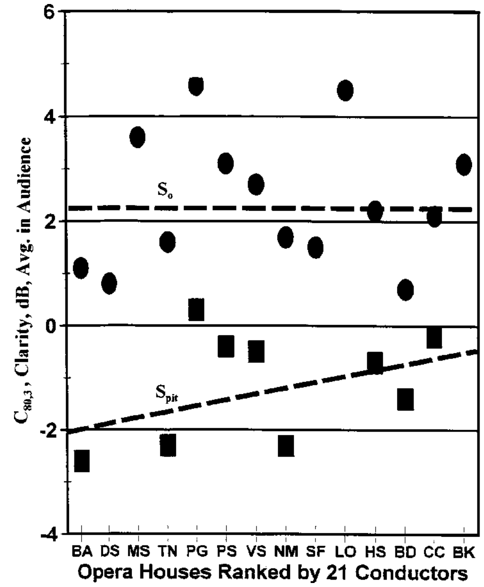

FIG. 10. The clarity factor $C_{80,3}$ plotted against the rank-orderings of the opera houses by the conductors. The upper half is for the source at S_0 and the lower at S_{pit}.

Comment

During the time of the measurements in the Teatro Colón in Buenos Aires BA, a room-tight stage set was in place. Hence, the BA plot lies on the A line. Two halls have relatively small stage houses, Washington WJ and Budapest Erkel BE, so their plots are near line A. The ratios between the stage houses' volumes and the audience chambers were smaller in Chicago CC and Seattle SO than those along line B, so they lie between A and B. At the time of the New York NM measurements, a steel shutter was closed at the rear of the front stage and both sides were largely closed off by reflective stage sets. So its plot lies near Chicago. Obviously, the acoustics behind the proscenium opening is an important factor in determining G, and indicates to opera producers the value of fairly complete and heavy (preferably wooden) stage sets.

Figure 9 is the same as Fig. 8, except that the omnidirectional source was in the center of the pit. Lines A and B are shifted from their values in Fig. 8 by about 1.0 dB to the left, i.e., the pit location reduces the energy radiated by the source by that amount, except for the Vienna Staatsoper VS for which G_M *increases* by 1.2 dB. (The probable reason is discussed in Sec. III B above.) The output of the source in the pit (Fig. 9) is affected by the acoustics behind the proscenium opening, also showing a difference between the lines of about 3 dB.

Although a decrease of 1.0 dB in the radiated strength of an orchestra is significant, the total power from a large orchestra is much larger than that from a singer, so that the orchestra generally has to be restrained in important singing passages. Assistance to the strength of the singers' voices can be obtained architecturally by incorporating special sound reflecting surfaces above and to the sides of the proscenium as are found in Tokyo's New National Theater TN (Beranek *et al.*, 2000).

H. Clarity factor $C_{80,3}$

The clarity factor $C_{80,3}$ (average over the 500, 1000, and 2000 Hz bands) is a measure, in dB, of the strength of the early sound to the reverberant sound, and, hence, a greater positive value indicates that the room reverberation does not decrease the intelligibility of the singing voice as much. Shown by the circles in Fig. 10, values of $C_{80,3}$, with the source at S_0 and averaged over the house, are plotted against the ratings of the acoustics in the audience areas by the conductors (highest rating at the left of the bottom axis). These data with the source in the pit are shown by the squares. For the source at S_0 the mean value is $+2.3$ dB and the standard deviation is 1.2. With the source in the pit, the mean value is -1.2 dB and the standard deviation is 1.0. The dashed lines show that for singers, all values of clarity between $+1$ and $+5$ seem acceptable, while for the orchestral music, less clarity, i.e., 0 to -3 dB, is favored. C_{80} is a function of both the architectural and the stage set design. In general, C_{80} has little or no effect on the overall rating of the acoustics by these 21 conductors.

I. Spaciousness $[1-\mathrm{IACC}_{E3}]$

Of the objective parameters that we tested against the subjective judgments of acoustical quality by conductors, the ''spaciousness'' factor $[1-\mathrm{IACC}_{E3}]$, for the source at S_0, had the highest correlation. Its value is increased by stronger early lateral reflections from side walls, balcony fronts, and reflecting panels that arrive at the listeners' ears within 80 ms after the direct sound. This measure is most effective for judging acoustical quality when its value is determined from the average of its values in the three octave bands, 500, 1000, and 2000 Hz (Hidaka *et al.*, 1995; Okano *et al.*, 1998).

The measured values of $[1-\mathrm{IACC}_{E3}]$, for all halls for which both ratings and these measured data exist, are plotted against the conductor's ratings in Fig. 11. From house to

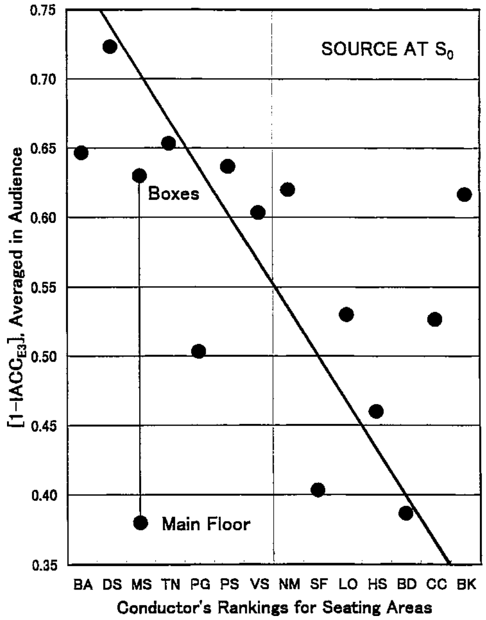

FIG. 11. The spaciousness factor $[1-\mathrm{IACC}_{E3}]$ with the source at S_0 is plotted against the names of the halls rank-ordered according to the conductors' ratings of the acoustical quantities for the audience areas. The higher ratings are toward the left end of the abscissa.

house the variation in spaciousness is the same as for concert halls (Beranek, 1996), i.e., 0.72–0.39 vs 0.71–0.41.

Comment

One sees that there are several discrepancies between measured $[1-\mathrm{IACC}_{E3}]$ and the conductors' ratings, which can mostly be explained by deficiencies in the other important factors. The high measured spaciousness value of 0.62 for the New York Metropolitan NM is accompanied by a lower rating mainly because of its very large size (Table I), which demands that only singers with strong voices be engaged. Milan La Scala MS is a mixed-bag case. In the boxes its values for measured spaciousness average 0.63 (four measurements at two levels) compared to an average of 0.38 on the main floor (six measurements) and its rating is ''one of the best.'' Unquestionably, conductors enjoy MS's pit acoustics, and, in addition, one might speculate that when they listen to an opera they sit in the management's box. One European conductor who rated La Scala one category below the top rating wrote, ''It [the acoustic] was quite disappointing....But ''La Scala'' gives a lot of atmosphere and...this ...distracts the objective acoustic sensitivity. If you feel, that Serafin, De Sabata, Toscanini and others did not complain about the acoustic, why should you....something like this.'' The Paris Garnier House PG is rated higher than its spaciousness measure, probably because of its high intimacy factor (Table VIII) and its great beauty. The measured high spaciousness value for the Berlin Komischeoper BK is counterbalanced by its poor Texture (Fig. 14), which is certainly apparent to trained ears. The excellent sound in the pit of the Prague Staatsoper PS may influence the magnitude of the conductors' subjective rating for the audience areas. Interestingly, when the omnidirectional source is in the pit the spaciousness values (averaged throughout the audience area) are almost equal in all but the lowest rated halls (Table IV)!

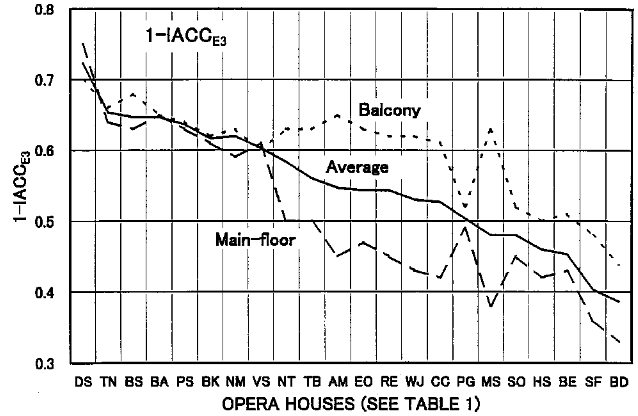

FIG. 12. Plot of $[1-\mathrm{IACC}_{E3}]$ against the names of the halls rank-ordered according to the values of measured spaciousness, which were averaged for the seating areas indicated. The solid line is the average at all receiver positions; the two broken lines are the averages for the balconies and the main floor, respectively. Source at position S_0.

Because the correlation between $[1-\mathrm{IACC}_{E3}]$ and the subjective judgments is sufficiently high overall (see Appendix D), it is an important objective parameter to be used *along with the others* in the design and evaluation of opera houses.

Figure 12 illustrates that in over half of the opera houses measured spaciousness is lower on the main floors than in the balconies (boxes). The main reason is that an insufficient number of early lateral reflections are directed to the main floor in many classical horseshoe-shaped opera houses. That is to say, the balcony fascia do not direct early reflections into those areas and the side wall surfaces have a large number of openings. Also, there may be improperly oriented surfaces next to the proscenium or (open) boxes almost at the proscenium, both cases near stage level. We have learned from discussions with local opera-goers that for these types of houses the sound is superior in the upper tiers.

Another reason for believing that $[1-\mathrm{IACC}_{E3}]$ is a good parameter to use in opera house design is that it seems to be less affected by conditions on stage than others. In Table VI, where in one case a highly reflective fire curtain was closed and in two cases the proscenium curtains were open, its values varied over a relatively small range, 0.58 to 0.65, although RT_M varied greatly: 1.49–2.26 s. In only two halls, Tokyo Bunka Kaikan TB and Osaka Festival Hall OF, measurements were made (unoccupied) with and without an orchestra enclosure (Beranek, 1972, Japanese language). In the former, the values were 0.6 with and 0.56 without, and in the latter 0.52 and 0.49, respectively. Thus even in a multi-

TABLE VI. Measurements of $[1-\mathrm{IACC}_{E3}]$ and reverberation time in the Tokyo NNT Opera House TN, under the three different conditions indicated.

Stage condition	Audience area	$1-\mathrm{IACC}_{E3}$	RT_M (s)
Fire curtain closed	Unoccupied	0.61	2.26
Nothing	Unoccupied	0.65	1.79
Reflecting stage set	Occupied	0.58	1.49

TABLE VII. Comparison of $[1-\mathrm{IACC}_{E3}]$ for several source positions in three opera houses. The data for the different source positions are averaged at the same seats in the different houses. The source position S_H is on the center line at the distance behind S_0 given in the parentheses. S_L of Milan is moved 4 m from S_0 to state right, and S_L of Paris is moved 3 m to stage left and 1.5 m behind S_0. Number in parentheses refers to the distance behind S_0.

Source position	BK, Berlin, Komischeoper	MS, Milan, Teatro alla Scala	PG, Paris, Opera Garnier
S_0	0.65	0.48	0.57
S_H	0.49 (5 m)	0.48 (7 m)	-
S_L	-	0.49	0.64

purpose hall, $[1-\mathrm{IACC}_{E3}]$ seems to be a useful parameter for assistance in rating acoustical quality.

One other factor, which needs more investigation, may explain in part why conductors rate Milan MS high and Berlin Komischeoper BK low. Table VII shows that $[1-\mathrm{IACC}_{E3}]$ in MS varies hardly at all for three positions of the sound source on stage, while in BK it is 0.49 and 0.65 for two stage positions. Further discussion is given in Appendix C.

IV. THE REFLECTOGRAMS

A. Introduction

Reflectograms were faithfully taken at every seat position and for every source and stage condition in every hall that was measured by the Takenaka Institute for each of six frequency bands. Do reflectograms aid in evaluating the acoustical quality of opera houses? Three aspects were studied in an attempt to answer this question: (a) initial-time-delay gap; (b) number of significant reflection peaks in the first 80 ms after arrival of the direct sound (in C&OH, p. 485, this is called ''TEXTURE''); and (c) visual rating of the ''quality'' of the reflection stream in the first 200 ms, i.e., the absolute amplitude and the evenness of the reflections both in amplitude and time distribution. The results were: (a) ITDGs are of significance; (b) there are a greater number of reflection peaks in the best houses, but the range is not large enough to be reliable for estimating acoustical quality; and (c) visual ratings of the reflectograms are purely subjective and not reliably quantifiable.

B. Intimacy ITDG

The initial-time-delay gap measured near the center of the main floor (a position or positions near there are usually chosen as the lone number to be used for indicating the ''intimacy'' of a hall for music) is generally determined by the first sound reflection from a side wall or a balcony front after arrival of the direct sound. In practice, this generally means that ITDG is shorter in smaller halls and can be made shorter in larger halls if the walls, balcony fronts, and reflecting panels are shaped to return early reflections to the seats on the main floor. By proper design, which is easier if the house is not horseshoe-shaped, ITDG can be made less than 20 ms. Table VIII lists the ITDGs as determined from the average of the values found at audience positions 101 and 102 on the main floor of 19 opera houses with the source at S_0. All halls

TABLE VIII. Values of the initial-time-delay gap ITDG determined from the reflectograms. The numbers are the average of the ITDGs at audience positions 101 and 102, near the center of the main floor.

	Opera house	ITDG ms
WJ	Washington, JFK Center, Opera House	15
BS	Budapest, Staatsoper	15
PG	Paris, Opéra Garnier	15
MS	Milan, Teatro alla Scala	16
PS	Prague, Staatsoper	16
VS	Vienna, Staatsoper	17
BE	Budapest, Erkel Theater	17
NM	NY, Metropolitan Opera	18
BA	Buenos Aires, Teatro Colón	18
BK	Berlin, Komischeoper	20
TN	Tokyo, New National Theater	20
DS	Dresden, Semperoper	20
SO	Seattle, Opera House	25
RE	Rochester, Eastman Theater	26
TB	Tokyo, Bunka Kaikan	26
AM	Amsterdam, Music Theater	32
BD	Berlin, Deutscheoper	33
HS	Hamburg, Staatsoper	34
CC	Chicago, Civic Opera House	41

rated high in quality have ITDGs in the region of 20 ms or less. This is consistent with the findings for concert halls (C&OH, p. 483). Four of the lowest ranked houses have ITDGs greater than 30 ms.

C. Texture

Texture is defined in Beranek (p. 25, 1996): ''Texture is 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.''

Counting the number of significant reflection peaks from a reflectogram is not easy. A single reflection will often appear to be divided in two. Using best judgment, a count of the number of reflections in the first 80 ms for 22 houses was made at 2 frequencies and averaged. The most were found for Milan, Buenos Aires, Tokyo TN, Budapest Staatsoper, and Berlin Deutsche. The least were found for Hamburg, Seattle, Prague, and Rochester. But the most was 15 and least was 11, so that use of the reflectograms to rank-order acoustical quality does not seem very helpful.

The visual rankings of the reflectograms of the same 22 houses were made by comparisons like those shown in Figs. 13 and 14. Because the length of these reflectograms is 200 ms, they relate to the definition above plus the beginnings of the reverberant sound field discussed next. The three chosen as best are Tokyo NT, Buenos Aires, and Vienna. The three chosen as of lower quality are Hamburg, Chicago, and Berlin Deutsche. The others are inbetween. This exercise seems

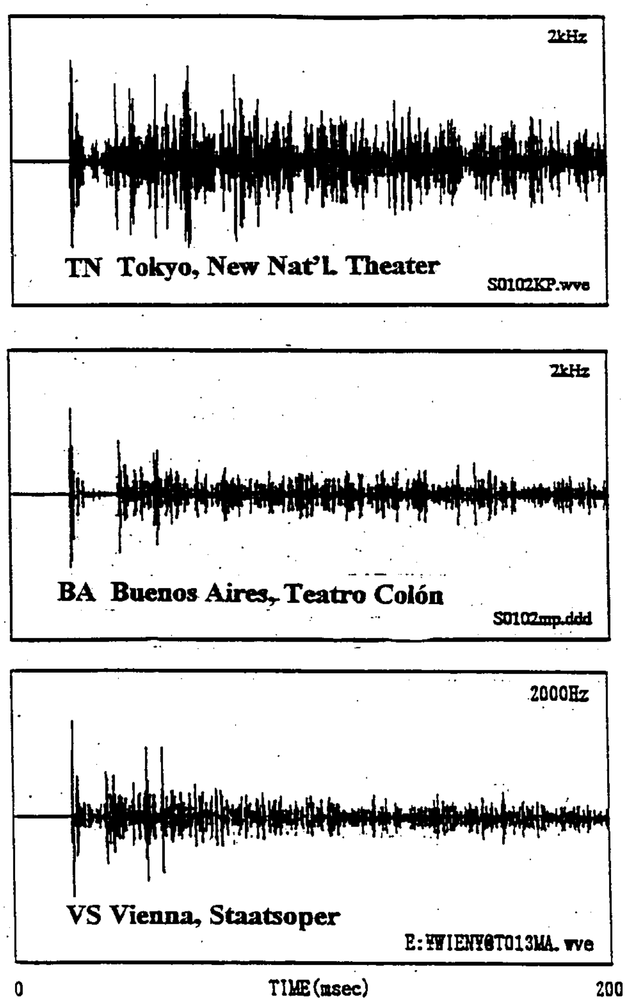

FIG. 13. Reflectograms at receiver position 102 on main floor and source at S_0. These three reflectograms were chosen by visual judgments of ''texture,'' and represent those of the 22 houses that were judged best.

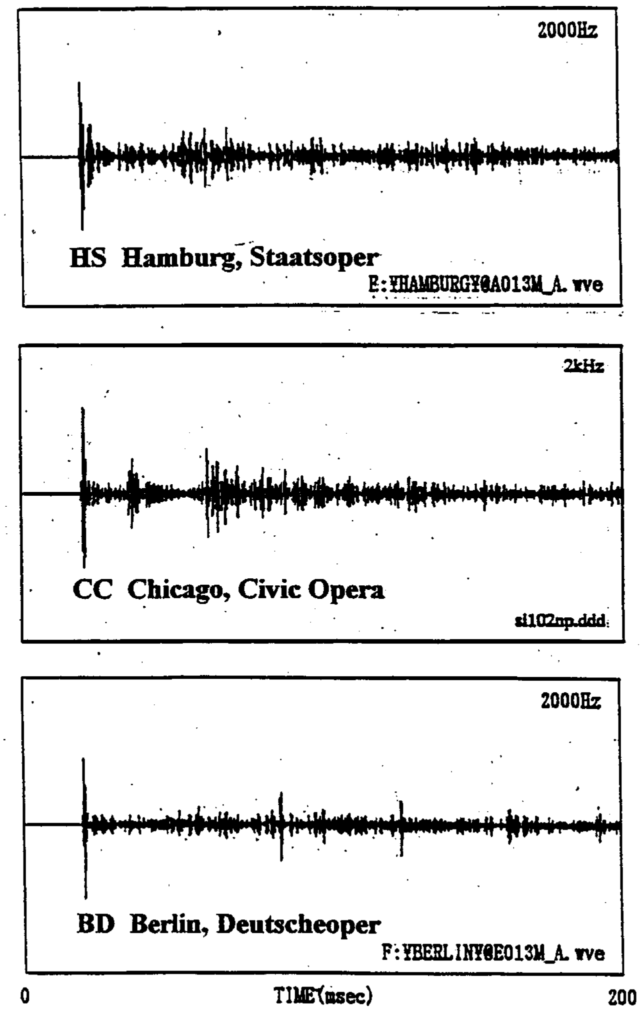

FIG. 14. Same as Fig. 13 except it includes the three halls for which the visual judgments indicated the ''texture'' to be least good among the 22 houses.

helpful in separating the very best from the ones of lesser quality, but it is not a quantitative measure and is of limited help in establishing relative ratings.

D. Diffusion

Every opera house and concert hall with ratings above the level of ''passable'' has architectural means for bringing about diffusion of the reverberant sound field [Haan and Fricke have shown that sound-diffusion in concert halls is a major acoustical parameter (1993)]. A few of the best venues have small-scale irregularities on balcony fronts, lower side walls, and reflecting panels. Such irregular surfaces diffuse the high frequency portions of the early reflected sound waves, thus adding ''patina'' to the overall sound.

Diffusion of the reverberant sound field is usually accomplished by means of coffers, niches, projecting curved, or triangular surfaces and the like on walls and ceiling, particularly in the upper parts of the hall. Unfortunately there is no standardized way to measure the amount or effectiveness of diffusion on the quality of sound and there are no data available on opera houses. But anyone who has ever heard sound in a venue for music with flat smooth walls and ceiling can understand the importance of sound diffusing surfaces. Lacking measurements for evaluating the quality of diffusion in the 23 halls of Table I, we are unable to use it as an objective parameter to add to the five important parameters, reverberance (clarity), spaciousness, initial-time-delay gap, strength, and bass response. It remains, along with texture, of great importance, but with no means for quantifying it except visually.

V. CONCLUSIONS

Five independent (orthogonal) objective acoustical parameters in opera houses were measured and studied: reverberation time at mid-frequencies, RT_M (occupied house); spaciousness $[1-\mathrm{IACC}_{E3}]$ (unoccupied); intimacy ITDG (determined from reflectograms); strength of sound throughout the house at mid-frequencies G_M (unoccupied); and bass ratio BR (occupied), which is the ratio of summed reverberation times in the 125/250 Hz bands to those in the 500/1000 Hz bands.

(1) The reverberation times with full occupancy in the four most highly rated houses (aside from Munich and Naples which are highly rated but for which we have no data) (Fig. 3) are 1.6, 1.6, 1.2, 1.5, respectively. Conductors

and music critics have stated that houses with RTs of 1.1–1.3 s are too dry and that 1.4–1.6 s is the optimum range. Although highly correlated with RT and EDT, the (unoccupied) house-averaged clarity factor, $C_{80,3}$, should lie between 1 and 3 dB throughout the audience areas with the source at S_0. Negative values are desired for orchestral music (source at S_{pit}).

(2) The optimum range for (either unoccupied or occupied) hall-averaged spaciousness factor $[1-\mathrm{IACC}_{E3}]$ should exceed 0.6 (Fig. 11). To achieve such values, the side walls and balcony fronts must be shaped to provide an adequate number of early, lateral sound reflections to the main floor, a deficiency of which was found to exist in half of the houses. Sound reflecting surfaces adjacent to the audience side of the proscenium can profitably be added to strengthen the levels of the singers' voices to the main floor and lower balconies. The favorable results accruing from using such surfaces is shown by the TN reflectogram in upper Fig. 13. These surfaces should also be designed to provide uniform sound radiation from singers located over a large area of positions on the stage.

(3) The initial-time-delay gap ITDG measured at locations near the center of the main floor, which is an acceptable measure of intimacy, should be 20 ms or less (Table VIII).

(4) The optimum range for (unoccupied) hall-averaged sound strength G_M with the omnidirectional source on stage at position S_0 is 1–4 dB (Fig. 8). With this same source condition on stage, the use of an acoustically closed stage set (simulating a room with a closed ceiling) results in an increase in G_M of about 3 dB over that measured in a highly absorbent stage house without a set. Although the increase in strength of a soprano's voice will not be this great at high frequencies because of the directionally of her voice, a large part of this increase will be effective for the lower voices. An increase of 2–3 dB is a significant difference.

(5) The bass ratio, determined from the reverberation times in the four octave bands from 125 to 1000 Hz, should, in opera houses, be larger than 1.05 (Table I).

(6) The texture factor, as observed from reflectograms, should be favorable. That is to say, there should be at all seats a substantial number of early reflections, many of them lateral, in the first 80 ms after the direct sound arrives, and they should be uniformly spaced, adequate in level and as nearly uniformly strong as possible. In the best houses, the number of such reflections near the center of the main floor is about 15 (Figs. 13 and 14).

(7) Finally, a hall aspiring to be in the top ranks, must have diffusion and ''patina'' producing surfaces—large irregularities on the walls and ceiling where the reverberant sound is formed, and small irregularities on lower side walls and balcony fronts from where early sound is reflected. Haan and Fricke (1993) have found diffusion in concert halls to be of major importance.

The authors have attempted to incorporate all of these factors into the design of the Opera House in the New National Theater of Japan, located in Tokyo (Beranek *et al.*, 2000). Although only time will reveal the true success of that venue for opera, two years of service without complaints and a high rating to date from conductors and music critics, give us confidence in offering the above conclusions. Above all, this result shows that an opera house which is not in the tradition of a horseshoe-shape, can share the praise given the best of houses of that shape and yields the same measured data.

ACKNOWLEDGMENTS

The authors wish to express their gratitude to N. Nishihara of Takenaka R&D Institute for her assistance in the data analysis. Thanks are due A. Kotschy of Budapest, Dr. D. Stanzial of Ferrara, and Dr. J. Novak of Prague for their efforts in arranging for the measurements in part of the halls and in helping invite conductors to respond to questionnaires, and to Dr. John A. Swets for helpful suggestions. We are especially grateful to the 22 opera conductors who responded to the questionnaire. We wish also to acknowledge that during our measurements the staffs of all the houses were very cooperative.

APPENDIX A: CORRELATION MATRIX AMONG OBJECTIVE PARAMETERS IN OCTAVE BANDS

Listed in Table AI are correlation coefficients among objective parameters calculated from the results of measure-

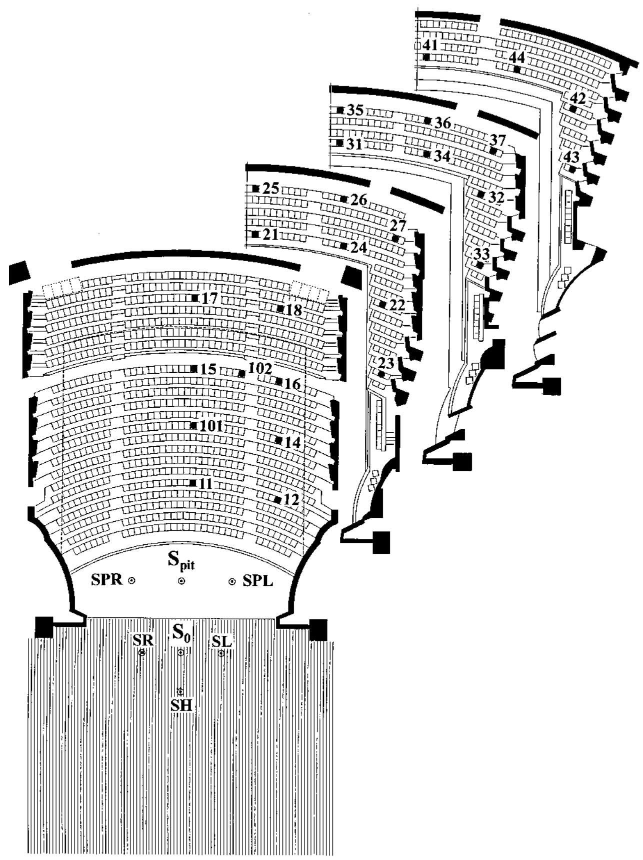

FIG. A1. Source positions and receiver locations in the New National Theatre Opera House, Tokyo. These positions and locations were used typically in all of the opera houses studied, although the time available for the measurements may have reduced the number of audience locations to as few as 10 to 15. Positions S_0 and S_{pit} represent the source positions most often quoted in this paper and Position 102 represents the main-floor position most quoted because it is off center and is usually a choice seat.

TABLE AI. Correlation coefficients among objective acoustical factors calculated from the results of measurements in 23 opera houses listed in Table I in each of the six octave bands with mid-frequencies from 125 to 4000 Hz.

		RT	EDT	C_{80}	G
125 Hz	RT	-			
	EDT	0.93	-		
	C_{80}	−0.68	−0.83	-	
	G	−0.05	−0.01	−0.02	-
250 Hz	RT	-			
	EDT	0.95	-		
	C_{80}	−0.85	−0.84	-	
	G	0.22	0.20	−0.43	-
500 Hz	RT	-			
	EDT	0.96	-		
	C_{80}	−0.79	−0.83	-	
	G	−0.04	−0.02	−0.03	-
	IACC_E	0.12	0.20	−0.18	−0.26
1000 Hz	RT	-			
	EDT	0.98	-		
	C_{80}	−0.86	−0.87	-	
	G	−0.13	−0.16	0.11	-
	IACC_E	−0.08	0.03	0.12	−0.47
2000 Hz	RT	-			
	EDT	0.94	-		
	C_{80}	−0.87	−0.90	-	
	G	0.07	−0.05	0.06	-
	IACC_E	−0.12	0.05	0.20	−0.28
4000 Hz	RT	-			
	EDT	0.91	-		
	C_{80}	−0.80	−0.86	-	
	G	−0.14	−0.25	0.16	-
	IACC_E	−0.14	0.08	0.10	−0.19

ment in 23 opera houses listed in Table I. The values are determined for each of the six octave bands with mid-frequencies from 125 to 4000 Hz. Typical measurement positions are shown in Fig. A1.

APPENDIX B: MEASUREMENT METHOD OF IMPULSE RESPONSE BY STRETCHED PULSE

The stretched impulse is a modification from the delta function, whose phase term in each frequency is shifted in the frequency domain from the original function (Aoshima, 1981; Hidaka *et al.*, 1998). Since this impulsive signal has a stretched waveform on the time axis as shown in Fig. B1(A), the sound power for each frequency of this signal can be much larger than that of the original delta function, provided the sound generating system has sufficient power. Accordingly, the impulse response measurement of the room under noisy circumstances can be achieved with superior S/N ratio, when the stretched impulse is utilized instead of the delta function. In this case, the impulse response is numerically obtained later by inverse filtering of the phase shift filter above mentioned. Figure B1(B) shows the ideal impulse with limited frequency range up to 20 000 Hz that is obtained by the convolution of the inverse filter.

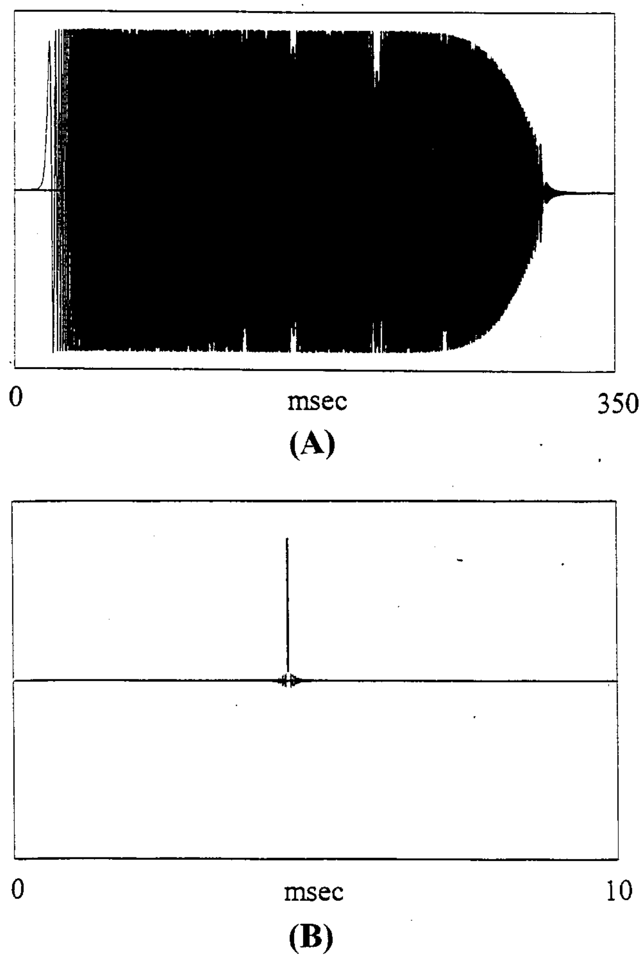

FIG. B1. Waveform of (A) the stretched impulse signal, and (B) the exact impulse wave compressed by the phase shift filter.

APPENDIX C: DISTRIBUTION OF LATERAL REFLECTIONS IN A HORSESHOE HALL

As a supplemental study to the result discussed in Section IV.B the distribution of the first-order reflections from the side walls to the main floor was determined by ray tracing for the cases of the on-stage source position at S_0 and at a position on the centerline backward for the houses BK, PG, and MS. Table CI shows the ratio of the audience area at which first-order lateral reflection arrives versus the whole audience area of the main floor. In the Berlin Komischeoper, the ratio of the covered area to the total floor audience area

TABLE CI. The ratio of audience area covered by reflections from the side walls versus the whole audience area of the main floor, calculated for the three opera houses: Berlin Komischeoper BK, Paris Garnier PG, and Milan La Scala MS. The source position S_0 is on the centerline, 3 m from the edge of the stage. The lower two rows show the source at 8 and 10 m, respectively, from the stage edge.

	BK	PG	MS
S_0	81	98	100
S_0+5 m	61	97	97
S_0+7 m	50	90	86

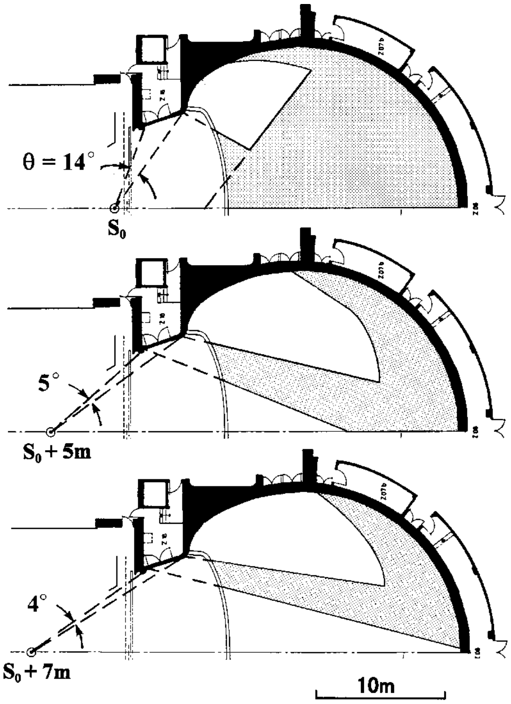

FIG. C1. Area covered by lateral reflections from lower side walls on main floor in Berlin Komischeoper for three source positions: S_0 (upper) and S_0 plus five and seven meters backward (middle and lower). At S_0, a larger portion of a singer's voice energy ($\theta = 14°$) reaches the main floor audience than reaches there when the singer moves up-stage 5 or 7 m ($\theta = 5°$ or 4°). Also, the area covered by the reflected sound decreases.

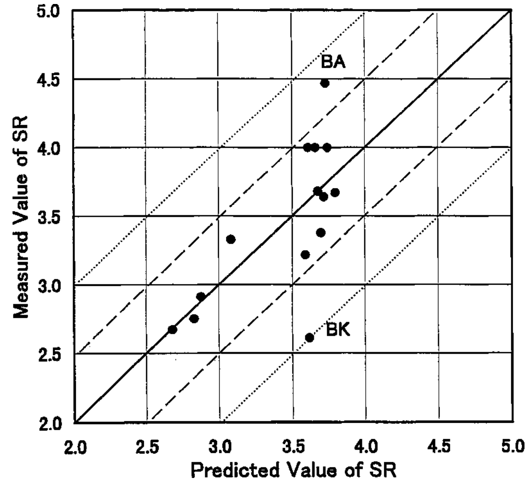

FIG. D1. Plot of the predicted subjective ratings (SR) of the acoustics in the audience areas of 14 opera houses. The solid line means that the predicted values equal the measured values. The broken lines and dotted lines mean ± 0.5 and ± 1 relative to the solid line.

by the lateral reflections is fairly low. But for the Paris, Garnier and the Milan, La Scala the ratio is high, even though the source is moved backward by up to 7 m, which is approximately the maximum acting zone. Most of the first-order reflections come from the side walls around the proscenium opening and at the level of the main audience area.

Figure C1 shows the covered area for the Berlin Komischeoper BK, where not only the lateral reflections do not cover enough of the center audience area, which is most important, but also the covered area shifts when the sound source moves. This result comes from the circular shape of BK, the only one with this shape among the researched 23 halls. The comparison indicates that the sound changes greatly when the sound source is moved. In opera houses, acoustical uniformity over a great range of a singer's position is vital. Accordingly, the lower subjective judgements for BK might be caused by this effect, although the acoustical coverage for the S_0 position is not unfavorable. Practically, there can exist strong (first-order) reflections from the part of the ceiling near the proscenium opening and, often, from the stage set in addition to the lateral reflections discussed here. However, reflections like those shown in Fig. C1 are very important since they arrive first at the receiving point on the main floor.

APPENDIX D: MULTIPLE REGRESSION ANALYSIS BETWEEN SUBJECTIVE JUDGEMENT AND OBJECTIVE PARAMETERS

By executing a multiple regression analysis between the subjective judgments of acoustical quality in the audience area (Fig. 3) and the seemingly two most important measurable room acoustics parameters in Table I, the best regression equation, which minimizes Akaike's Information Criterion, defined as -2 (maximum log-likelihood of statistical model) $+2$ (number of parameters in the model) was determined (Akaike, 1973). The model that produced the least AIC is,

$$\mathrm{SR} = 1.2[1 - \mathrm{IACC}_{E3}] - 0.039\mathrm{ITDG} + 3.67. \qquad \text{(A1)}$$

SR means the subjective rating from 1 to 5 as in Fig. 2. The relations between the conductors' SRs (measured) and those calculated from Eq. (A1) are shown in Fig. D1. The multiple coefficients of correlation of Eq. (A1) is 0.69, which judges this prediction as ''rather good,'' and the partial regression coefficients of $[1 - \mathrm{IACC}_{E3}]$ and ITDG are 0.49 and -0.67, respectively. Hence, using only 2 of the 7 identified acoustical parameters for this calculation, 12 opera houses out of the 14 fall between ± 0.5 of the measured values, and the remaining 2 are within ± 1. (Note that the conductors' ratings of the acoustics in the audience areas show that values of ITDG between 15 and 20 ms are equally good as are values of $[1 - \mathrm{IACC}_{E3}]$ greater than 0.6.) But, even this two-parameter result can be considered acceptable for practical purposes because we must also consider that the judgements by the opera conductors based on criteria like ''Poor'' to ''One of the Best'' are heuristic. When BK is excluded from the data base, because it appears to be heavily influenced by other factors, as discussed in Appendix C, R increases to 0.83. We could expect to obtain a more reliable equation if the other five parameters could be taken into account. This exercise demonstrates, however, that $[1 - \mathrm{IACC}_{E3}]$ and ITDG are important objective parameters for approximating the acoustical quality of opera houses, provided the RT_M is 1.3 s or greater, the house is not overly large (or reflective sets are used so that G_M is reasonable), there are adequate sound diffusing surfaces in the house and the bass ratio BR is above 1.0. This also assumes that there are no negative effects, such as noise, echoes or focusing.

Akaike, H. (**1973**). *Information Theory and an Extension of the Maximum Likelihood Principle* (Akademiai Kiado, Budapest).

Aoshima, N. (**1981**). ''Computer-generated pulse signal applied for sound measurement,'' J. Acoust. Soc. Am. **69**, 1484–1488.

Barron, M. (**1993**). *Auditorium Acoustics and Architectural Design* (E and FN Spon and Chapman & Hall, London).

Beauvert, T. (**1996**). *Opera Houses of the World* (The Vendomes Press, New York).

Beranek, L. L. (**1962**). *Music, Acoustics, and Architecture* (Wiley, New York; in Japanese, Kajima Institute, Tokyo, 1972).

Beranek, L. L. (**1972**). [Same as Beranek (1962), except translated with additions into Japanese] Kajima Institute, Tokyo.

Beranek, L. L. (**1992**). ''Concert hall acoustics—1992,'' J. Acoust. Soc. Am. **92**, 1–39.

Beranek, Leo (**1996**). *Concert and Opera Halls: How They Sound* (Acoustical Society of America, Woodbury, NY).

Beranek, L. L., and Hidaka, T. (**1998**). ''Sound absorption in concert halls by seats, occupied and unoccupied, and by the hall's interior surfaces,'' J. Acoust. Soc. Am. **104**, 3169–3177.

Beranek, L. L., Hidaka, T., and Masuda, S. (**2000**). ''Acoustical design of the Opera House of the New National Theatre, Tokyo, Japan,'' J. Acoust. Soc. Am. **107**, 355–367.

Cremer, L., Mueller, H., and Schultz T. J. (**1982**). *Principles and Applications of Room Acoustics, Vol. 1* (Applied Science Publishers, Essex, England and Elsevier, New York). [Originally published in German without later additions: Cremer L., and Mueller, H., *Die Wissenschaftlichen Grundlagen der Raumakustik*, Vol. 1, Hirzel Verlag (1978)].

Haan, C. H., and Fricke, F. R. (**1993**). ''Surface diffusivity as a measure of the acoustic quality of concert halls,'' Proceedings of the Conference of the Australian and New Zealand Architectural Science Association, Sidney, pp. 81–90.

Hidaka, T., Beranek, L. L., and Okano, T. (**1995**). ''Interaural cross-correlation, lateral fraction, and low- and high-frequency sound levels as measures of acoustical quality in concert halls,'' J. Acoust. Soc. Am. **98**, 988–1007.

Hidaka, T., Beranek, L. L., Masuda, S., Nishihara, N., and Okano, T. (**2000**). ''Acoustical design of the Tokyo Opera City (TOC) Concert Hall, Japan,'' J. Acoust. Soc. Am. **107**, 340–354.

Hidaka, T., Beranek, L., and Nishihara, N. (**1998**). ''Relation of acoustical parameters with and without audiences in concert halls and a simple method for simulating the occupied state,'' J. Acoust. Soc. Am. **103**, 2955(A).

ISO 3382 (**1997**). ''Acoustics—Measurement of the reverberation time of rooms with reference to other acoustical parameters.''

Moatti, J., Kleinefern, F., Vermeil, J., and Laulhére-Vigneau, C. (**1989**). *Operas d'Europe* (Plume, Paris).

Okano, T., Beranek, L. L., and Hidaka, T. (**1998**). ''Relations among interaural cross-correlation coefficient ($IACC_E$), lateral fraction (LE_E), and apparent source width (ASW) in concert halls,'' J. Acoust. Soc. Am. **104**, 255–265.

Schmidt, W. (**1985**). ''Die Raumakustik in Zuschauerraum, Die neue Semperoper in Dresden,'' Institute für Kulturbauten, Berlin, **2**, 20–24.

Veneklasen, P., and Christoff, J. P. (**1964**). ''Seattle Opera House—Acoustical design,'' J. Acoust. Soc. Am. **36**, 903–910.