Interaural cross-correlation, lateral fraction, and low- and high-frequency sound levels as measures of acoustical quality in concert halls[a]

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Subjective ratings of acoustical quality in concert halls were determined from interviews of conductors, musicians, music critics, and informed listeners during which they were asked to judge the quality of the acoustics and to rank the order of those halls each knew. Subjective ratings on 34 halls were divided into three principal groups: excellent, very good, and less good. No bad halls were studied. The use of the interaural cross-correlation coefficient (IACC) and lateral efficiency (LF) as correlates with the subjective ratings were analyzed in depth. In order to make IACC sensitive to quality ratings, a multi-octave-band average was developed, based on Blauert *et al.* [Acustica **59**, 292 (1986)] and on a subjectively derived set of equal apparent source width (ASW) contours that showed the 0.5-, 1.0-, and 2.0-kHz octave bands to be of equal and principal importance to ASW. This IACC_3 was divided into two components, IACC_{E3}, integrated over the first 0.08 s after arrival of the direct sound, and IACC_{L3}, integrated over 0.08–1 s. Subjective judgments were also performed to determine the effects of increased sound levels of symphonic music at frequencies above or below 355 Hz on ASW. It was found that changes in the low-frequency levels (GL) made greater changes in ASW than changes in the high-frequency levels (GH). Because the difference between the low- and high-frequency levels in real halls does not exceed ±5 dB and because both are inversely related to [EDT/Volume], it suffices to measure GL. Thus IACC_{L3} and GL appear valuable for determining ASW and the degree of sound-field diffusion in the frequency range from 100 to 3000 Hz for symphonic music in concert halls. The measured quantity $[1-\mathrm{IACC}_{E3}]$ alone was found to separate exactly the 17 concert halls for which data were available into three category groups. The constituents of these three groups were the same as those determined from the interviews. The measured lateral fraction (LF) for the 24 halls for which data were available was also compared to the subjective groupings. The average measured values of LF for these halls covered a small range and there were so many overlaps among halls when separation of the halls into three rating groups was attempted that LF was judged not to be suitable for rating the acoustical quality of occupied concert halls. © *1995 Acoustical Society of America.*

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I. MUSIC AND LISTENING

Music is commonly identified as a series of sounds that has several components, including pitch, timbre (tone color), texture, and rhythm. Any examination of the perception of music, including the effect of an enclosure in which it is performed, is enormously complex. Deryck Cooke, a British musicologist, argues in *The Language of Music* (1959), that music has the essential attributes of communication, just as speech does. But music does not convey concepts, only feelings, though these may be recognized and to some extent classified.

Thus, in attempting to evaluate quantitative measures that might give aid to the successful design or evaluation of a concert hall, we are faced with several conundrums: How does the hearing process relate to the perception of music? Should consideration be given to the concept of music as a form of communication? Who is a valid judge of the quality of acoustics of a concert hall? Do the measured acoustical characteristics of unoccupied concert halls correlate with subjective judgments by qualified listeners of the halls' acoustics during symphonic concerts? This paper deals with these questions, but it is principally devoted to the efficacy of and the precautions that must be taken when using the interaural cross-correlation coefficient (IACC) as a *partial* measure of concert hall quality and its relation to the proposed alternate measurement, the lateral efficiency (LF). This paper

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also presents the influence, separately, of low-frequency and upper frequency sound levels on concert hall quality.

II. JUDGMENTS OF ACOUSTICAL QUALITY OF CONCERT HALLS

Basic to this study is a knowledge of the acoustical quality of a significant number of concert halls in rank order. Several laboratory investigations have been made of the subjective preferences of subjects, usually university students, for particular sound fields recorded binaurally in unoccupied concert halls or in synthesized equivalents of occupied halls. These studies were generally aimed at determining which of several objective measurements of the sound fields correlated best with the subject's preferences A summary of these studies is given in Beranek (1992) [references include Siebrasse (1973), Gottlob (1973), Schroeder *et al.* (1974), Wilkens (1975), Lehman (1976), Cremer and Mueller (1982), Ando (1977, 1985), Hawkes and Douglas (1971), Yamamoto and Suzuki (1976), Kimura and Sekiguchi (1976), Tachibana *et al.* (1989), Morimoto *et al.* (1989), Morimoto and Maekawa (1989), Fasold *et al.* (1982), Fasold *et al.* (1986), and Beranek (1962)]. Barron's studies (1988) were made in occupied halls. No one of the prior studies published a rank order of the halls that were judged by the subjects. Let us define:

Concert hall acoustical quality is the subjective judgment of the quality of the acoustics of a hall for full symphony performance at regular concerts.

According to the references just cited, it can be characterized objectively by a matrix of acoustical attributes, a number of which can be determined from known acoustical measurements. The data obtainable were taken in unoccupied halls with a nondirectional source on stage and with binaural and monaural microphones at several positions in the hall, whose outputs fed into digital recorders. The recorded signals enable calculation of reverberation time, sound-pressure level, bass ratio, lateral fraction, interaural cross-correlation coefficient, initial-time-delay gap, ratio of energy in the early reflections to that in the later reverberant sound, and an on-stage parameter that helps measure the degree of communication among players. These measurements are made as a function of frequency, generally at 125, 250, 500, 1000, 2000, and 4000 Hz, except for the initial-time-delay gap which is usually determined at a mid-main-floor position.

There are architectural features associated with the stage alone that are hard to measure and evaluate and that may affect the orchestral sound or the ease of playing of the musicians, including balance among the orchestral sections, balance between soloists and orchestra, and smooth blending of the overall orchestral sound.

Acoustical quality can also be affected negatively by noise, echoes, and tonal distortion—the latter caused by hall resonances, focusing, and sound-grating effects.

Are there "good" and "bad" acoustics or is acoustics a mere matter of taste? It is hard to believe that acoustics could stand alone as the one factor in the world lacking in degrees of quality.

It is common knowledge that the acoustics of a new hall cannot be judged reliably until the hall is filled for the opening concert. Appraising the acoustics in an unoccupied hall can mislead the listener since many subjective acoustical parameters change with the degree of occupancy, viz., reverberance, strength of bass as well as of the mid- and higher frequencies, warmth, clarity, and even the way the orchestra plays.

The research methods used previously (Schroeder *et al.*, 1974; Cremer and Mueller, 1982) would be ideal if the binaural recordings had been made at several positions in many halls during regular concerts. Further, the subjects chosen for the binaural playback sessions should be those most qualified to judge symphonic musical quality as affected by the acoustics of occupied halls. Such a research project would be very expensive and obtaining the help of skilled subjects for the necessary lengths of time would seem to be excessively difficult.

In this paper we have based the rankings of the acoustics of concert halls on the opinions of those who listen often to symphonic music in many halls—conductors, musicians, music critics, acoustical consultants, and selected listeners, those who have evidenced interest in the subject and who have traveled to many of the halls. Their opinions were obtained by one-on-one interviews or responses to letters of inquiry. The procedure was described in Beranek (1962).

McAdams (1982) wrote, "We may never have the ability to predict the experience of a listener since a lot of what is perceived by an actively attentive listener ultimately depends on what the listener brings to the music... ." It is for this reason that we selected the above persons as our principal judges of concert hall quality.

We are also mindful of the admonition of music critics who warned us that, "all knowledge of a musical phenomenon must arise from experiencing it, and judgments can only be communicated to those who have also experienced it." The authors have traveled to many countries to visit the halls and one of the authors has listened to symphonic music in all but one of halls listed in this paper. We have attended regular concerts in some halls up to 20 times and each time at two locations, one before and one after intermission.

Typical quotes from the conductors and music critics are to be found in Beranek (1962) between pp. 83 and 392 and pp. 426 and 433. Where too few of them knew the halls, additional subjective ratings were obtained from acoustical consultants and music lovers who travel often and attend symphonic concerts in many countries.

Fifty-five concert halls were included in this subjective survey. For only 34 of these halls have we both subjective rankings and IACC or LF data, or both. They are listed in Table I in six categories of acoustical quality: A+ (superior), A (excellent), B+ (excellent to good), B (good), C+ (good to fair), and C (fair), along with their size and reverberation times. No poor halls were studied.

The category groupings were determined from intercomparisons of interviews. We are well aware that the combination of their remarks and our interpretation does not constitute a scientific canvas of expert opinion. As is inevitable in category scales, some halls fall in the borderlines between categories, but it is unlikely that any hall would be judged more than one category higher or lower. The rankings within

TABLE I. Subjective rank ordering of concert halls in this study for which IACC or LF data are available. Most halls are the homes of excellent orchestras. Local audiences are, in general, satisfied with their acoustics. Takenaka Research Institute data are used where available, augmented through the courtesy of the National Research Council of Canada, Michael Barron, Sandy Brown Associates, Anders Gade, and others. No opera houses are included.

	City and name of concert hall	No. of seats	Volume in cubic meters	RT occupied sec	EDT Unoccupied sec	BR Occupied
A+	Vienna, Gr. Musikvereinssaal	1680	15 000	2.0	3.0	1.11
A+	Boston, Symphony Hall	2625	18 750	1.85	2.4	1.03
A+	Amsterdam, Concertgebouw	2037	18 780	2.0	2.6	1.09
A	Berlin, Konzerthaus (Schauspielhaus)	1575	15 000	2.0	2.4	1.18
A	Tokyo, Hamarikyo Asahi Hall	552	5800	1.7	1.8	0.94
A	Zurich, Grosser Tonhallesaal	1546	11 400	2.0	3.1	1.20
A	Basel, Stadt-Casino	1448	10 500	1.8	2.2	1.18
A	Cardiff, Wales, St. David's Hall	1955	22 000	2.0	2.1	0.98
A	Costa Mesa, Segerstrom Hall	2903	27 800	1.6	2.2	1.32
B+	Cleveland, Severance Hall	2101	15 690	1.5	1.7	1.14
B+	Christchurch, Town Hall	2662	20 500	2.1	1.9	1.01
B+	Baltimore, Joseph Meyerhoff Hall*	2467	21 520	2.0	2.3	1.10
B+	Salt Lake, Utah, Symphony Hall	2812	19 500	1.7	2.0	1.00
B+	New York, Avery Fisher Hall	2742	20 400	1.8	2.0	0.95
B+	Berlin, Philharmonie Hall	2325	26 000	1.95	2.1	1.05
B+	Bristol, Colston Hall	2121	13 450	1.7	1.8	1.05
B+	Liverpool, Philharmonic Hall*	1824	13 560	1.5	1.8	1.00
B+	Toronto, Roy Thompson Hall	2812	28 300	1.8	1.9	1.06
B+	Jerusalem, Binyanei Ha'Oomah	3142	24 700	1.75	1.85	1.20
B+	Washington, Kennedy Conct Hall	2759	19 300	1.8	1.8	1.06
B+	Worcester, MA, Mechanics Hall	1343	10 760	1.6	2.1	1.16
B+	Salzburg, Festspielhaus	2158	15 500	1.5	1.8	1.10
B+	Copenhagen, Radiohuset, Studio 1	1081	11 900	1.5	2.0	1.07
B+	London, Royal Festival (Res. on)	2901	21 950	1.6	1.7	1.17
B+	Munich, Philharmonie am Gasteig	2487	29 800	1.95	2.1	1.00
B+	Stuttgart, Liederhalle, Grosser Saal	2000	16 000	1.6	2.1	0.99
B+	Paris, Salle Pleyel*	2386	15 500	1.5	1.8	1.25
B	Tel Aviv, F. R. Mann Auditorium	2715	21 240	1.55	1.7	0.98
B	San Francisco, Davies Hall*	2743	24 070	1.85	2.1	1.05
B	Montreal. Salle Wilfrid-Pelletier	2982	26 500	1.7	1.9	1.21
B	Edmonton, Alberta Jubilee Aud.	2678	21 500	1.4	1.4	0.97
C+	Buffalo, Kleinhans Music Hall*	2839	18 240	1.3	1.6	1.26
C+	London, Barbican Lrg Concert Hall*	2026	17 750	1.7	1.9	1.23
C	London, Royal Albert Hall	5080	86 650	2.4	2.65	1.13

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

each category may not be meaningful because a different choice of interviewees might have produced a different sequence.

Because there are only a few halls in each of the categories A+, B, C+, and C, we have combined the six categories into three groupings in our analyses, namely, group (A+,A), group B+, and group (B,C+,C).

Except for reverberation times (RT) and bass ratios (BR), all of the objective data presented in this paper were taken in unoccupied halls. Several measuring groups contributed to this study, especially Takenaka Research Institute of Chiba, Japan; National Research Council of Ottawa, Canada; Michael Barron of Bath, England; and Sandy Brown Associates of West Lothian, Scotland. Many other individuals and institutions supplied RT data for both occupied and unoccupied halls.

Generally, the four laboratories named above employed one to three source positions on stage and 8–20 microphone or binaural-head positions in the seating areas to determine the unoccupied hall measurements (see Fig. A4 in the Appendix for the Takenaka Institutes' positions). In cases of symmetrical halls, measurements were usually made in one-half hall only.

Comparison was made with a similar subjective study of concert hall rankings (Fricke and Haan, 1995) where an entirely different group of musicians and music critics were invited to record their judgments on a printed questionnaire. Sixty concert halls were listed on the questionnaire that they sent to musicians and seventy-four were listed on those sent to music critics. Their responses can also be divided into three groups. Except for five halls, the same halls fall into the same three groupings as those listed in this paper.

III. SPATIAL IMPRESSION (SI)

Beranek (1962) found that if the sound reflecting surfaces in a hall are arranged so that the first reflection from a pulsed sound source, located at the soloist position on stage, arrives at the ears of a listener, seated in the center of the main floor, within about 22 ms after the direct sound, the hall will sound, subjectively, intimate, as though the music played in it were being played in a smaller hall. The time difference between arrival of the direct sound and the first reflection is called the "initial-time-delay gap" (t_I).

Because narrow rectangular concert halls are generally rated highest by musicians and music critics, it follows that an excellent hall should exhibit five or more nearly evenly spaced prominent reflections in the first 60 ms of a reflection pattern (Beranek, 1962, pp. 69, 448–450). Beranek called this parameter "texture."

Marshall (1967, 1968) was the first to conclude that among the early reflections in rectangular halls that make up the attribute of texture, many reflections must arrive at the listener's position from *lateral* directions if the acoustics of the hall are to be rated highly.

Schroeder *et al.* (1974 and *Forward* to Ando, 1985) found that "*interaural dissimilarity* was the most important parameter governing the subjective preference: ... *independent of individual tastes*" (Schroeder's emphasis).

Schubert (1966) and Barron (1971) describe various subjective effects of lateral reflections and note that lateral reflections, arriving within 60 ms or so after arrival of the direct sound, contribute to the sensation of "spatial impression."

Spatial impression is called, in the literature, various names—spaciousness, objective envelopment, source broadening, apparent source width, and so forth. We propose to use spatial impression as a generic term and to use two subcomponents, defined as follows:

Apparent source width (ASW) is the apparent auditory width of the sound field created by a performing entity as perceived by a listener in the audience area of a concert hall.

Lateral sound reflections create temporal, spectral, and amplitude differences in the sound pressures at the two ears, and, in general, the greater the difference in the sound arriving at the two ears from a single source (the orchestra), the greater the apparent source width.

Listener envelopment (LEV) is the subjective impression by a listener that (s)he is enveloped by the sound field, a condition that is primarily related to the reverberant sound field.

The objective measurement related to LEV should determine the spatial diffusion of the reverberant sound field, including the general directions of its components. Arbitrarily, the reverberant sound field is generally said to begin 80 ms after arrival of the direct sound.

IV. LF AS A MEASURE OF APPARENT SOURCE WIDTH (ASW)

Barron and Marshall (1981) have defined ASW as "the subjective sensation associated with early lateral reflections;" that is to say, "as the lateral reflection level is increased, the source appears to broaden and the music gains body and fullness." They postulated and found, in a laboratory experiment, that listeners could relate the sensation of ASW to a monaural acoustical measurement, called the *lateral energy Fraction*" (LF'), defined mathematically as

$$\mathrm{LF}'=\left[\int_0^{0.08} p^2(t)\cos\theta\, dt\right] \Big/ \left[\int_0^{0.08} p^2(t)dt\right] \qquad (1a)$$

or, using a pressure-gradient microphone,

$$\mathrm{LF}=\left[\int_{0.005}^{0.08} p_8^2(t)dt\right] \Big/ \left[\int_0^{0.08} p^2(t)dt\right], \qquad (1b)$$

where θ is the lateral angle (where $\theta=0$ is 90° from straight ahead), $p_8(t)$ is the sound pressure measured at a location in a hall by a figure-8 microphone with the null axis pointed to the source, and $p(t)$ is the sound pressure measured at the same point by a nondirectional microphone. Because $p_8^2(t)$ produces a directivity factor of $\cos^2\theta$, Eq. (1b) discriminates against energy from angles incident on the microphone between 10° and about 45° from straight ahead compared to Eq. (1a).

Usually, the integration for LF is performed over the first 80 ms after arrival of the direct sound. When so measured, it often is called LEF, but in this paper we designate it as LF_E. Kleiner (1989) has developed a method for measuring LF' [Eq. (1a)], and comparative results have been published by Bradley (1994).

Gade (1985, 1989, 1991), from objective measurements in 35 unoccupied European halls, found that for near-rectangular halls, the correlation coefficient between LF and the width of a hall is -0.82 and for fan-shaped halls 53% of the variance is explained by average width and only 26% by wall-spread angle. He also showed a high correlation for all halls with reverberation times between 1.9 and 2.2 s at 500 Hz. Since the initial-time-delay gap t_I, measured at a center main-floor location in *near-rectangular halls*, is also closely related to mean widths, it can be determined directly from architectural drawings and used as a crude approximation of ASW.

V. [1−IACC] AS A MEASURE OF ASW

It is obvious that a sound wave arriving at a listener's position from a lateral direction will excite the two ears differently (see Fig. 1), while a sound wave arriving from straight ahead will excite the two ears alike. A *binaural* measure of the difference in sound at the two ears and, hence, of lateralness, is the "interaural cross-correlation function" (IACF_t):

$$\mathrm{IACF}_t(\tau)=\frac{\left[\int_t^{t_2} p_L(t)p_R(t+\tau)dt\right]}{\left[\int_{t_1}^{t_2} p_L^2(t)dt\int_{t_1}^{t_2} p_R^2(t)dt\right]^{1/2}}, \qquad (2)$$

and L and R designate the entrances to the left and right ears, respectively. The maximum possible value of Eq. (2) is unity.

Because the time it takes for a sound wave impinging perpendicular to one side of the head to travel to the other side is about 1 ms, it is customary to vary τ over the range of -1 to $+1$ ms. Further, to obtain a single number that mea-

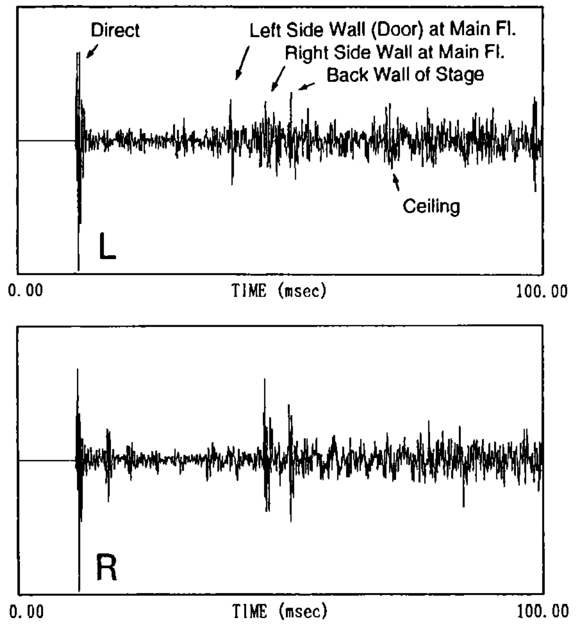

FIG. 1. Example of impulse response at both ears, L and R, with Kemar dummy head near center of main floor facing source on stage in a concert hall.

sures the maximum similarity of all waves arriving at the two ears within the integration limits and the range of τ, it is customary to select the maximum value of Eq. (2), which is called the "interaural cross-correlation coefficient" (IACC):

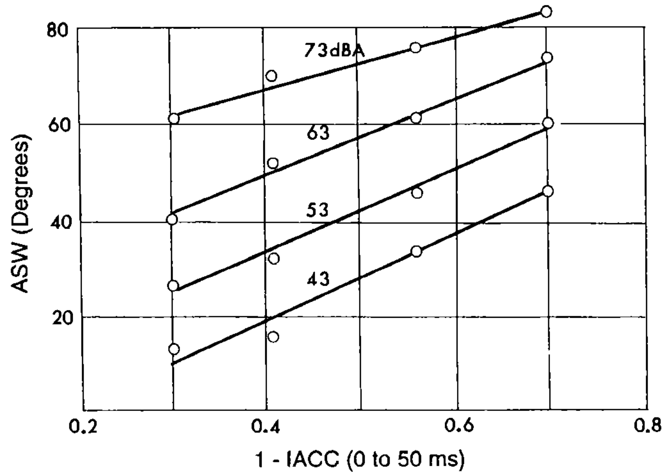

FIG. 3. Subjectively determined ASW as a function of $[1-\mathrm{IACC}_{50}]$ with sound level dBA as parameter (after Keet, 1968).

$$\mathrm{IACC}_t=|\mathrm{IACF}_t(\tau)|_{\max}, \quad \text{for } -1<\tau<+1. \tag{3}$$

Examples of $\mathrm{IACF}(\tau)_{\mathrm{E(arly)}}$ ($t_1=0$ to $t_2=80$ ms), $\mathrm{IACF}(\tau)_{\mathrm{L(ate)}}$ (80–3500 ms), $\mathrm{IACF}(\tau)_A$ (0–3500 ms), and IACC_E, IACC_L, and IACC_A (as indicated by the dots on the curves), for four octave frequency bands, are shown in Fig. 2.

Keet (1968, 1969) was the first to relate apparent (subjective) source width ASW with a quantity that closely re-

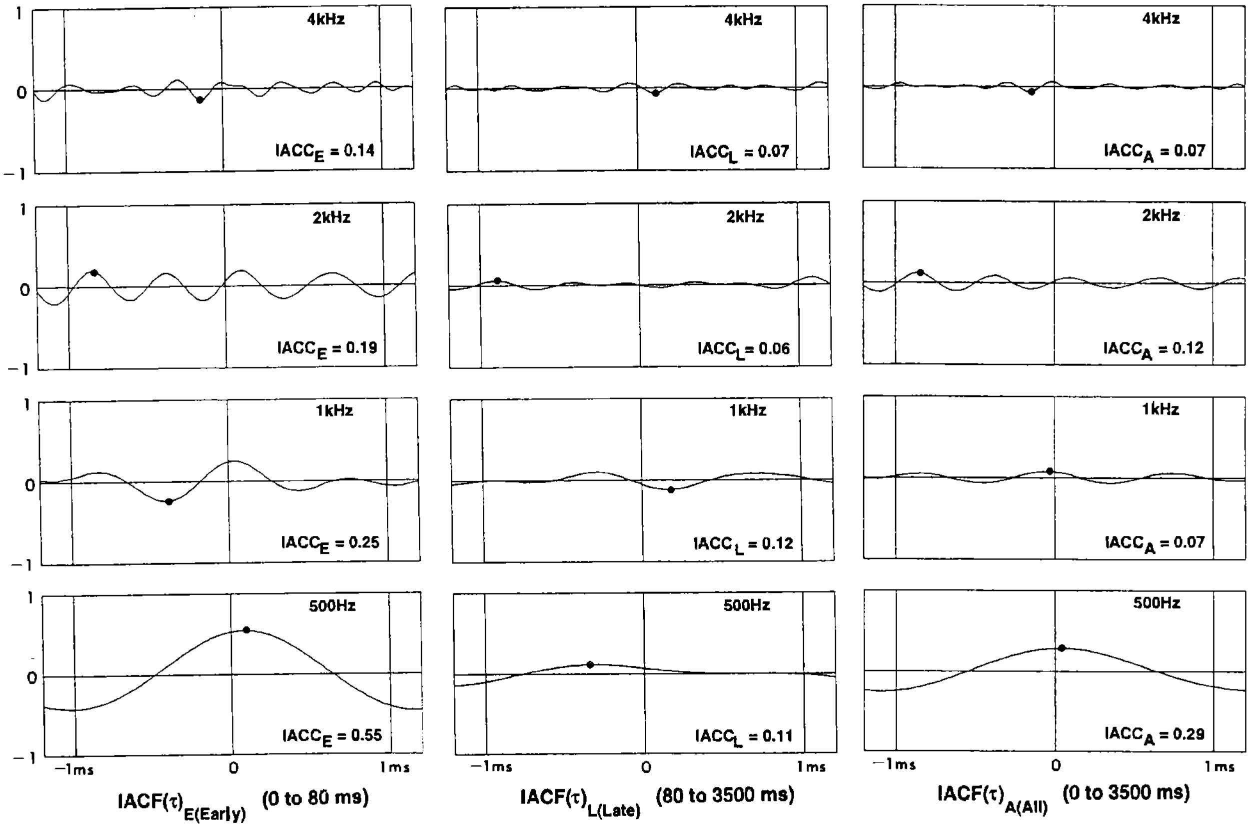

FIG. 2. Interaural cross-correlation function IACF(τ) and interaural cross-correlation coefficient IACC with source at S-0 and head at position 21 (see Fig. A4), for frequencies 500 Hz, 1, 2, and 4 kHz. Left: IACC_E(0–80 ms); center: IACC_L(80 ms–3.5 s); right: IACC_A(0–3.5 s); in an unoccupied concert hall. The points on the curves from which the IACC values are read are indicated by small dots.

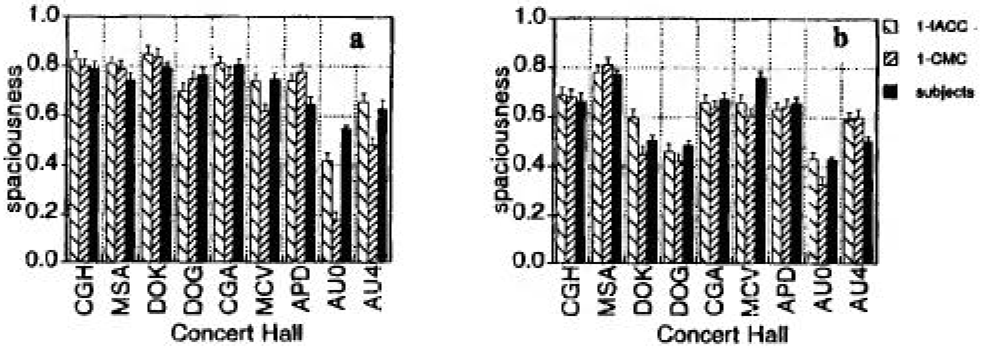

FIG. 4. [1−IACC], [1−CMC], and the perceived spaciousness measured in the paired-comparison experiment for the central source position and two dummy head (receiver) positions. Signals were equalized for middle ear transmission (error bars indicate the standard deviation). Nine halls were involved. (a) Receiver position in the back of the hall and (b) receiver position in the front of the hall (Potter, 1993).

sembles $(1-\text{IACC}_{50})$. Specifically, instead of using the output of two microphones at the two ear canals and Eq. (3), he measured the cross correlation between two cardioid microphones positioned with their principal directivity axes 90° apart. Keet's results, with recorded dry music as a source, are given in Fig. 3, which shows that (subjective) ASW is linearly related to his $(1-\text{IACC}_{50})$ for each fixed dB(A) level. Further, his data show that ASW widens by about 1.5° for each decibel dB(A) increase in sound level. Bradley *et al.* (1993) found that, at 1000 Hz, a 10% change in IACC was approximately equivalent to a 10-dB change in level.

Gottlob (1973) and Schroeder *et al.* (1974) found from subjective tests that the IACC ($t_1=0$ and $t_2=50-140$ ms) was one of three orthogonal acoustical measures that correlated well with listening preferences (recorded classical orchestral music as a source). The other two were reverberation time and ratio of early to total sound energy. Loudness was held constant during the subjective judgments made by their subjects and the initial-time-delay gap for all halls was about the same.

Ando (1985) established that IACC(A) (determined for all reflections from all angles, with integration limits of zero to several seconds, using various motifs of music as sound sources and using A weighting) is one of four orthogonal acoustical parameters that explained the subjective preferences of the listeners in his experiments. The other three orthogonal factors were initial-time-delay gap, loudness, and reverberation time.

VI. PSYCHOPHYSICAL BASIS FOR IACC

Potter (1993) investigated the physical parameters influencing the perceptual attributes of spaciousness (image broadening, ASW) in order to gain more insight into this complex phenomenon, and to establish a relation between psychoacoustic measures and room acoustics. His research is founded on the physiologically derived central spectrum theory for binaural hearing. This model describes the processing of interaural time or phase differences in the frequency region for which the temporal fine structure of signals is preserved through phase locking in the auditory neurons. His references include Jeffress (1948), Patterson (1976), Bourk (1976), Bilsen (1977), Raatgever (1980), Raatgever and Bilsen (1986), Bakkum (1986), Yin and Chan (1990), and Raatgever and Keulen (1992). Based on that model, he derived a new measure for spaciousness, called the central modulation coefficient (CMC) (Potter and Raatgever, 1990; Potter *et al.*, 1991).

The derivation of CMC is accomplished in two steps. First, a lateralization function $F_{\text{lat}}(\tau_i)$ is calculated by integrating the three-dimensional central activity pattern over the frequency range for the acoustic signal under investigation. Then the mean modulation depth in the lateralization function $F_{\text{lat}}(\tau_i)$ is determined and named the "central modulation coefficient" (CMC).

Among the procedures Potter used to verify the accuracy of this method was to calculate CMC from physical measurements made in eight unoccupied concert halls in the Netherlands and to compare the values with subjective judgments of ASW made by subjects listening to binaural recordings made in those halls. Included were the well known De Doelen Concert Hall in Rotterdam (DOG, 2230 seats, 2.3 s) and the Concertgebouw in Amsterdam (CGA, 2206 seats, 2.6 s). The signal for the tests was wideband noise (70 Hz–8 kHz) which was played in the halls at a center-stage position through an onmidirectional loudspeaker. Binaural recordings of the outputs of a KEMAR dummy head fitted with middle ear simulators were made at two positions, front (row 9) and rear (row 20) of each hall. These recorded signals were used both in the perceptual evaluations and in the physical determinations of CMC (70–2500 Hz) and IACC (250–2000 Hz).

To establish the ends of the subjective scale, binaural recordings of the same noise were made in anechoic and reverberation chambers and were presented to the subjects at a sensation level of 60 dB, the same level as were the binaural signals recorded at the two positions in the halls. The subjective spaciousness for the reverberation room was set at 1.0 and for the anechoic room at 0.0.

The judgments were paired comparisons, and the results for the two receiver positions are shown in Fig. 4. Qualitative comparisons were also made with anechoic recordings of symphonic music played and recorded in the halls.

Potter's conclusions are that [1-CMC], based on the central spectrum model for binaural hearing, is an effective indicator of perceived spaciousness, thus establishing a link between room acoustics and psychological acoustics. These results, he says, also provide a psychophysical basis for the use of the [1−IACC]. He adds, "The similarity between the two physical measures [CMC and IACC] and the perceived spaciousness is remarkable....The band-passed (250–4000 Hz) IACC fits marginally better than CMC for individual experiments....The experimental results obtained provide a psycho-physical basis for the use of the IACC for the determination of spaciousness in room acoustics."

Potter also compared the calculated energy fraction LF and the lateral efficiency LE with the subjective judgements in those halls. The correlations were lower. He concludes that LF and LE "...seem to determine a necessary condition for the creation of spaciousness, but not a sufficient one."

VII. BANDS OF EQUAL IMPORTANCE TO ASW

A. Evidence

Blauert (1983) states that all spectral contents of early lateral reflections contribute to spaciousness, where the higher frequency components mainly cause sideward broadening of the source ASW and low-frequency components add to front–back extension (Blauert and Cobben, 1978). Blauert and Lindemann (1986) found that spaciousness increases with bandwidth even, to some extent, with components in the spectral range above 3 kHz. Blauert *et al.* (1986) indicate that in their experiment when all frequencies above 100 Hz are present, spaciousness did not increase as the band was widened to include lower frequencies, possibly because the energy in the music samples there was low.

Our paper discusses the effect of energy level at both low and high frequencies on ASW (Sec. XI.) The 1986 data also indicated that spaciousness increased less rapidly above about 3000 Hz.

Barron and Marshall (1981) found that early lateral reflections at frequencies below the 1000-Hz octave band are essential for the creation of a high ASW. For frequencies in the 4-kHz octave, the broadening effect is greatly diminished.

B. Quest for most sensitive IACCs

As reviewed in Sec. I, music, at least at higher frequencies (above 200 Hz), has many of the essential attributes of speech communication. This led us to investigate whether dividing the frequency spectrum into bands of equal importance to "music communication" would provide us with a more sensitive "index" than IACC(A) to represent ASW. This procedure is similar to the use of the four-band speech interference level (SIL) (ANSI, 1977, R. 1986) to estimate the interference of a noise with speech communication. SIL is more sensitive than, say, dB(A) as an indicator of the effects of noise on speech intelligibility.

The primary basis for dividing the spectrum into bands of equal contribution to ASW is taken from Blauert *et al.* (1986). From subjective judgments, they obtained curves for "normalized auditory spaciousness" (AS) for the case of two discrete "reflections" following the "direct" sound (music), one delayed by 20 ms and the other by 30 ms, presented to listeners through earphones. Spaciousness was defined for the subjects as the "amount of spatial extension of the auditory event." By the method of paired comparisons, five or six subjects equated the spaciousness of 15 s of anechoic low- and high-passed musical signals. Ten high- or low-passed filter cutoffs were used from 0.1 to 6 kHz. For the maximum bandwidth (60 Hz–6 kHz) the sensation level was about 77 dB (SL), decreasing as the bandwidth of the reflections was restricted.

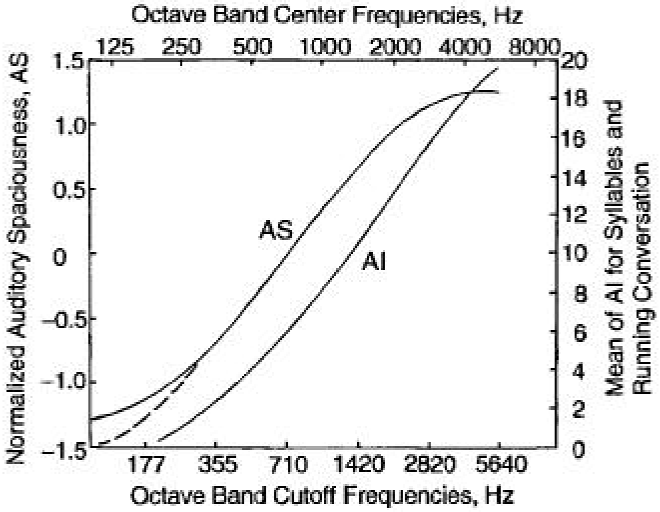

FIG. 5. Left curve (AS) is normalized auditory spaciousness taken from Fig. 2 of Blauert *et al.* (1986). Right curve (AI) is articulation index, the average of AI for syllables (French and Steinberg, 1947) and AI for running conversation (Studebaker *et al.*, 1987).

The smoothed result of the experiment is shown as curve AS in Fig. 5. For comparison, the cumulative articulation index (AI) curve from which the SIL was derived is also shown (Studebaker *et al.*, 1987; French and Steinberg, 1947). The AS curve is primarily meaningful in the frequency range of 0.15–3 kHz, and lies about 1 oct below the AI curve. From the experiments of Groot (1979) and Potter (1993) it is possible that the curve in the region below 300 Hz should drop off faster as shown by the dashed extension.

Using either version of the curve, it is seen that AS can be divided into four frequency regions of roughly equal importance by the four octave bands with midfrequencies at 250, 500, 1000, and 2000 Hz which cover the spectrum from 177 to 2840 Hz.

We have already stated that Blauert and Cobben (1978) have determined that the higher frequency components mainly cause sideward broadening of the source. Hence, above about 200 Hz, AS of Fig. 5 is tantamount to the ASW. Potter (1993) and Keet (1968, 1969) showed that [1−IACC] is a measure of ASW. Hence we use the AS curve as the basis for subdivision of IACC into three or four bands and to learn by further studies whether such a subdivision is satisfactory.

C. Equal ASW contours

Okano *et al.* (1994) reported on experiments designed to determine the relation between ASW and IACC for each of the octave frequency bands from 125 to 4000 Hz. They presented subjects with pairs of music signals that were synthesized to represent the sound in a concert hall. The first signal presented was always used as the reference. It had a duration

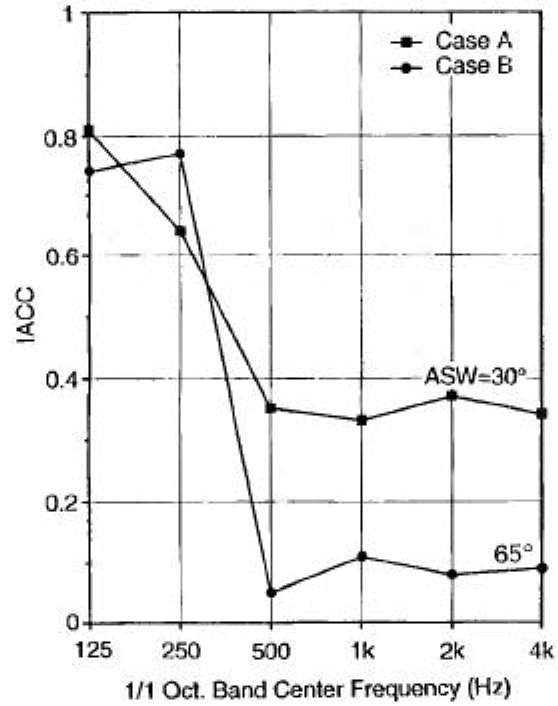

FIG. 6. Subjectively determined equal ASW contours as a function of octave-band midfrequencies (after Okano *et al.*, 1994).

of 5 s and was taken from the end of the Fourth Movement of Bruckner Symphony No. 4. It was packaged in two forms, cases A and B.

Case A consisted of a direct sound and two lateral reflections at ±60°, delayed 16 and 20 ms with pressure amplitudes equal to 0.75 and 0.79 of the direct sound. Case B consisted of a direct sound plus 12 lateral reflections with delay times between 20 and 64 ms and pressure amplitudes that decreased downward from 0.79 of the direct sound for the first reflection to 0.48 for the last arriving reflection. The reflections came from horizontal angles at ±15° to ±90° in steps of 15°. Two additional reflections were added with horizontal angles of ±45° and azimuth angles of 45°.

Presented at levels of 67 dB(A), reference signal case A had an ASW judged to be equal to 30° and case B equal to 65°. Reverberation with an RT=2 s starting at 100 ms could be added, but was found not to influence the results.

For case A, the subject could vary the level of both reflections in the second (nonreference) signal to change the ASW, and for case B, the levels of half the reflections in the second signal could be varied. These variations also changed the values of IACC.

Two "equal ASW" contours analogous to "equal loudness" contours were then determined. The results are shown in Fig. 6. Each of the six bands for the two ASW curves must have the IACC shown on the ordinate to have an ASW equal to that of the reference 1-kHz band.

This figure shows that for each of the ASW contours the four highest octave bands have approximately the same IACC values and thus are apparently of equal importance in determining the total ASW of a musical field in a concert hall. The 125- and 250-Hz bands are of much less importance in evaluating a concert hall sound field, because [1−IACC] for those bands is significantly smaller than the [1−IACC]'s for each of the other four bands.

D. Choice of three-band IACC

Although Fig. 6 shows that the fourth band is important in determining ASW, we have chosen to use only three bands with midfrequencies at 500, 1000, and 2000 Hz in concert hall evaluations for three reasons: (1) the level of the music in the fourth band (4 kHz) for a typical symphonic piece is approximately 15 dB lower than the levels in the 0.5- to 2-kHz bands; (2) Potter (1993) concluded that "Only for signals with an interaural correlation lower than 0.5, could a limited contribution to the spaciousness be expected of the high-frequency region [over 2 kHz] due to the natural envelope ... encountered for certain types of music; (3) the Blauert *et al.* data of Fig. 5 show that, for musical sounds, there is little contribution to ASW above 3000 Hz. We shall use the average of a simple summation of the three bands with center frequencies at 500, 1000, and 2000 Hz to determine the most sensitive form of IACC and shall designate it "IACC_3."

Confirmation of our selection of the average of the IACC_E's in the 500-, 1000-, and 2000-Hz bands is shown in Table II. Comparison of the averages of the 0.5/1/2 column with the 0.5/1/2/4 column in the three regions of concert hall quality shows that the range from group (A+,A) to group (B,C+,C) is 0.58−0.37=0.21 for the three-band average, and is 0.53−0.36=0.17 for the averages of the 500-, 1000-, 2000-, and 4000-Hz bands.

VIII. INTEGRATION LIMITS OF IACC

Our next step was to determine where to set the integration limits of the impulse response. In Figs. 7–10 IACCs are shown for two unoccupied rectangular halls, Boston Symphony Hall and Baltimore's Meyerhoff Symphony Hall (before recent renovations), both with reverberation times (unoccupied) of 2.4 s at 500 Hz. In Figs. 7 and 9, the integration limits [Eq. (3)] are 0 and t (designated IACC_E's) and in Figs. 8 and 10, the integration limits are t and 3.5 s (IACC_L's).

Figures 7 and 9 show that the time that separates the early reflections from the late reflections exists in the range from 50 to 200 ms. This was confirmed by plotting the same type of graphs for eight concert halls at three seats (24 graphs), and determining the IACC_E's for t equal to 50, 80, 100, and 200 ms. The IACC_E's for 0–80 and 0–200 ms were found to have sufficiently high correlations to permit selection of any time in this range to divide "early" from "late." We have chosen 80 ms.

There are several other logical reasons for choosing 80 ms. First, measurements of RECC(t) [log of the time integral of $p^2(t)$ with integration limits of 0.005 to T] (Toyota *et al.* 1988) show that RECC rises until about 80 ms and then flattens out. Second, McAdams (1982) suggests that fusion of modulated music in the auditory system may occur for $t<80$ ms. Third, Barron (1971) gave the reason for selecting 80 ms for C_{80} and LF_E as deriving from the fact that the time limit after which discrete reflections become disturbing to music is ~80 ms. Finally Beranek's studies (1962) that relate firmation of IACC$_{E3}$ as a sensitive parameter for rating the acoustical quality of concert halls. All IACC data were taken by Takenaka or Bradley as indicated.

		All measurements made in unoccupied halls. In final three columns data are corrected for halls with nonupholstered seats.														
ta m	City and name of hall	125	250	500	1000	2000	4000	125/250	Avg.	500/1000	Avg.	0.5/1/2	Avg.	0.5/1/2/4	Avg.	IACC$_{E3}$ unoccupied with/corr.
A	Vienna, Gr. Musikvereinssaal	0.92	0.76	0.42	0.32	0.34	0.40	0.84		0.37		0.36*		0.37		0.29
A	Boston, Symphony Hall	0.95	0.82	0.49	0.30	0.27	0.23	0.89		0.40		0.35		0.32		0.35
A	Amsterdam, Concertgebouw	0.94	0.78	0.46	0.42	0.51	0.44	0.86		0.44		0.46*		0.46		0.38
A	Berlin, Konzerthaus (Schauspiel)	0.92	0.80	0.37	0.29	0.42	0.36	0.86	0.86	0.33	0.38	0.36*	0.37	0.36	0.36	0.34
A	Tokyo, Hamarikyo Asahi Hall	···	···	0.40	0.29	0.21	0.17	···		0.34		0.30		0.27		0.30
A	Zurich, Grosser Tonhallesaal	0.93	0.79	0.48	0.27	0.33	0.28	0.86		0.38		0.36*		0.34		0.29
A	Basel, Stadt-Casino	0.89	0.78	0.46	0.34	0.33	0.29	0.84		0.40		0.38*		0.36		0.36
A	Costa Mesa, Segerstrom Hall	0.92	0.80	0.47	0.37	0.31	0.30	0.86		0.42		0.38		0.36		0.38
R	Cleveland, Severance Hall	0.95	0.87	0.51	0.41	0.30	0.32	0.91		0.46		0.41		0.39		0.41
A	Baltimore, Joseph Meyerhoff Hall†	0.95	0.84	0.53	0.44	0.40	0.26	0.90		0.49		0.46		0.41		0.46
A	Salt Lake, Utah, Symphony Hall	0.93	0.81	0.48	0.40	0.35	0.26	0.87		0.44		0.41		0.37		0.41
A	Berlin, Philharmonie Hall	0.96	0.88	0.60	0.50	0.53	0.45	0.92	0.89	0.55	0.47	0.54	0.44	0.52	0.42	0.54
B	Jerusalem, Binyanei Ha'Oomah	···	···	0.55	0.40	0.40	0.48	···		0.48		0.45		0.46		0.45
R	Washington, Kennedy Conct Hall	0.94	0.74	0.42	0.40	0.36	0.30	0.84		0.41		0.39		0.37		0.39
R	Worcester, MA, Mechanics Hall	0.95	0.81	0.47	0.45	0.44	0.42	0.88		0.46		0.45*		0.45		0.43
A	San Francisco, Davies Hall†	0.95	0.87	0.65	0.54	0.50	0.40	0.91	0.92	0.60	0.65	0.56	0.58	0.52	0.53	0.56
R	Buffalo, Kleinhans Music Hall†	0.97	0.90	0.79	0.61	0.37	0.38	0.94		0.70		0.59		0.54		0.59

ee column to right headed IACC$_{E3}$ with/corr.

ions either recently completed, underway, or in planning to improve the acoustics.