Concert hall acoustics: Recent findings

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Concert hall acoustics: Recent findings[a]

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I. INTRODUCTION

In recent years a number of papers have appeared in a variety of technical publications that deal with both the physical and psychological aspects of the acoustics of concert halls. An attempt is made in this paper to relate these findings to what we measure and observe in existing halls of various sizes, shapes, and details and to more definitely guide future design toward increasingly successful results.

II. BRIEF HISTORY

The highest rated concert halls acoustically were built before 1901.[1] They are Grosser Musikvereinssaal in Vienna, Symphony Hall in Boston, and Concertgebouw in Amsterdam. All three are rectangular (shoebox) in shape and have lightly upholstered seats. To listeners, the sound in them is beautiful, almost luxurious; because of the rich reverberation, the quantity of early lateral reflections that give breadth to the music, the balance of tone among the orchestral sections, the loudness of the sound, and the dynamics that brings listeners to their feet following a fortissimo conclusion. Also, the quality of the sound is nearly uniform in about 90% of the seating areas and the players clearly hear each other on stage, certainly in Boston and Vienna.

Since the advent of the Berlin Philharmonie Hall in 1963, architects and owners have often placed beauty and novelty of architecture above acoustics. In Berlin nearly half of the audience is seated to the sides and rear of the stage. Even though the orchestral balance differs considerably from one seat location to another, that hall has been a success, partly because of the striking architectural design, partly because necessary early lateral reflections reach many seats from the fronts of the seating blocks, and partly because the seats are not heavily upholstered—a very important factor.

III. SUBJECTIVE RANKING OF CONCERT HALLS ACCORDING TO THEIR SOUND QUALITY

Over a period of 40 years (1960–2002) this author conducted interviews and made questionnaire surveys of over 150 conductors, music critics, and concert aficionados in an effort to determine how well-known concert halls rank acoustically. The interviews were used to acoustically rank order 58 halls and the results were published in 2003.[1,2] No hall had less than six qualified raters. Recently Skålevik has made a similar ranking, but using an on-line questionnaire. For his rank orderings the number of raters was 59 and 482 votes were distributed over 79 halls.[3] In Tables I(a)–I(c) the results of the two studies are combined to obtain a ranking of a number of well-known concert halls.

The rankings by the two methods are close except for Zurich and New York's Carnegie. A closer look at the interviews made it apparent that the on-line results were preferable. The author has attended concerts in all of the N/A halls and the on-line rankings for them are judged acceptable. On the other hand, the interviews in connection with the Cardiff hall were so convincing that they were chosen over the on-line result.

One purpose of Tables I(a) and I(b) is to illustrate the shape of the halls with the best acoustics. It is clear that the high-ranking halls are predominately shoebox in shape. Note that there are no fan-shaped halls. The range of rankings for surround halls alone is shown in Table I(c).

IV. LISTENERS' PREFERENCES: PERCEPTIONAL DIFFERENCES AMONG ASSESSORS OF CONCERT HALL ACOUSTICS

Having identified some of the world's well-known concert halls, let us now look at recent research that deals with how listeners perceive the sound fields that surround them.

Lokki,[4] in the Media group at Aalto University, Finland, reported the preferences of 17 assessors listening to 3 recorded excerpts of symphonic music, 20 s. each, from different periods and different sized orchestras, and with the assessors located 12 m in front of the orchestra in 9 halls. How was this possible?

The researchers created an orchestra of loudspeakers distributed on the stage at 34 positions like a real orchestra: For each instrument (for example, a cello), a real performer recorded the symphonic music from different periods in a sound-dead room, while listening with earphones to the composition that was played by a pianist and at the same time both player and pianist seeing the conductor on a screen in front of them. Individual instruments were connected to the 34 position loudspeaker orchestra. The music from the loudspeaker orchestra was played in each of the 9 halls and in each the sound was recorded on an array of microphones located 12 m in front of the loudspeakers. This recorded music was taken to the laboratory and played back to the 17 listeners who were seated in a dead room within a circle of 24 loudspeakers. The reproduced sound for each hall was completely realistic to anyone who goes regularly to concerts.

The 17 assessors both rank-ordered the 9 halls and produced reasons for their preferences. Details are given in Ref. 5. They fall primarily into two groups. The first group stated that they preferred a hall with high definition and clarity along with adequate loudness, reverberation, and bass. The second group preferred a louder and considerably more reverberant sound with strong envelopment and strong bass. All assessors disliked weak and distant sound. The best-liked hall was shoebox shaped with a width of about 21 m and a high ceiling—in it there are strong reflections from the sidewalls and a later, weaker reflection from the ceiling. The least liked hall was a long fan-shaped hall with a low ceiling, where measurements showed a strong early reflection from the ceiling and no reflections from the side walls.

It is interesting that listeners in Boston Symphony Hall can also be divided into two groups, (and possibly three counting those in between) namely, those who like the sound best in the front two-thirds of the main floor and those who prefer the sound in the upper rear second balcony. The difference is readily apparent to anyone by listening to the first half of an

[a]Portions of this paper were presented in a keynote lecture in Birmingham, England, October 15, 2014, at the 40th anniversary celebration of the founding of the (British) Institute of Acoustics.
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TABLE I. Combined rankings of concert halls. Shu = Shoebox; Par = Parallel sidewalls but not Shu; Sur = Surround; Odd = None of the three; N/A = Not in Beranek's survey.

Hall and type		Ber58 Halls	On-Line No. of raters	On-Line Rating
(a) Ten concert halls with the highest rankings				
Vienna, Musikvereinssaal	Shu	1	23	4.8
Boston, Symphony Hall	Shu	2	16	4.4
Amsterdam, Concertgebouw	Shu	4	23	4.6
Berlin, Konzerthaus	Shu	3	16	4.1
Tokyo, Opera City Concert Hall	Shu	5	3	4.3
Basel, Stadt Casino	Shu	8	5	4.4
Birmingham, Symphony Hall	Par	N/A	7	4.4
Lucerne, Cultural Ctr. Hall	Shu	N/A	13	4.3
Cardiff, St. David's Hall	Sur	9	6	4.0
Dallas, Meyerson Center	Par	10	3	4.3
(b) Other high ranking halls				
Cleveland, Severance Hall	Odd	21	5	4.2
Fort Worth, Bass Hall	Odd	N/A	5	4.0
Vienna, Konzerthaus	Shu	22	8	4.0
Berlin, Philharmonie Hall	Sur	16	21	3.9
Zurich, Tonhallesaal	Shu	6	8	3.8
New York, Carnegie Hall	Par	7	18	3.8
Tokyo, Suntory Hall	Sur	17	4	3.8
(c) Surround halls in surveys, with a range of rankings				
Cardiff, St. David's Hall		9	6	4.0
Berlin, Philharmonie		16	21	3.9
Tokyo, Suntory Hall		17	4	3.8
Mexico City, Salla Nazahualcoyotl		N/A	3	3.7
Rotterdam, De Doelen Concertgebouw		23	6	3.2
Toronto, Roy Thompson Hall		24	3	3.0
Philadelphia, Verizon Hall, Kimmel Ctr		N/A	7	2.7

orchestral concert on the main floor and the second half in the rear second balcony. On the floor the sound is clear and loud with full bass, with many early reflections, none of which mask the direct sound, and with reverberation that is beautiful. In the rear second balcony the reverberant sound almost immediately follows the arrival of the direct sound and it is loud and completely enveloping. Those who have subscription seats in the upper balcony praise the sound. The author of this paper, preferring clarity to the sound, identifies with the main-floor group.

We will now deal with the sound that reaches our ears within about 100 ms after the arrival of the direct sound.

V. SOUND FIELD IN A HALL

When a musical note is suddenly sounded on the stage, say by a violin, the sound radiates outward from the instrument and then strikes walls, ceiling, and audience. Each surface then reflects a sound wave that subsequently bounces around the room from one surface to another. At a listening position in Boston Symphony Hall located just off the center line and two-thirds the distance from the stage to the main-floor rear wall, i.e., 26 m from the stage, actual measurements give the rise in the energy density following the arrival of the first seven strongest reflections at a central seat as shown by the stepped heavy line in Fig. 1.

The first reflection in Fig. 1 is from the lowest sidewalls and the under surfaces of the first balconies. The second is from the under surfaces of the second balconies and their fronts. The third is from the back of the stage. The fourth is from the rear bends in the balcony fronts. The fifth is from the ceiling. And so on. The first, second, and fourth are lateral reflections. How do these reflections interact with the direct sound?

This author's listening experience agrees with Griesinger's argument that the early reflections should not be so strong and arrive so early as to

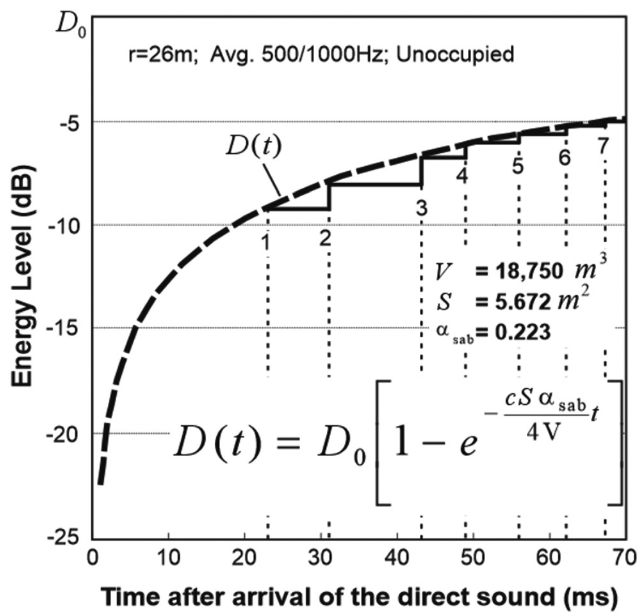

FIG. 1. Measured rise in energy density at a seat 26 m from the source (located on the stage in Boston Symphony Hall) owing to the first seven major reflections (unoccupied hall and at mid-frequencies).

mask a person's ability to hear the direct sound clearly.[6] It is from the direct sound that one can clearly distinguish a succession of musical notes. Griesinger suggests a test as to whether the direct sound can be clearly heard is whether a listener can accurately judge the lateral direction from which the sound of an instrument on stage is coming (some argue that clarity and lateral direction are not that closely related, but it seems obvious that if one can accurately locate a source laterally, the direct sound must be adequately clear). He states that if the direct sound is not clear the music will not be compelling. This identifies Griesinger with the first group of Sec. IV.

It seems obvious from Fig. 1 that before the first reflection there is time during which one could hear the direct sound. But it is not obvious how the ear-brain system distinguishes between the direct sound and the mix of direct and reflections that follows. According to Griesinger the mechanism relies on the pressure peaks at the fundamental frequency that are created by the phase relationships between the upper harmonics. Reflections randomize these phases, and the ear-brain system can easily detect the difference. The 23 ms shown in Fig. 1 sometimes may not be enough. But if the direct sound is stronger than the buildup of reflections for long enough, the direct sound can be easily detected.

The sooner first-order reflections come the stronger they are, and the less time there is for the direct sound to be detected. The times of arrivals of the lateral reflections depend on the width of the hall, i.e., the narrower the hall the sooner they arrive. The arrival times also depend on the distance of the listener from the orchestra. Reflections arrive sooner after the direct sound in the rear of a hall than in the front. As you walk back in a hall there is a clear point where the sound—once clear and sharply localized—coalesces into the reverberant sound. When the listener moves sideways from the center-line of the Boston Hall at the 26 m position to a position near the left sidewall, the direct sound and the first reflection from that wall arrive at nearly the same time, but the reflection from the right side wall comes to the listener at a later time. The listener then has a larger space between the direct and the right side first reflection for hearing the direct sound.

The essence of Griesinger's paper as interpreted by this author is shown in Fig. 2.[6]

The area with closed circles is taken from Fig. 1 and represents the rise in strength of the reflected sound energy. The slope of the rise would be steeper in a hall with a lower reverberation time (RT) than the 2.5 s here.

The gray area is associated with the direct sound. Obviously, the strength of the direct sound also sets the level of the reflected sound. The range of the direct sound shown here is from −20 to −10 dB relative to the energy level at which the reverberant sound builds up to at about 2.5 s (0 dB on the ordinate). The diagram implies that below −20 dB the direct sound

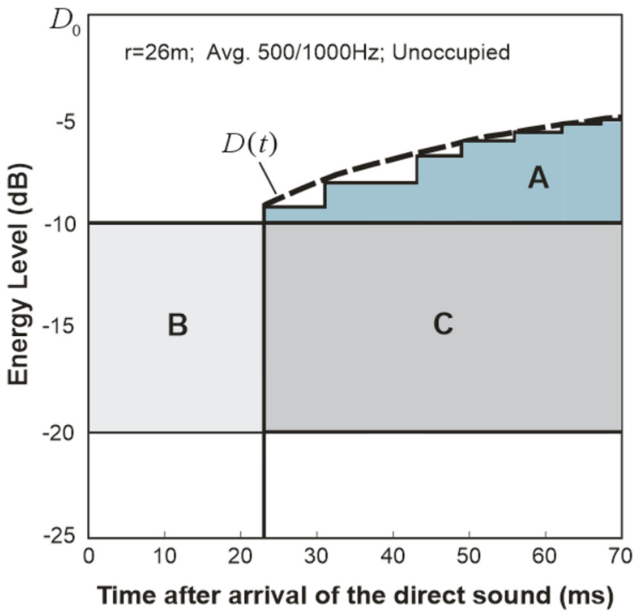

FIG. 2. (Color online) Presentation of the early reflection sound field in Boston Symphony Hall in approximate conformance with Griesinger's theory about hearing the direct sound clearly.

will not cause firings of the nerve impulses in the hearing mechanism and that the range of 10 dB determines the principal quantity of firings associated with the direct sound. Griesinger claims the −20 dB cutoff was not chosen by a physiological measurement. It was chosen as a free parameter to fit the threshold of localization data obtained from an experiment with about 20 subjects.

If Area (B + C) is larger than Area (A + C) the direct sound should be clearly heard, i.e., is not masked by the reflections. Since Area (B + C) for this position in Symphony Hall holds the equivalent of about 600 closed circles and Area (A + C) about 416, the difference between the two is 184 closed circles. The number of circles along the abscissa is equivalent to 37. Dividing 184 by 37 = 5 vertical layers. Each vertical layer is 0.7 dB, hence 5 layers equals 3.5 dB. Following Griesinger further, if this number equals 3 dB it is called the "threshold of localization, LOC." A value of LOC of +3 dB predicts reliable detection of the direct sound and good clarity. Thus, in Fig. 2, the direct sound is clearly detectable. This seat is one of the best in Boston Symphony Hall for people who like the combination of clarity and reverberation. For positions farther back in the hall, all the reflections come in earlier and soon the clarity requirement is no longer satisfied. Listeners report that the first two or three rows in the first balcony, center, of Boston's hall are as far back as clarity of the direct sound is achieved (r = 33–35 m).

In a private communication,[7] Lokki writes, "My understanding is that the Boston Hall is so good because the clear early reflections from flat walls combine with the direct sound well in our hearing system making the total sound louder and maybe also wider. In addition, the early reflections give a character to the sound and increase the spatial and dynamical responsiveness of the hall, which results in more expressive music." This excellent statement does not invalidate the previous theory. One hears as a whole the sound before and after the 100 ms mark—the direct sound, the early reflections, and the later reverberant sound—they all merge in our consciousness—and it is this combination that determines the overall perceived sound quality. But some listeners prefer to hear the direct sound clearly before its reflections arrive and others prefer to hear the direct sound in closer proximity to its early reflections and the reverberant sound. The data in Fig. 1 were measured in Symphony Hall and that sequence of sounds certainly must be related to Boston Hall's highly acclaimed acoustics.

Acousticians sometimes speak of Source Presence and Room Presence. Source Presence is that sound which reaches the listener before the reverberation becomes appreciable. It usually includes the direct sound and early reflections up to about 100 ms after arrival of the direct sound. Room Presence deals with the reverberant sound field that follows.[8]

Haapaniemi and Lokki[9] studied whether the early or late part of the acoustic response (source or room presence) is more useful in distinguishing one concert hall from others. Using the loudspeaker orchestra and the playback room described above and 12 listeners they found that each of the 8 well-known halls could be identified better by source presence than by room presence.

Pätynen *et al.*[10] demonstrate that when an orchestra plays fortissimo the frequency spectrum changes. They made measurements of the spectra of orchestral sounds from 29 publically-released recordings of Bruckner Symphony No. 4, third-v movement, bars 19–26, during which segment the orchestra dynamics increases from pianissimo (*pp*) to fortissimo (*ff*). It was found that between 400 and 2000 Hz the spectrum for the (*ff*) sound is about 7 dB more intense than that for the (*pp*) sound and that between 2000 and 8000 Hz the increase is more than 15 dB (see upper curve in Fig. 3).

Now another factor. Because of the size of the head, when the sound arrives from a lateral direction, sideways, the intensity at the closer ear of a listener, in the 2000 to 8000 Hz region, is 1 to 5 dB greater than that when the sound arrives only from the front. With reflections from both sides of a shoebox hall this difference will occur at both ears. Hence, in a shoebox hall, the difference in the intensities between (*pp*) and (*ff*) that arrives at the ears between 2000 and 8000 Hz is 8 to 12 dB greater [7 dB + (1 to 5 dB)]. From measurements in 10 European concert halls, in this frequency region, the sound at the ears in a shoebox hall is on average about 2 dB greater than that from a non-shoebox hall (See lower curve of Fig. 3). Among individual halls in this group this difference is as much as 5 dB. This range falls between the "1 to 5 dB" as noted above. This is another reason why the shoebox shape is the best for a concert hall.

VI. EARLY LATERAL REFLECTIONS

It is almost universally agreed that properly-delayed early lateral reflections add to the quality of sound in a concert hall. Listeners in controlled tests find that the source of sound is widened by these reflections. Marshall[11] was the first to recognize their importance. Marshall and Barron[12] devised a measure that is easily made using two readily available microphones. One microphone measures the sound from lateral directions and the other measures the total sound. The ratio of their outputs (differences in decibels) determines a quantity called lateral fraction. A more accurate measure is the Binaural Quality Index (BQI).[13]

The acoustical quality in a hall is better if a significant number of early lateral reflections occur before about 100 ms after arrival of the direct sound. This requirement is better fulfilled in shoe-box shaped halls than in other shapes. It is difficult in a surround hall to produce more than a couple of lateral reflections in that time period because the audience is usually on steeply raked seats surrounding the stage. In the Philharmonie Hall in Berlin, a surround hall, this problem is at least partially solved. There, the audience area is broken up into blocks, often called trays or vineyards. At the front of these blocks are reflecting surfaces that send lateral reflections outward. This

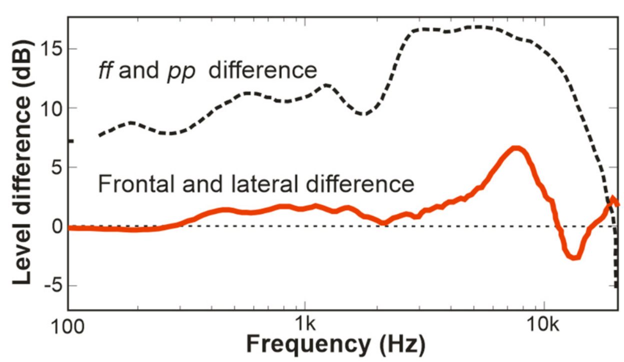

FIG. 3. (Color online) Curves showing: (upper) difference in sound level between full symphony orchestra playing at *ff* and *pp* levels; (lower) difference between binaural loudness levels at the ears of a listener with sound coming from frontal direction (reference-0 dB) and laterally from sidewall reflections (courtesy T. Lokki).

means that any one block may experience lateral reflections arriving from other blocks, although this is not true at all blocks and the number of arriving reflections may be small. In the Boston hall of Fig. 1, the first, second, and fourth reflections are from lateral directions. The total number of reflections of all strengths and directions in Boston is about 10 during the first 80 ms.

But these lateral reflections can also be a problem. If a hall is too wide a large number of seats will hear the sound muddled. One example that the author experienced recently was in a well-known hall with parallel sidewalls and a width of 34 m. At a seat back 14 m from the first violins, 12 m from the left wall, and 22 m from the far right wall, reflections from the right wall were so late and so high in amplitude that they overlapped and muddled the following sound, producing a clear double image. The time difference was about 100 msec. But a parallel-sided concert hall that is too narrow is also a problem because the first reflection arrives soon and is very loud, so that the direct sound is unclear. [There are many successful chamber music halls that are rectangular in shape and narrower than the above, but in them the stages are smaller, the audiences are less, and the RTs are shorter than in halls for symphonic music (see Sec. XI).]

In another paper, Lokki[14] discusses the shoebox vs surround shape further. He writes that most people prefer the acoustics that renders the sound of an orchestra intimate and close, with good clarity and openness, and the sound has to be loud enough to envelop the listener. To render orchestral sound with large dynamics and full spectrum, the concert hall has to create quite strong early lateral reflections with full bandwidth, *hopefully from surfaces that do not modify the phases of different frequency components*. Thus, the best seats are in shoebox halls with near-flat sidewall surfaces at the lower levels. These halls also have a near-flat floor on the audience area enabling nice enveloping reverberation. If the audience area is steeply inclined, the seated persons behind block the enveloping reverberation from reaching those seated in front. In the upper rows of seating in one surround hall, starting half-way back from the stage, sound arriving below 30° and from the rear does not reach a person sitting in front. Also, as an example of bad reflections, in the Berlin Philharmonie some seats receive quite late side reflections that might be perceived as echoes.

Kirkegaard[15] has published measurements of the sound fields in two halls with different types of sidewall surfaces. In New York's Carnegie Hall the sidewall surfaces, which are responsible for reflecting the early sound, are smooth and flat and are constructed of plaster on heavy masonry. The musical sound in Carnegie has warmth and purity. In New York's Avery Fisher Hall, the equivalently located sidewall surfaces are a series of vertical stepped surfaces, each about 1 m wide, which are of 1.9 cm thick wood over an airspace that is on average about 5 cm deep (photos are in Beranek[16]). The stepped wood panels are screwed to a 15 cm concrete block. This construction yields a sound that is harsh and strident, particularly when the level of the music increases above *mezzo forte*. [This author believes that fine-scale diffusion on the lower side-walls—that diffuses the incident sound at frequencies above 3000 Hz—makes the reflected sound mellower without affecting the clarity.]

To measure the reflected sound from these surfaces, Kirkegaard placed a dodecahedral loudspeaker at a soloist position on the stage. A highly directional microphone at a mid-main-floor position was aimed at the house-left sidewall at an angle from which a specular reflection from the source would be expected to emanate. The results are shown in Fig. 4. Observe the frequency region above 250 Hz. In Carnegie, the identity of the succession of notes is clearly preserved at these frequencies. In Avery Fisher, the sound at these frequencies is extraordinarily dense—it is obviously smeared.

Kahle Acoustics[17] presents a method for calculating the strength of the early lateral reflection energy that reaches the audience area from reflecting surfaces. The procedure assumes that the reflecting surfaces will be flat, non-diffusing, and non-absorbent. The path from a non-directional source to a surface and from it to the audience area is shown in Fig. 5. The equations are found in Ref. 17.

This method shows that obtaining sufficient early sound strength in a large hall requires that the early reflections arrive at the listeners' ears from surfaces low in the room. That is to say, when the reflecting surface is vertical and near the seating area, the reflected sound extends over a greater seating area. The Kahle paper presents a successful application to a 2750 seat hall in which a number of large, flat surfaces are incorporated, mainly

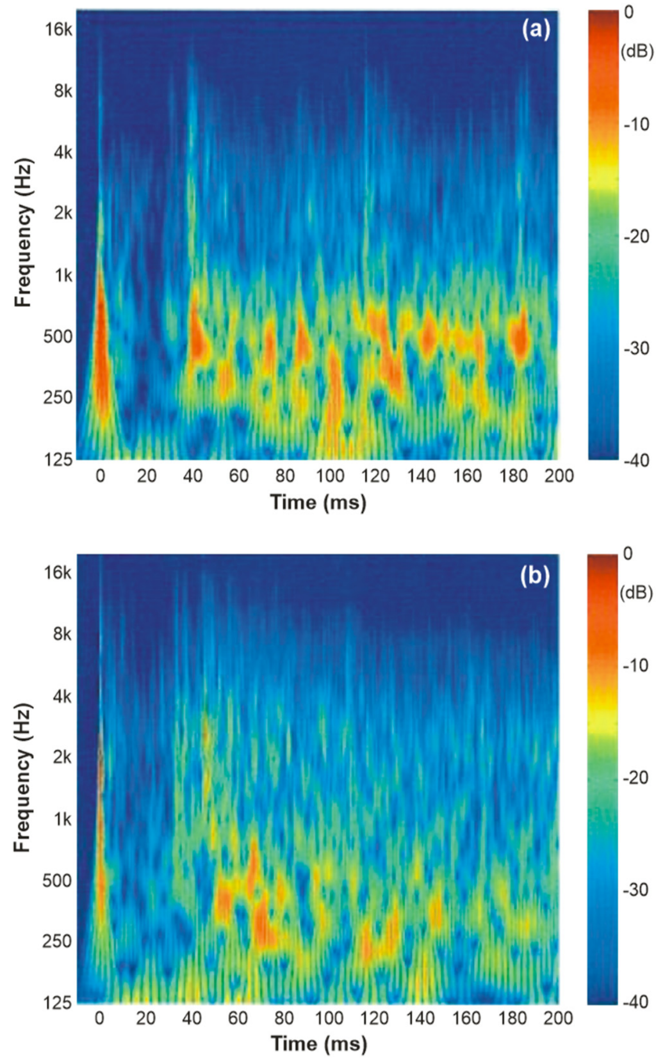

FIG. 4. (Color online) (Above) Wavelet configuration for Carnegie Hall. (Below) Wavelet configuration for Avery Fisher hall.

on the side walls and balcony fronts, that reflect the early sound to the audience areas.

In all of the highly rated halls there are statues, niches, large diameter partial cylinders, and the like, on the upper side walls. Also there are coffers or other irregularities on the ceiling. These items make the reverberant sound more pleasant.

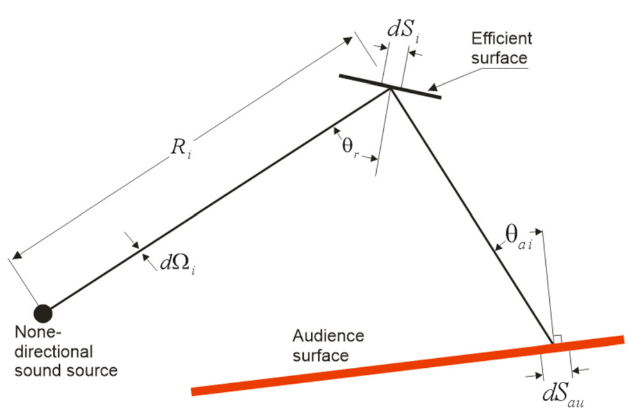

FIG. 5. (Color online) Means for calculating G contributed by flat reflecting surfaces in a concert hall.

VII. SOUND STRENGTH G, HALL SHAPE, AND AUDIENCE ABSORPTION

A. Sound strength G

Let us now look at the average sound strength G in a hall. The loudness of the music in a concert hall is closely related to the average sound strength G in decibels. An increase of about 3 dB is equivalent to doubling the size of the orchestra.

Measured values of G in halls where heavily, medium, and lightly upholstered seats exist are shown in Table II at mid-frequencies. The average strength G is about 1.5 dB lower in halls with heavily upholstered seats as compared with those with lightly upholstered seats. This difference is about 0.7 dB when the comparison is with medium upholstered seats.

It must be recognized at the outset that all halls in this table have an occupied RT at mid frequencies of about 2.0 s, which means that the sound field is near diffuse. Second, there are no odd shapes, i.e., no long and narrow halls, or halls with low ceilings. No hall is fan-shaped and in all halls the sound absorption is primarily from the audience area. It is amazing that, except for the Berlin Philharmonie, all of the surround halls for which such data exist have heavily upholstered seats. The best known shoebox halls have lightly upholstered seats. A hall was judged to have heavily upholstered seats if after full occupancy the RT decreased by about 0.2 s and to have lightly upholstered seats if the change was about 0.7 s. By interpolation, if the change was about 0.4 s the hall had medium upholstered seats.

The most highly rated halls acoustically are shoebox in shape and have measured G's of 5 to 6.5 dB (full occupancy and at mid-frequencies). In them symphonic music from the Baroque, Classical, and Romantic periods are equally enjoyed by music aficionados. Recently, three music aficionados, after attending concerts is the Sapporo. Disney and Paris halls (all surround shaped and with heavily upholstered seats) reported to the author that music from the Romantic period (e.g., Mahler) was satisfactory but music from earlier periods was "weak" or "low in level."

Bradley and Soulodre[18] found that the perception of bass sound in concert halls at low frequencies is directly related to sound strength G and not at all to the RT. They also conclude that the perception of bass is related to both the energy in the early sound and the late sound, although more so to late arriving sound.

TABLE II. Average sound strength G in decibels at mid-frequencies for halls with three different upholsterings.

Concert hall	Type	G_{MID} occupied
Heavily upholstered seats		
Belfast, Waterfront Hall	SUR	3.7
Cardiff, St. David's Hall	SUR	3.6
Sapporo, Kitara Hall	SUR	3.2
Los Angeles, Disney Hall	SUR	3.0
Munich, am Gasteig	FAN	2.6
	Average	3.2
Medium upholstered seats		
Vienna, Konzerthaus	SHO	4.3
Berlin, Philharmonie	SUR	4.2
Baltimore, Meyerhof Hall	OVAL	4.0
Manchester, Bridgewater Hall	SUR	3.7
Tokyo, Met Arts Space	Fan	3.5
	Average	3.9
Lightly upholstered seats		
Vienna, Muzikvereinssaal	SHO	6.5[a]
Amsterdam, Concertgebouw	SHO	5.1
Tokyo, Tokyo Opera City Hall	SHO	4.9
Boston, Symphony Hall	SHO	4.1
Tokyo, Suntory Hall	SUR	3.7
	Average	4.7

[a]Not in avg., some seats bare.

Another question has arisen. Is the decrease in sound energy as one goes from the front of a hall to its rear related to its shape or to some other factor?

Barron has published that in any space with a near-diffuse sound field the G levels at a given frequency drop off with distance in accordance with the ratio of the volume of the hall to the RT at that frequency,[19,20] that is, according to the formula

$$G \text{ (at frequency } f) = 10\,\mathrm{Log}\,[100/r^2 + (31\,200\,T/V)e^{-0.04r/T}], \quad \mathrm{dB} \tag{1}$$

where r is the distance from the source in meters, T is the RT at frequency f, and V is the volume of the hall in cubic meters. The shape of the hall does not enter into the formula. Calculations of G from this formula for 13 well known halls appear in Table III. It is seen that the decrease in G between $r = 10$ m and $r = 40$ m is 3.9 dB for halls with seats that are heavily upholstered and 2.7 dB for halls with seats that are lightly upholstered. In the formula, T is proportional to V divided by total room absorption, then T/V is inversely proportional to the total room absorption, and thus G decreases as the total room absorption increases.

Hidaka found that G falls off about 2.5 dB between 10 and 40 m in classical shoebox-shaped halls and about 4 dB in surround shaped halls. But all the surround halls he measured had highly upholstered seats while all the shoebox halls had lightly upholstered seats. He speculated that the difference was due to shape. But we must conclude that for these halls the fall-off was not due to shape but due to average room absorption.

However, both Gade[21] and Barron show that in some halls the decrease in G with distance is less or greater than that predicted by Eq. (1). Gade has formulas that, for different types of halls, show G [from Eq. (1)] to be only about half of the contribution to the drop of measured G. Barron gives examples that show G (measured) drops off more rapidly than G [from Eq. (1)] only when the hall has an unusual shape (Barbican Hall in London) or when measurements are made under balconies.

Bradley and Soulodre[18] found that the perception of bass sound in concert halls at low frequencies is directly related to sound strength G and not at all to the RT. They also conclude that the perception of bass is related to both the energy in the early sound and the late sound, although more so to late arriving sound.

B. RECC

Early lateral reflections sufficient in number and strength exist in the best concert halls. Hidaka decided to explore whether the total sound energy, in contrast to the lateral sound energy alone in the source-presence time period, is important in determining acoustical quality.[22] The measuring method he chose was first proposed by Toyota[23] and is called "*reflected energy cumulative curve* (*RECC*)," defined by the formula

$$\mathrm{RECC}(t) = 10\log\left(\int_{5\,\mathrm{ms}}^{t} p^2(t)dt/K\right) \quad \mathrm{dB}, \tag{2}$$

$$K = \int_0^{\infty} p_0^2(t)dt, \tag{3}$$

where $p(t)$ is a room impulse response measured between source and receiver, and $p_0(t)$ is that measured at 10 m from the same sound source in a free space. For Hidaka's measurements an omni-directional source was placed 3 m from the stage lip at the center of the stage.

He speculated that this measurement is more important at a low frequency (e.g., 125 Hz) than at mid-frequencies. Soulodre *et al.*[24] determined that the separation time between source presence and room presence at 125 Hz is 160 ms and at mid-frequencies is 80 ms. Hidaka used 160 ms. RECC does not take into account the general belief that when the first reflection comes from an overhead surface, the perceived sound quality is less than when the first reflection comes from a side surface.

For six concert halls, plots of RECC as a function of time after arrival of the direct sound is given in Fig. 6 for the frequency 125 Hz. Its value at 160 msec is a measure of the cumulative energy that is due to early reflections. The RECC for the Berlin Philharmonie hall is high for a surround hall, which indicates that there are strong early reflections at most positions in the hall—which is not true for the other surround halls shown.

TABLE III. Calculation of G—BARRON's theory—for $r = 10$, 20, 30, 40 m, at 125 to 1000 Hz, unoccupied seats, where V = Volume of the hall, m^3, and T = reverberation time, s.

		10 m G, dB	20 m G, dB	30 m G, dB	40 m G, dB	Decrease 10 to 40 m G, dB	V/T m^3/sec
Heavily upholstered							
Los Angeles. Disney Concert Hall	SUR	4.6	1.7	1.2	0.5	4.1	13 700
Sapporo, Kitara Concert Hall	SUR	4.9	2.9	1.8	1.1	3.8	12 500
Copenhagen, Danish Concert Hall	SUR	4.5	2.5	1.1	0.3	4.2	14 000
Cardiff, St. David's Hall	SUR	5.0	3.2	1.8	1.0	4.0	11 600
Belfast, Waterfront	SUR	4.9	3.2	2.0	1.5	3,4	12 300
Munich, Philharmonie am Gasteig	FAN	5.0	3.1	1.8	1.3	3.7	12 000
	Average	**4.8**	**2.8**	**1.6**	**0.9**	**3.9**	**12 700**
Medium upholstered							
Berlin, Philharmonie Hall	SUR	5.7	4.0	2.8	2.3	3.6	9500
Manchester, Bridgewater Hall	SUR	6.6	5.3	4.4	3.9	2.6	7100
	Average	**6.1**	**4.7**	**3.6**	**3.2**	**2.9**	**8300**
Lightly upholstered							
Berlin, Konzerthaus	SHO	7.9	6.8	5.9	5.4	2.5	5300
Vienna, Grosser Musikvereinssaal	SHO	8.1	7.0	6.2	5.7	2.4	5000
Amsterdam, Concertgebou	SHO	6.9	5.5	4.6	4.1	2.8	7000
Tokyo Opera City Concert Hall	SHO	6.8	5.3	4.2	3.5	3.3	7000
Baltimore, Meyerhoff Hall	OVAL	6.5	5.2	4.2	3.7	2.8	7700
	Average	**7.2**	**6.0**	**5.0**	**4.5**	**2.7**	**6500**

Furthermore, RECC is the only measure in this paper that clearly gives a reason why the Berlin Hall has been so successful. One might question whether only one position of the source on the stage is adequate. Hidaka says (private communication),[25] "In regard to the single position that I used for the dodecahedral source, I found that for two to four source positions, the parameter did not vary significantly as long as the seats' average was taken."

Measurement of RECC for 23 concert halls at 125 Hz at both main floor and balcony positions is shown in Fig, 7. Because it is possible to achieve more early reflections in a shoebox hall than in a surround hall, nine out of top ten halls (Amsterdam and higher) are Shoebox.

Also there are small differences between $RECC_E$ measured at the main floor and at balcony seats. The surround halls have lower values except for the Berlin Philharmonie. The Munich Philharmonie Hall at the left end is fan shaped which indicates that only a few early lateral reflections are possible.

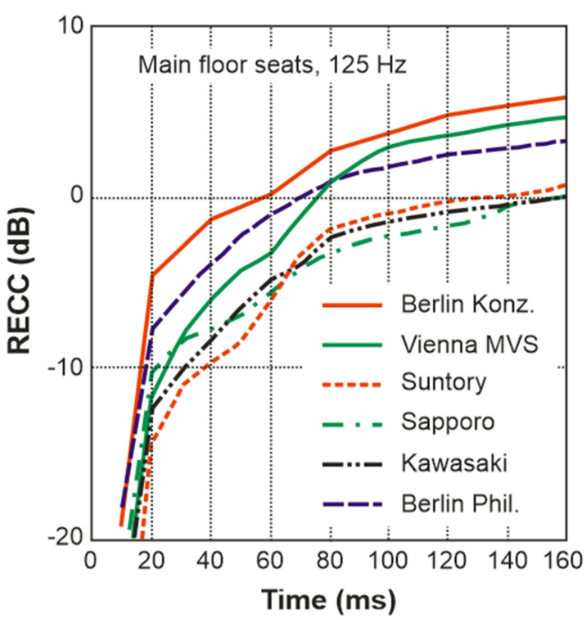

FIG. 6. (Color online) $RECC_{E,\ low}$ averaged over main floor seats at 125 Hz for six concert halls.

Let us compare the sequence of halls in Table I with the sequence of those that also appear in Fig. 7. The latter sequence is B**asel**, **Berlin-Konzerthaus**, Vienna, Tokyo-TOC, Amsterdam, Berlin-Philharmonie, and Sapporo. The subjective and RECC rankings are nearly the same. Hidaka found the same results for RECC at mid frequencies—at the 95% level.

[Notes: Boston Symphony Hall is left off this graph because the data taken when the hall is unoccupied are not comparable with those of other halls because the Boston chairs are mounted on a thin, raised plywood base instead of on a solid base. This thin plywood mounting results in very large low frequency absorption. The addition of a seated audience loads up the base so the absorption when occupied is as though the seats were on a rigid base. Also note: "Orange County" is the 1986 Segerstrom Hall.]

VIII. MUSIC DYNAMICS

The thrill of hearing Beethoven's *Ninth Symphony* or Mahler's *Eighth Symphony* is enhanced immeasurably by the dynamic response of the concert hall. Pätynen and Lokki, using their loudspeaker orchestra, have investigated how varying music dynamics affects the perception of room acoustics in different concert halls. They selected as their dynamic music signal, the II movement from Bruckner's Symphony No. 8, which includes a long full-orchestra crescendo near the end of the first theme. The assessors in the experiment heard a presentation that contained the bars 41–43 and 53–55 without pause between. All other musical factors remained nearly constant. The signal was merged with the recorded acoustic fields at three locations in six European concert halls. Three were rectangular, two were surround, and one was fan shaped. They found that the variation in music dynamics is perceived differently depending on the concert hall and on the listening position. The authors conclude, "Our findings indicate that the perceived contrast in varying music dynamics is generally more pronounced in rectangular-shaped halls. The most distinct perceptual factors differentiating the dynamics in halls include loudness, reverberance, and width of hall. The outcome of this study confirms the hypothesis that the halls render music dynamics differently, and those halls that render pronounced dynamics appear high on the earlier list of subjectively preferred halls." (See Table I above.)

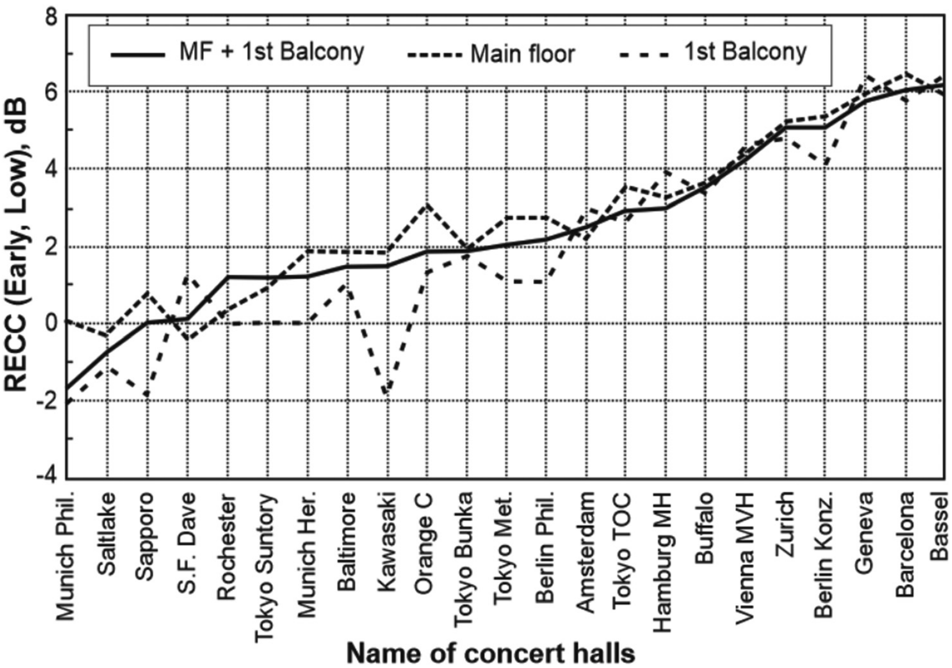

FIG. 7. A plot of RECC at 125 Hz for main floor, first balcony, and main floor plus first balcony seats in 23 concert halls.

IX. SEAT UPHOLSTERING AND HALL DIMENSIONS

The data in Table IV are for halls with a RT of 2.0 s at middle frequencies, hall occupied. The dimensions of a hall are greatly affected by the type of seats chosen. Table IV yields the following: (1) Hall volume over total hall surface area (V/S_{tot}); (2) surface area under each seat (S_T/N); (3) the hall volume per seat (V/N); (4) derived average ceiling height. These data are used in Secs. X and XI.

As shown in the last column of Table IV, the derived average ceiling height in the group is equal to the volume V divided by the area of the seating S_T [S_T includes the areas of the aisles, the area of the stage, and under-balcony areas]. In halls with heavily upholstered seats, the height is 20% greater than with medium upholstered seats and 30% greater than in halls with lightly upholstered seats. Remember that the area of the balconies is included in the total seating area. In Boston Symphony Hall, for example, only about 60% of the main floor seating area is beneath the ceiling. The remaining floor area is beneath the first balcony, and the area of the first balcony is mostly beneath the second balcony, and the distance between the second balcony and the ceiling is about half of that between the main floor center and the ceiling. Thus, the average ceiling height is 12.3 m compared to the center-hall ceiling height of 18 m.

TABLE IV. Physical dimensions of groups of concert halls with heavily-upholstered, medium-upholstered, and lightly-upholstered seats. All halls have occupied RTs at mid-frequencies of about 2.0 s. The upholstering can be (or not be) on the front and back of the backrest, top and bottom of the seat bottom, and on top of and beneath the arm rests. It can vary in thickness and on the type of cloth or leather material that covers it.

Concert hall	Type	RT changes	V over total hall area m	Seating area over N m^2	Volume per seat m^3	V over seating area m
Heavily upholstered seats						
Belfast, Waterfront	SUR	0.2	3.47	0.76	13.7	18.1
Los Angeles, Disney	SUR	0.2	3.68	0.75	13.6	18
Sapporo, Kitara	SUR	0.2	3.51	0.81	14.3	17.8
Copenhagen, Radio	SUR	0.1	3.54	0.78	15.6	20.1
Cardiff, St. David's	SUR	0.2	3.52	0.73	11.3	15.5
		Average	3.54	0.77	13.7	17.9
Medium upholstered seats						
Tokyo, Met Arts Sp.	FAN	0.5	3.25	0.74	12.4	16.8
Munich, am Gasteig	FAN	0.3	3.66	0.73	12	16.3
Vienna, Konzert	SHO	0.3	3.46	0.55	8.9	16.3
Baltimore, Meyerhof	OVAL	0.3	3.68	0.68	8.7	12.9
Manchester, B.W.	SUR	0.4	3.58	0.78	10.6	13.5
Berlin Philharmonie	Sur	0.3	3.89	0.70	9.5	13.5
		Average	3.59	0.70	10.4	14.9
		Ratio	1	1.1	1.3	1.2
Lightly upholstered seats						
Vienna, GMVS	SHO	1.1	3.66	0.67	8.9	13.4
Boston, Symphony	SHO	0.6	3.25	0.58	7.1	12.3
Amsterdam, Concert	SHO	0.6	3.48	0.63	9.2	14.6
Tokyo, Suntory	SUR	0.6	3.43	0.77	10.5	13.6
Tokyo, Opera City	ODD	0.8	2.55	0.75	9.4	12.5
		Average	3.27	0.68	9.0	13.3
		Ratio	1.08	1.1	1.5	1.3

X. CHOOSING THE DEGREE OF SEAT UPHOLSTERING IN A CONCERT HALL

A. Heavy upholstering

Advantages. With heavily upholstered seats the RT (assuming about 2.0 s fully occupied at mid-frequencies) is nearly the same with and without audience—about 0.2 s difference. (With lightly upholstered seats the RT is about 0.6 s higher.). A small difference in RT is an advantage for the musicians because the sound they hear is nearly the same during rehearsals as during concerts. Another advantage is that a listener can choose his/her concert seat at rehearsals. Of course, heavily-upholstered seats can be more comfortable. In small halls, heavily-upholstered seats are an advantage because they prevent the strength of the sound from being too loud.

Disadvantages. Above all, heavily upholstered seats reduce the strength of the sound in the hall. The area per seat in halls with heavily upholstered seats is seen from Table I to be about 0.77 m^2. With medium upholstered seats the area per seat is about 0.70 m^2 and for lightly upholstered seats about 0.68 m^2. As seen in the last column, the average ceiling height for a hall with heavily-upholstered seats must be about 20% higher than that for medium-upholstered seats, and about 40% higher for lightly upholstered seats (for the same number of seats). The visual difference in the ceiling height is a factor in the architectural design. Certainly, the cost of construction of a larger hall resulting from larger heavily upholstered seats and the later operating expenses are greater. Larger seats may also mean a greater distance between the farthest seat and the stage.

B. Light upholstering

Advantages. The higher G for concerts makes the hall excellent for the lighter music of the Baroque and Classical periods, without detracting from the hall's response to music of the Romantic period. With the rear side of the backrest and the arm rests hard, high frequency sounds reflect and this adds to the brilliance of the high tones. With the lower ceiling height the hall may visually be more intimate and the building cost is less.

Disadvantage and a means for overcoming it. The RT increases considerably when the hall is unoccupied compared to occupied, i.e., it is up about 0.6 s (from 2.0 to 2.6 s). This makes the hall with partial occupancy largely unsuited for speech and less desirable for orchestral rehearsals. In a new hall a large area of a heavy curtain could be hung from tracks on either side of the hall located above the top balcony. This curtain would be retracted into pockets on either side and the retraction could be motorized. Another possibility is banners retracted vertically. In a hall with the dimensions of Boston Symphony Hall, 360 m^2 of material could be added, which would reduce the unoccupied RT at mid-frequencies from 2.5 to 2.1 s. This change would make a large difference.

XI. RANGE OF DIMENSIONS AND PROPOSED SEATING CAPACITY

Shoebox-shaped halls. In a shoebox-shaped hall, in accordance with the presentation in this paper if one is to hear successive notes clearly, unmuddled by later lateral reflections, the hall's width should not be greater than about 25 m. To avoid having early lateral reflections arrive too soon and mask the direct sound, its width should be larger than about 15 m. Audiences do not like to be seated too far from the performers. Thus listeners' distances should not exceed about 40 m measured from the edge of the stage. With these restrictions and with seat and row-to-row spacing that are not larger than today's standards, the audience size should be limited to between 2200 and 800 seats. An orchestra in a hall with fewer than 800 seats will be too loud. Obviously, to have RT's and G's more nearly the same, the largest halls would need to have lightly upholstered seats and the smallest halls heavily upholstered seats and thus seat counts would need to be adjusted. As stated earlier, these conclusions relate to symphonic-music halls and not to chamber-music halls (see below).

Surround-shaped halls. Surround-shaped halls have been successful in large part for visual reasons. Definitely, there are seats in front of the orchestra where the quality of the music is often as good as that in a shoebox-shaped hall and music aficionados seek out those locations. The most successful surround halls economically are located in cities like Los Angeles and Berlin, where tourists help keep a hall fully occupied because they go primarily to see the interesting architecture. Surround-shaped halls should not be too long, say, less than about 40 m measured from the edge of the stage. It is difficult to name a maximum width because the reason for locating the seats there is largely visual. In two well-known surround halls with audiences of about 2200, the overall width (wall to wall) is about 40 m. These considerations suggest that a surround-shaped hall can hold larger audiences than a shoebox-shaped one, say up to 3200 seats. In any hall larger than 3200 seats the sound will be weak. It hardly seems that a minimum size can be specified, because if the hall is too small it is not suited for seating around a stage that accommodates a full-sized symphony orchestra.

Fan-shaped halls. A fan-shaped concert hall should be considered for audiences of more than 3200. The Tanglewood Music Shed seating 5000 and with overhead reflecting panels and a high ceiling is a successful venue.

Chamber-music halls. Chamber-music halls differ in that they seat less, are narrower, have smaller performing groups, and lower RTs, hence smaller volumes. Hidaka and Nishihara made measurements in nine well-known European chamber-music halls.[26] The following was found: average number of seats, 480; average width, 13.3 m; average RT at mid-frequencies, occupied, 1.4 s.

Directed sound halls. No attention has been paid in this paper to directed energy halls of which the Town Hall in Christ Church, New Zealand, was best known (destroyed by earthquake). Bradley and Soulodre[27] state the reason: "Prior to this (our) new study, increased spaciousness was generally assumed to require strong early lateral reflections. This has led to the introduction in some newer halls of large reflector panels designed to add strong early lateral reflections. Such reflectors can lead to what has been called "a directed sound hall", where a large portion of early reflected energy is directed onto the audience where it is heavily absorbed/ This leads to sound fields with impulse responses that decay more rapidly initially than later. In these halls, there can be an apparent lack of late arriving or reverberant energy in spite of an adequate RT. Such halls could thus be lacking in both listener envelopment and (strength of) reverberance."

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