CONCERT HALL DESIGN: NEW FINDINGS

L L Beranek 10 Longwood Drive, Westwood, MA 02090

1. INTRODUCTION

Briefly covered is the change in architectural design of concert halls since early in the twentieth century up to the present time. The characteristics of six highly rated concert halls are presented. Audiences are divided on the type of sound field preferred and where to sit in a concert hall. The growth of sound in a concert hall is analyzed with emphasis on hearing the direct sound clearly. The desirability of early lateral reflections and their dependence on hall shape is stressed. The strength (loudness) of the orchestral sound with emphasis on the degree of seat upholstering and the cubic volume are presented. Finally, maximum and minimum dimensions and seating capacities for shoebox-shaped, surround-shaped, and fan-shaped concert halls are proposed.

2. BRIEF HISTORY[1]

The highest rated halls acoustically were built before 1901. They are Grosser Musikvereinssaal in Vienna, Symphony Hall in Boston and Concertgebouw in Amsterdam. All three are 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, and the loudness 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, 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 behind and to the sides of the stage. That hall has been a success even though the orchestral balance differs considerably from one seat location to another both because the sounds of the various instruments are radiated in different directions and because the listeners on the sides are much closer to one part of the orchestra than to others. In front of the orchestra, most surround halls lack the rich sequence of early reflections experienced in rectangular halls. Of the surround halls Berlin Philharmonie is the best. Also, at piano concertos, with the lid up, listeners at the rear of the stage hear only the low tones, which is also true for soprano voices because their high tones are mainly projected forward.

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 (a few well traveled) concert aficionados, in an effort to determine how well-known concert halls rank acoustically. About 80 of the interviews were used to acoustically rank order 58 halls and the results were published in 2003.[2] In 2013, Skålevik published the results of a recent online questionnaire that ranked 77 concert halls according to their acoustical quality. In Table 1 the results of the two studies are combined to obtain a choice of the top ten concert halls. Only if a hall was on both lists is it included.

A listener's rating depends on where he sits. There are large differences between the sound in the balcony(s) and that in the main floor seats. It is possible that the raters in one group were mostly in one location and those in the other group were mostly in the other location.[3] I want to be quick to say that some halls of high quality did not appear in one or the other in our lists. Examples of halls that some say should be included here are, Lucerne Culture and Congress Center, Congress Hall; Manchester Bridgewater Hall; and the Berlin Konzerthaus (Schauspielhaus). The principal purpose of this table is to illustrate the shapes of halls with excellent acoustics.

Table 1. Ten highly-rated concert halls as determined from studies by Beranek and Skålevik.

Ten highly rated concert halls

Only halls are listed that appeared in both studies.
Some halls of equivalent acoustical quality did not appear in either study.

	Beranek Interview Rating	Skålevik Online Rating	Online No. of Raters	Hall Shape
Vienna, Musikvereinssaal	1	1	12	Rect
Boston, Symphony Hall	2	2*(Tie)	10	Rect
Amsterdam Concertgebou	5	2*	14	Rect
Tokyo Opera City	6	4	3	Rect
Vienna, Konzerthaus	9	3	5	Rect
Dallas, Myerson Symphy	11	5	5	Parallel*
Zurich, Tonhallsaal	7	11	4	Rect
Cardiff, St. David's Hall	10	6	5	Sur
Berlin, Philharmonie	16	18	13	Sur
Tokyo, Suntory Hall	17	21	4	Sur

* Main-floor sidewalls parallel

SIX TOP QUALITY HALLS

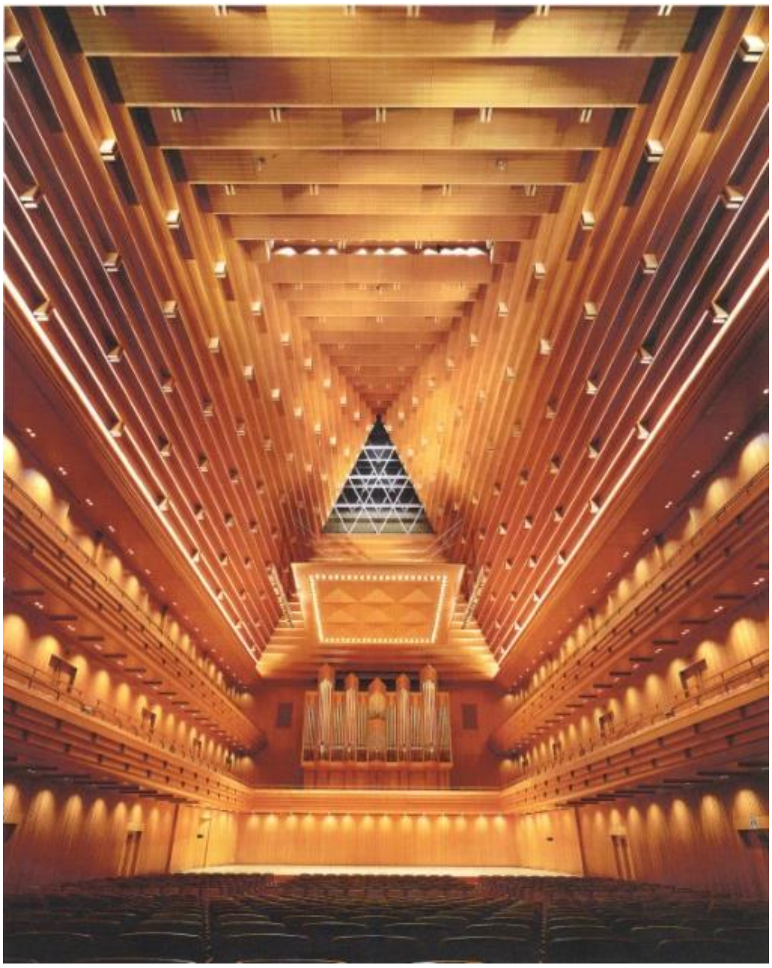
4.1 Vienna, Grosser Musikvereinssaal. (1870) 1,680 Seats.

The Musikvereinssaal is the most famous concert hall in the world because so many European composers have heard their works premiered here, and the music directors for the Vienna Philharmonic, the resident orchestra, have included the celebrated names of the past and present. It is rectangular in shape, like a shoebox, and has one balcony on the sides and two balconies on the rear. Everywhere are gilt, ornamentation, and statues. Except for the doors, the sidewalls and ceiling are either plaster on brick or plaster on wood lathe. The irregularities around the windows diffuse the reverberant sound and give it a beautiful quality. The main floor seating is flat, and a few members of the audience sit at the rear corners of the stage. The reverberation time is 2.0 s at mid-frequencies when the hall is fully occupied. The sound at most seats is clear, loud, and the reverberation is enveloping. Any hall with these characteristics is excellent for music of the Classical and Romantic periods.

4.2 Boston, Symphony Hall. (1900) 2,625 Seats.

Boston Symphony Hall is America's most celebrated hall. It is shoebox in shape. There are two balconies on the sides and rear. The sidewalls beneath the balconies are flat, while those above the balconies are irregular because of niches and statues. The ceiling is coffered. The balcony fronts are largely open grilles. The orchestra sits in a separate stage house. The audience floor is modestly sloped upward from front to rear. The sound is clear, brilliant, and loud, without being overly loud. The reverberation time at mid-frequencies is 1.9 s. The orchestral tone is balanced and the ensemble is excellent, partly because the stage area is small, which means the orchestra is compact. During May, June and December, the sloped floor and seats are replaced by tables for "pops" concerts and the capacity is reduced to 2,369 seats.

4.3 Tokyo Opera City, Concert Hall. (1997) 1,636 Seats.

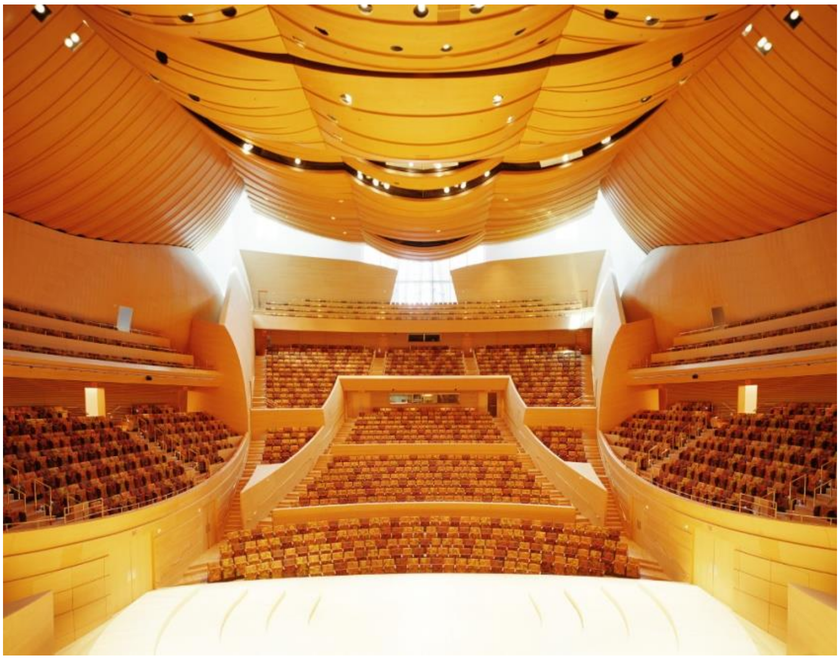


The TOC Concert Hall is basically a shoebox hall with two balconies on the sides and rear and a moderately raked main floor. The unusual feature is the pyramidal ceiling, the peak of which is 28 m above the main floor and is located above the front of the stage. This ceiling does not adversely affect the quality of the reverberation. There is a sound-reflecting canopy over the stage to enable the musicians to hear themselves better and to strengthen the direct sound in the front main-floor seating. The flat smooth sloped ceiling walls have sound diffusing elements on them, which enhance the reverberation. The reverberation time at mid-frequencies, with the hall fully occupied, is 1.96 s. The sound is clear, warm, enveloping, and reverberant, quite similar to that in the Vienna and Boston halls. The sound strength G is about the same as that in Vienna.

4.4 Los Angeles, Walt Disney Concert Hall. (2003) 2,265 Seats.

(Not included in Table 1 because the hall was built after the Beranek interviews.)

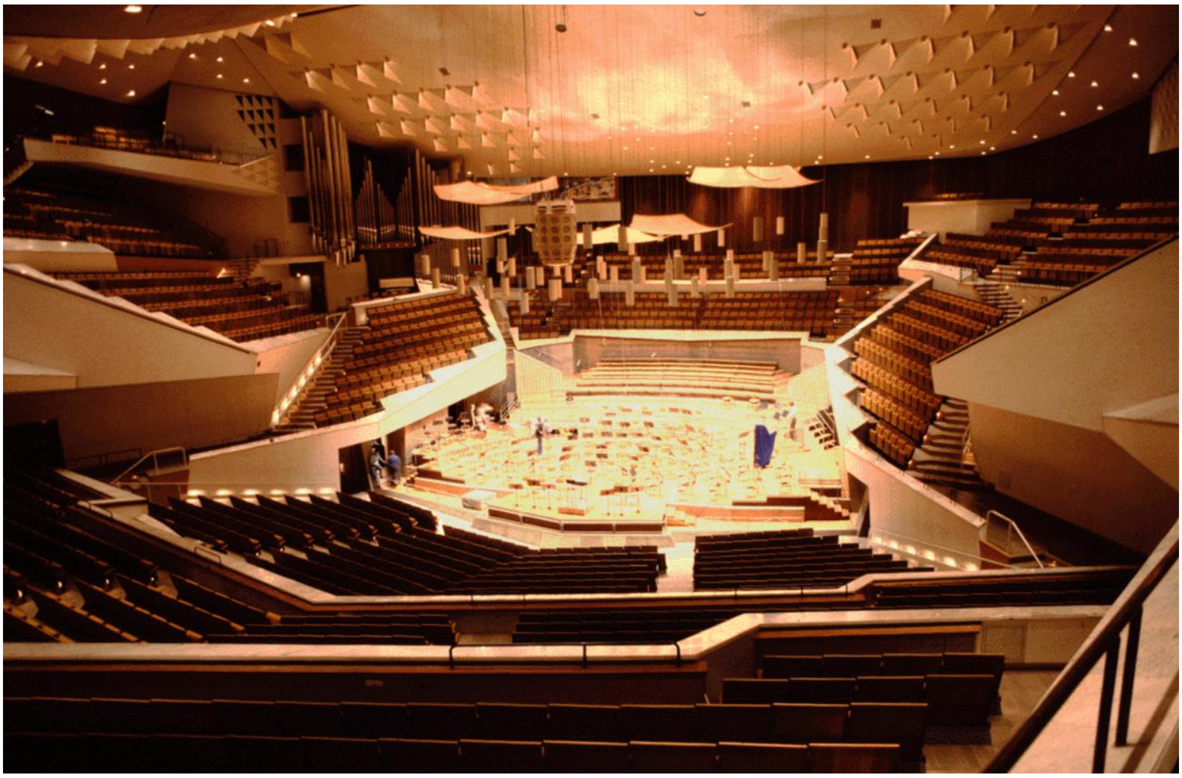
View to the rear. The white at the front is the stage floor



View to the front. The vertical "sticks" are organ pipes.

The Walt Disney Concert Hall was designed by the architect Frank Gehry. It is completely different from the three preceding halls. The lower curved surfaces on the sides extend from the front to the rear of the hall. The downward curved ceiling is like none other. Because the architect would not allow any hanging panels, the ceiling height above the stage floor dips down to 15.5 meters. As the seating area slopes upward between the stage and the rear of the hall, the ceiling also slopes upward. The reverberation time at mid-frequencies (average of 500-1000 Hz), fully occupied is 1.9 s, the same as in the Boston hall. About half of the audience is seated to the sides and rear of the stage. One advantage is that the listeners in the back row of the main floor are closer to the stage than in Boston (35 vs 40 m). Although the interior is wood, the wood is cemented to concrete backing, thus the sound absorption at low frequencies is low. The sound strength (i.e., G in dB) is lower by about 3 dB than in Boston/Amsterdam. This difference is not noticed by listeners, but the sound will not be as dynamic on crescendos. By contrast, in the three shoebox halls, listening is enhanced immeasurably by their louder dynamic response.

4.5 Berlin, Philharmonie Hall. (1963) 2,218 Seats.



The Berlin Philharmonie hall was the first surround hall built after WW-II. Architect Hans Scharoun felt that the normal placement of the orchestra at one end of the hall prevents audience and musicians from communicating freely and intensely. Hence, he proposed to surround the musicians with the audience. The acoustical consultant and, indeed, this author, advised against this departure from the highly successful shoebox shape. However, the famous conductor Herbert von Karajan said the orchestra would not object. That statement overcame the consultants' advice. Over 40 percent of the audience is to the rear and sides of the stage. The audience is broken up into blocks, the fronts of which reflect sound laterally to the audience in the middle of the hall and into the other blocks. These blocks are often called "vineyards." Also, the seats at the rear and in the upper blocks receive an early reflection from the convex, tent-shaped ceiling. Partly because of the beautiful and striking architecture, the hall has been a huge success. In the audience sections in front of he stage, the sound is beautiful, clear, balanced, and with a liveness that completely envelopments one. Those around the stage enjoy watching the facial expressions of the conductor and they say they have a feeling of being part of the performing group. The farthest seats are about 35 m from the front of the stage, compared to 40 m in Boston.

4.6 Paris, Philharmonie de Paris (2015) 2,400 Seats.

View to the front (Architect's drawing)

View to the rear (Architect's drawing)

The Philharmonie de Paris will open January 14, 2015. The distance from the stage to the farthest listener is 33 meters, 2 meters less than in Berlin and Los Angeles. The ceiling is not shaped to provide adequate overhead reflections to the orchestra as in Los Angeles, instead hanging panels (canopy) are provided. The area of the stage is 383 m^2, compared to Boston's 152 m^2 (220 m^2 when extended) and Los Angeles 250 m^2. Owing to the locations and shaping of the fronts of the various seating areas, it is stated that there is an interleaving of lateral and direct sounds that combines the equivalent of those in shoebox halls and other surround halls. The volume is 30,500 m^3 about the same as that in Los Angeles. Because of the heavily upholstered seats, the reverberation time (Avg. 500/100 Hz and hall occupied) is about 2.0 s.

5. Listeners' Preferences

Having become acquainted with some of the world's best concert halls, let us now look at recent acoustical research, in particular, how listeners perceive the sound fields that surround them.

5.1. Perceptional Differences Among Assessors of Concert Hall Acoustics

Lokki[4], in the Media group at Aalto University, Finland, reported the preferences of 17 assessors listening to four recorded excerpts of symphonic music, 2-4 min. each, from different periods and different sized orchestras, located 12 m in front of the orchestra in nine halls.

How was this possible? The researchers created an orchestra of 34 loudspeakers distributed on the stage 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 seeing the conductor on a screen in front of him. The 34 recordings for the individual instruments were connected to the 34 loudspeaker orchestra. The music from the loudspeaker orchestra was played back in each of the 9 halls and in each the sound was recorded on microphones located 12 m in front of the loudspeakers. This recorded music was taken back 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 nine halls and produced reasons for their preferences. They fell into two groups. The first group stated that they preferred a hall with high definition and clarity along with adequate loudness and bass. The second group preferred a louder and more reverberant sound with good 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. There, 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 are also divided into two groups, 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 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, without reflections that mask the early sound, and with reverberation that is beautiful. In the rear second balcony the reverberation almost immediately follows the arrival of the direct sound and it is loud and completely enveloping. One only has to ask anyone who has subscription seats in the upper balcony to say which is better and they respond vigorously that they like the sound there far better than that on the main floor. The author of this paper, who likes more clarity to the sound, identifies with the first group which prefers the main floor or the front half of the first balcony.

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

6. CLARITY OF THE SOUND IN A SHOEBOX 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 2/3 the distance from the stage to the main-floor rear wall, i.e., 26 m from the stage, the rise in the energy density following the arrival of the first seven strongest reflections at a central seat is shown by the stepped heavy line in Fig. 1. The zero point on the bottom scale is the time at which the direct sound arrives. The vertical axis is the total energy density in dB. The direct sound of a played note will probably continue throughout the 70 ms span that follows. The dashed curve D(t) shows the rise in energy density that would occur if the equivalent energy were to be fed gradually into the hall instead of arriving in separated reflections.

The first reflection 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 that they mask a person's ability to hear the direct sound clearly[5]. 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, and the listener tends to go to sleep. This identifies Griesinger with the first group of the previous section.

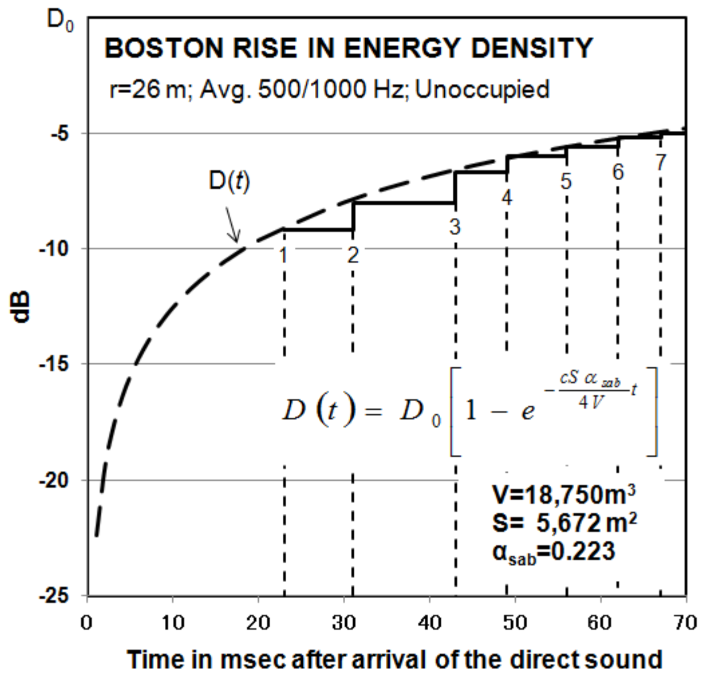


Fig. 1. Rise in energy density at a seat 26 m from the source (located on the stage in Boston Symphony Hall) owing to the first seven major reflections (unoccupied hall and at mid frequencies).

It seems obvious from Fig.1 that before the first reflection there is time during which one can hear the direct sound. The arrivals of the lateral reflections depend on the width of the hall, i.e., the narrower the hall the sooner they arrive. When the listener moves sideways from the center of the hall to a position near a sidewall, the direct sound and the first reflection from that wall arrive at nearly the same time and the reflection from the opposite side wall comes at a later time. This creates a larger space between the now-direct and the new first reflection for hearing the direct sound. At a position in-between, the sidewall reflection comes in so soon that due to the precedence effect it merges with the direct sound. At locations farther back in the hall the time between the direct and the first reflection becomes short and the reverberant sound predominates. Some suggest that, owing to the precedence effect, the first reflection of Fig.1 should merge with the direct sound. But, a listener only needs to sit at this seat to clearly hear the sidewall reflection separate from 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 than the 1.9 sec (occupied) for the Boston Hall. The crosshatched 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 1.9 sec (zero dB on the ordinate). It appears that Griesinger says that below -20 dB the direct sound 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. In any event, I am using that interpretation.

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 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.” Thus, in Fig. 2, the direct sound is 0.5 dB above the reverberant sound.

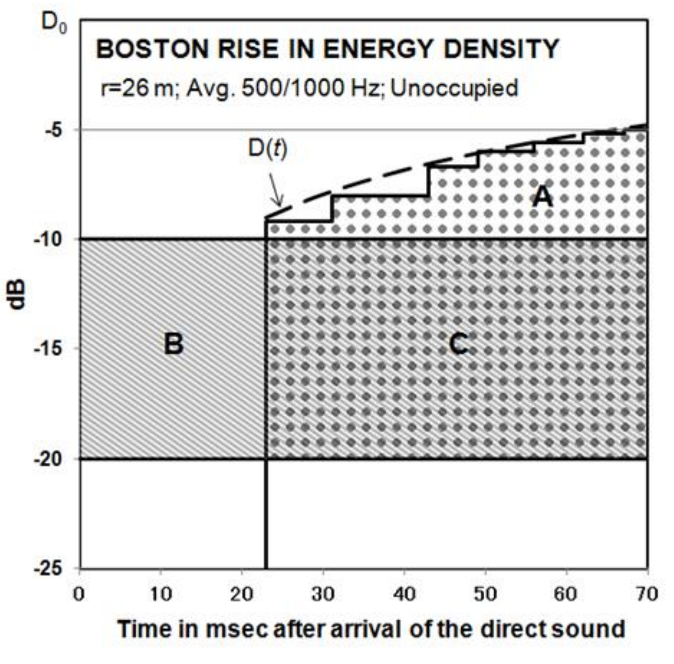


Fig. 2. Presentation of the early reflection sound field in Boston Symphony Hall in approximate conformance with Griesinger’s theory about hearing the direct sound clearly

Figure 2 is for a position a little off the centerline and at r = 26 m. If the listener moves laterally to a side wall, the first reflection vanishes and the second (now-first) reflection arrives at 45 ms from the opposite wall. Thus, the ratio (B +C) to (A + C) becomes larger. At a position half-way between the center line and the wall, the first reflection arrives at 11 ms and the second at 39 ms. Owing to the precedence effect, the first reflection will join with the direct sound and the clarity of the direct sound will also be assured[a].

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).

Acousticians often 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 80 ms after arrival of the direct sound. Room Presence deals with the reverberant sound field that follows.[6]

Haapaniemi and Lokki 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 eight well known halls would be identified better by source presence than by room presence.[7] Source presence is dealt with in the next section.

7. SHOEBOX SHAPED HALLS ENHANCE MUSICAL DYNAMICS

From the Finland group, Pätynen *et al* [8]demonstrate that when an orchestra plays fortissimo the frequency spectrum changes. They made measurements of the spectra of orchestral sounds from 20 publically-released recordings of Bruckner Symphony No. 4, third-movement, bars 19-26, during which segment the orchestra dynamics increases from pianissimo (*pp*) to fortissimo (*ff*). It was found that between 400 and 2,000 Hz the spectrum for the (*ff*) sound is about 7 decibels more intense than that for the (*pp*) sound and that between 2,000 and 8000 Hz the increase is more than 15 dB. (See upper curve in Fig. 3).

---

[a] Colin Gough, "Another important time-domain phenomenon in the perception of musical sounds is the precedence effect, which enables a listener to locate the source of a distant sound…Any [second] sound arriving in the first ms span simply adds to the perceived intensity of the first sound. This is very important in musical performance, with reflections from close reflecting surfaces adding strongly to the intensity and definition of the music." Part E "Musical Acoustics" in T. D. Rossing, *Handbook of Acoustics*, (Springer 2007).

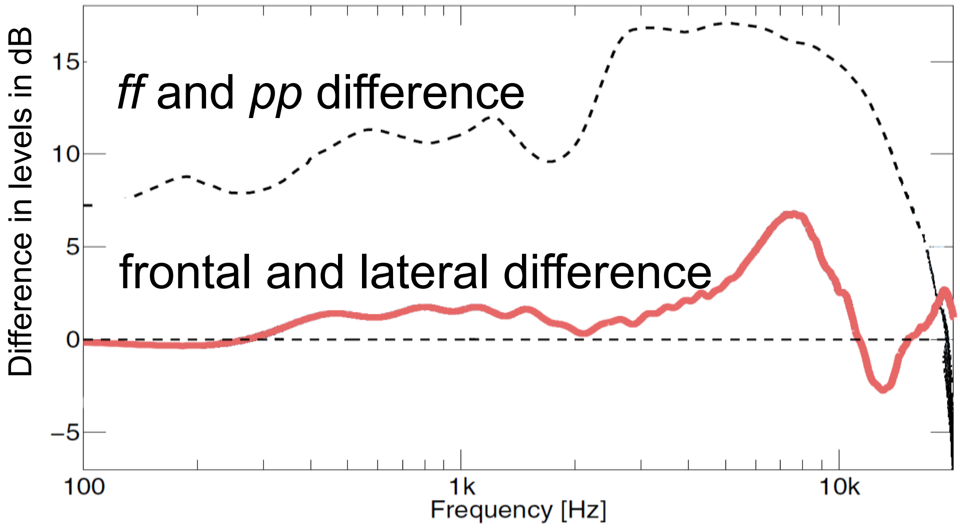


Fig. 3. Curves showing: (upper) difference in sound level between full symphony orchestra playing at *ff* and *pp* levels; (lower) difference between sound levels at the ears of a listener with sound coming from frontal direction and laterally from sidewall reflections (Courtesy T. Lokki).

Now another factor.

Because of the size of the head, when the sound arrives from a lateral direction, sideways, the intensity at the closest ear of a listener, in the 2,000 to 8,000 Hz region, is 1 to 5 dB greater than that when the sound arrives 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 2,000 and 8,000 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" above. This is another reason why the shoebox shape is the best for a concert hall.

8. EARLY LATERAL REFLECTIONS

It is almost universally agreed that properly-delayed early lateral reflections add to the quality of sound in a concert hall. Marshall[9] was the first to recognize their importance and he and Barron[10] 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 determines a quantity called lateral fraction (LF).

The acoustical quality in a hall is better if a significant number of early lateral reflections occur before about 80 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 fronts of these blocks are reflecting surfaces that send lateral reflections outward. This means that any one block may experience lateral reflections arriving from other blocks, although this is not true at all blocks. 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 direct sound muddled. One example that the author experienced recently was in a well-known hall with parallel side walls and a width of 34 meters. At a seat back 14 meters 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 direct sound, producing a clear double image. The time difference was 110 msec. Also a parallel-sided concert hall that is too narrow is a problem because the first reflection arrives too soon and is very loud, so that the direct sound is unclear[b].

In another paper, Lokki, discusses the shoebox vs. surround shape further.[11] 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. These halls also have a near-flat floor on the audience area enabling nice enveloping reverberation. If the audience area is strongly inclined, the seats behind block the enveloping reverberation from those in front. Also, as an example of bad reflections, in the Berlin Philharmonie a number of seats receive quite late side reflections that might be perceived as echoes.

Kahle Acoustics presents a method for calculating the strength of the early lateral reflection energy that reaches the audience area from reflecting surfaces.[12] The procedure assumes that the reflecting surfaces will be flat, non-diffusing and non-absorbent. The symbols are shown in Fig. 4.

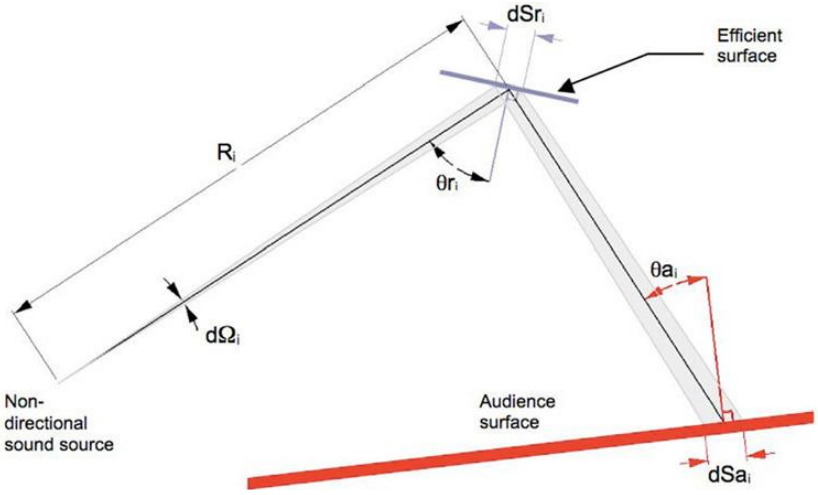


Fig.4. Means for calculating G contributed by flat reflecting surfaces in a concert hall.

The sound strength G (which is not equal in magnitude to that obtained with a dodecahedral loudspeaker)

$$G = 20 + 10 \log(\Omega_{eff}) - 10 \log(\cos \Theta_m) - 10 \log (S_{aud}) \quad \text{dB}$$

where, Θ_m = average angle of reflections on the audience surface

S_{aud} = area of audience, m

[b] Typical chamber music halls are different. The audience is near the performers so that the direct sound is louder, the performing group is smaller, and the reverberation time is much shorter than in the concert halls of Section 4.

Ωeff is the solid angle of all reflective surfaces measured from a non-directive sound source, determined as follows,

Let, $d\Omega i = dS_{ri}\cos(\theta_{ri})/R_i^2$

then , $\Omega_{eff} = \sum \frac{d\Omega i}{\cos\Theta ai}$

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. The Kahle paper presents a successful application to a 2750 seat hall in which a number of large, flat surfaces are incorporated, mainly on the side walls and balcony fronts, that reflect the early sound to the audience areas.

9. Acoustical Quality and Hall Shape

Hidaka has presented data that relate the shape of a concert hall to its acoustical quality.[13] Two measurements are involved. First, in the distance between 10 and 40 m from the source on stage, he finds that the sound strength G in the 125/250 Hz bands, with halls unoccupied, falls off about 2 decibels in classical shoebox halls, and about 4 decibels in surround halls. In the 500/1000 Hz bands, the levels decrease about 3 decibels in the shoebox and 5 decibels in the surround halls.

Next, Hidaka uses the rise in sound strength G with time to determine the total energy contributed by early reflections. The plotted quantity is "reflected energy cumulative curve RECC," defined,

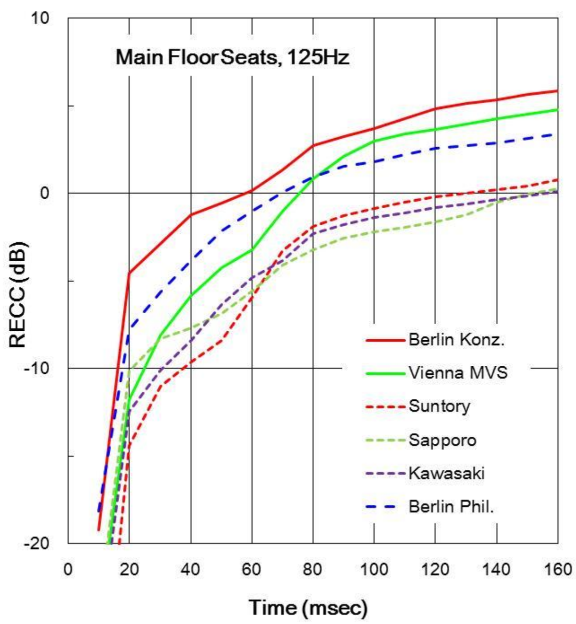


Fig. 5. $RECC_{E, low}$ averaged over main floor seats at 125 Hz for six concert halls.

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

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

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 the measurements an omni-directional source was placed 3 m from the stage lip at the center of the stage.

For six concert halls, plots of RECC as a function of time after arrival of the direct sound is given in Fig. 5 for the frequency 125 Hz. The value of RECC at 160 ms is a measure of the cumulative energy that is due to early reflections. It is interesting that the RECC for the Berlin Philharmonie hall is high which indicates significant strength from early reflections—which is not true for many other surround halls.

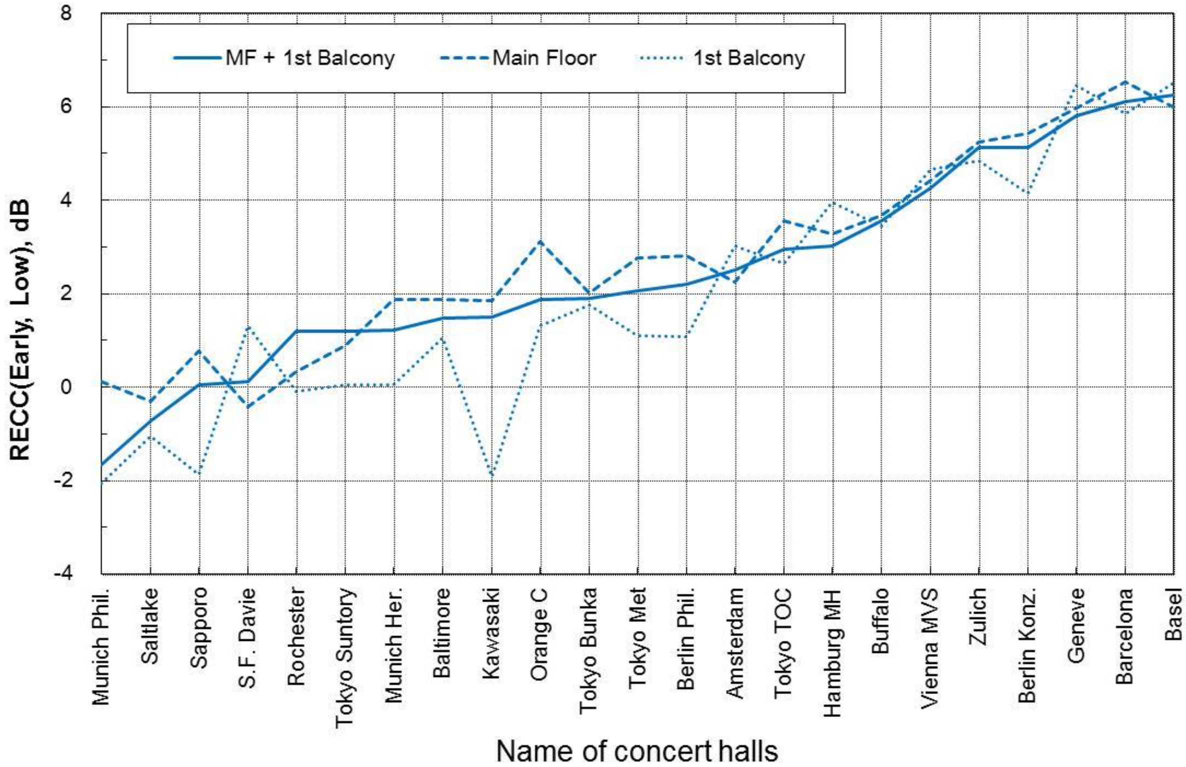


Fig. 6. A plot of $RECC_{E,\ low}$ for main floor, first balcony and main floor plus first balcony of 23 concert halls.

Hidaka postulates that $RECC_{E,\ Low}$ should be considered as an additional major independent parameter for measuring acoustical quality in concert halls, where "Low" indicates the average of the levels in the 125/250 Hz bands and "E" indicates the time span between 0 and 160 ms after arrival of the direct sound. The time 160 ms was determined by Soulodre *et al.*[14], as the separation time between ASW (apparent source width) and LEV (listener envelopment) at low frequencies. (80ms is the separation time at 500/1000 Hz.) The lower frequency, 125 Hz, is selected because more attention to low frequencies in concert hall design is needed

As expected, Fig. 5 shows that 9 out of top 10 halls (Amsterdam and higher) are shoebox, and that there are small differences between $RECC_E$ measured at the main floor and at balcony seats.. The surround halls have lower values except for Berlin Philharmonie. The Munich Philharmonie Hall at the left end is fan shaped and has the largest capacity and volume in this list. The balconies of the Kawasaki and Sapporo have the smallest value. In these two, the ratios of the main floor vs. total seating number are respectively 54.7 and 37.5 %, which might be a reason why there is a spread in judgments of acoustical quality for these halls among concert goers.

10. SEAT UPHOLSTERING

Let us go to Table 2. The degree of seat upholstering shown in that table was largely determined by the change in reverberation time when the seating area becomes occupied. The RT in all halls was about 2.0 sec when fully occupied. A change in RT of only 0.2 s after occupancy was associated with heavy upholstering. A change of 0.8 s was associated with light upholstering. Hence, medium upholstering was associated with a change of about 0.4 s. Of course, the difference in degree of upholstering can also be observed by visiting the hall. It can readily be observed during a visit that the seat upholstering is very light in the halls at the bottom of Table 2 and is heavy in the group at the top.

Table 2. Physical dimensions of groups of concert halls with heavily-upholstered, medium-upholstered and lightly- upholstered seats.1 All halls have an occupied reverberation time at mid-frequencies of about 2.0 s. The three groupings are based entirely on the difference between the reverberation times before and after the seats are occupied (see 2nd column). The upholstering can be (or not be) on front and back of the backrest, top and bottom of the seat bottom and top of and beneath the arm rests. It can vary in thickness and on the type of cloth or leather covering. A porous cloth that has been back sprayed so that it is non-porous also makes a significant difference.

Concert Hall	Type	RT Change s	V over total hall srea 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
		Average	3.55	0.77	14.3	18.5
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
Cardiff, St. David's	SUR	0.2	3.52	0.73	11.3	15.5
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
		Average	3.52	0.7	10.6	15.2
		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	0.67	9	13.3
		Ratio	1	1.2	1.6	1.4

From Table 2 we observe the following:

Hall volume over total hall surface area (V/S_{tot}): This ratio is nearly independent of size of hall, number of seats and hall shape. This is a well known fact because the mean-free-path between successive reflections in nearly all halls is known to be **$4V/S_{tot}$.**

Surface area under each seat (S_T/N): The average heavily upholstered seat in Table 2 covers a floor area of 0.77 sq.m. while the medium-upholstered seat covers an area of 0.70 sq.m. and the lightly-upholstered seat an area of 0.66 sq.m.

The hall Volume per seat (V/N): To obtain the desired 2.0 s reverberation time, the volume per seat for halls with heavily upholstered seats is about 1.3 times that for halls with medium-upholstered ones, and 1.6 times for halls with lightly-upholstered ones, both because the seats are larger and because they absorb more sound.

Average ceiling height: The average ceiling height in the group is equal to its 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. This ratio is shown in the last column of Table 2. In halls with heavily upholstered seats, the height is 20 percent greater than with medium upholstered seats and 40 percent 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 percent of the main floor 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.

11. SOUND STRENGTH G IN DECIBELS[15]

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 decibels is equivalent to doubling the size of the orchestra. Available measured values of G in halls where heavily, medium and lightly upholstered seats are known are shown in Table 3. The average strength G is about 1.0 decibel lower in halls with heavily upholstered seats as compared to those with medium upholstered seats. The difference comparing with lightly upholstered halls is about 2.4 dB. This difference in sound strength is most noticeable during loud crescendos.

Table 3. Sound strength G in decibels for halls with three upholsterings

Concert Hall	Type	G_{mid} Unoccup
Heavily Upholstered Seats		
Belfast, Waterfront Hall	(SUR)	3.7
Sapporo, Kitara Hall	(SUR)	3.2
Los angeles, Disney Hall	(SUJR)	3.0
Cardiff, St, David's	(SUR)	3.6
	Average	3.4
Medium Upholstered Seats		
Tokyo, Met Arts Space	(FAN)	4.2
Munich, am Gasteig	(FAN)	3.3
Vienna, Konzerthaus	(SHO)	5.0
Baltimore, Meyerhof Hall	(OVAL)	4.7
Berlin, Philharmonie	(SUR)	4.9
Manchester, Bridgewater	(SUR)	4.4
	Average	4.4
Lightly Upholstered Seats		
Vienna, Musikvereinssaal	(SHO)	7.8*
Amsterdam, Concertgebouw	(SHO)	6.4
Tokyo, Opera City	(ODD)	6.2
Boston, Symphony Hall	(SHO)	5.4
Tokyo, Suntory	(SUR)	5.0
.	Average	5.8
*Not in avg., some seats are bare		
London, Royal Festival, Before Renov.	(SHO)	-1.4

12. CHOOSING HEAVILY UPHOLSTERED SEATS IN A HALL

Advantages: With heavily upholstered seats the reverberation time 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 0.8 s higher.) A small difference in RT is an advantage for the musicians as the sound they hear is nearly the same during rehearsals as during concerts. Another advantage is that a listener can choose his/her concert seats at rehearsals. Of course, heavily-upholstered seats can be more comfortable. In small halls, heavily-upholstered seats prevent the strength of the sound from being too loud.

Disadvantages: The area per seat in halls with heavily upholstered seats is seen from Table 1 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 0.66 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 is greater.

13. CHOOSING LIGHTLY UPHOLSTERED SEATS IN A HALL

Advantages: The higher G for concerts makes the hall excellent for the lighter music of the Baroque and Classical periods, without detracting from the halls 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 cost is less.

Disadvantages: The reverberation time increases considerably when the hall is unoccupied compared to occupied, i.e., it is up about 0.8 sec (from 2.0 to 2.8 sec). Of course, lightly upholstered seats may be less comfortable.

14. RANGE OF DIMENSIONS AND PROPOSED SEATING CAPACITY

Shoebox-shaped Halls: In a shoebox-shaped hall, in accordance with the presentation above, if one is to hear successive notes clearly, un-muddled by late 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.

Surround-shaped Halls: Surround-shaped halls have been successful in 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 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 successful 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 larger hall the sound will be weaker. It hardly seems that a minimum size can be specified, because if the hall is too small it is not suited for seating around the stage for a full-sized symphony orchestra.

Fan-shaped halls: A fan-shaped concert hall should be considered for audiences less than 800 and more than 3200. The Tanglewood Music Shed seating 5000, and with overhead reflecting panels and a high ceiling, is a successful venue. With a small audience in a fan-shaped hall there are no lateral reflections to mask the direct sound and to add to the loudness, and this makes it better acoustically than a small shoebox-shaped hall.

Finally, there are many chamber music halls that are rectangular in shape, but in them the stages are smaller, the audiences are less, and the reverberation times are lower than in halls for symphonic music.

15. ACKNOWLEDGMENTS

The author wishes to thank Noriko Nishihara for her help in assembling the data for this paper and making the illustrations. Particular thanks are due Rob Harris and Anders Gade who made many suggestions during preparation of this paper. The measurements used were mainly obtained by the Takenaka R and D group in Chiba, Japan, under the direction of Takayuki Hidaka. Data and the dimensions of several of the surround-shaped halls were kindly supplied by Yasuhisa Toyota and Kayo Kallas of Nagata Acoustics in Los Angeles and in Tokyo Japan.

[1]Beranek, L., *Concert Halls and Opera Houses*: *Music, Acoustics and Architecture,* (Springer, New York, 2004).
[2] Beranek, L. "Subjective rank-orderings and acoustical measurements for fifty-eight concert halls," Acta Acustica united with Acustica, **89**, 494-508 (2003).
[3]Beranek, L., *Concert Halls and Opera Houses*: *Music, Acoustics and Architecture,* (Springer, New York, 2004) , pp. 111,112.
[4]Lokki, T., "Tasting music like wine. Sensory evaluation of concert halls," Physics Today, **69, 27-32 (Jan. 2014).**
[5] Griesinger, D., "What is clarity and how can it be measured," ICA 2013 Congress, Montreal, June 6-7.
[6] Kahle, E.," Room acoustical quality of concert halls," Building Acoustics, **20,** 265-282 (2013).
[7] Haapaniemi, A. and Lokki, T., "Identifying concert halls from source presence vs room presence," Jour. Acous. Soc. Am., **135**, EL311-EL317 (2014).
[8] Patynen, J., Tervo, S., Robinson, P. W., and Lokki, T. , "Concert halls with strong lateral reflections enhance musical dynamics," Proc. Natl. Acad. Scs., **111**, 4409-4414 (2014).
[9] Marshall, A. H., "Acoustical determinants for the architectural design of concert halls," Arch. Scio. Rev. Australia **11**, 81-87 (1968).
[10] Marshall, A. H. and Barron, M.. "Spatial responsiveness in concert halls and the origins of spatial impression," Applied Acoustics, **62**, 91-108 (2001).
[11] Lokke, T. "Throw away the [International acoustics] standard: your two ears work better," International Symposium on Room Acoustics, Toronto, Canada, (June 10, 2013)
[12] Jurkiewiczm, Y., Wulfrank, T., and Kahle, E., "How far should the geometry of a concert hall be optimized?, International Symposium on Room Acoustics, Toronto, Canada, (June 10, 2013); and "Architectural shape and early acoustic efficiency in concert halls (Letter), J. Acous. Soc. Am. **132**, 1253-1256 (2012).
[13] Hidaka, T., "A comparison of acoustical quality in concert halls as relate to hall shapes, 168th Meeting of the Acoustical Society of America, Indianapolis, Indiana, October 27-31 (2014)
[14] Soulodre, G. A., "The influenceof low-frequency energy on listener envelopment," J. Acoust. Soc. Am. **117,** 2491 (2005).
[15] Beranek, L., *Concert Halls and Opera Houses*: *Music, Acoustics and Architecture,* (Springer, New York, 2004). pp. 634-637. "Calibration of the dodecahedral sound source." All G data in this paper are for calibration by 'Reverberation Chamber Method,' as compared to extrapolation from a single position measurement of sound pr4essure level at 1 m from the acoustical center of the source. Values of G by the reverberation chamber method are about 1.2 dB higher than those by the other method. It has been shown that the reverberation chamber method yields the correct results. [See Beranek, L., "The correct method for calibrating dodecahedral sound sources," J. Acoust. Soc. Am. **135,** 223-230 (2014).]