ASPECTS OF CONCERT HALL ACOUSTICS

RICHARD C. HEYSER MEMORIAL LECTURE

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This paper starts with rank-ordering of halls into categories of acoustical quality

Then it treats the important acoustical parameters: Sound energy density buildup----reverberation time, T_{60}----early sound, including ITDG----apparent source width, ASW----listener envelopment, LEV----sound strength, G----Stage factors and various subjective considerations

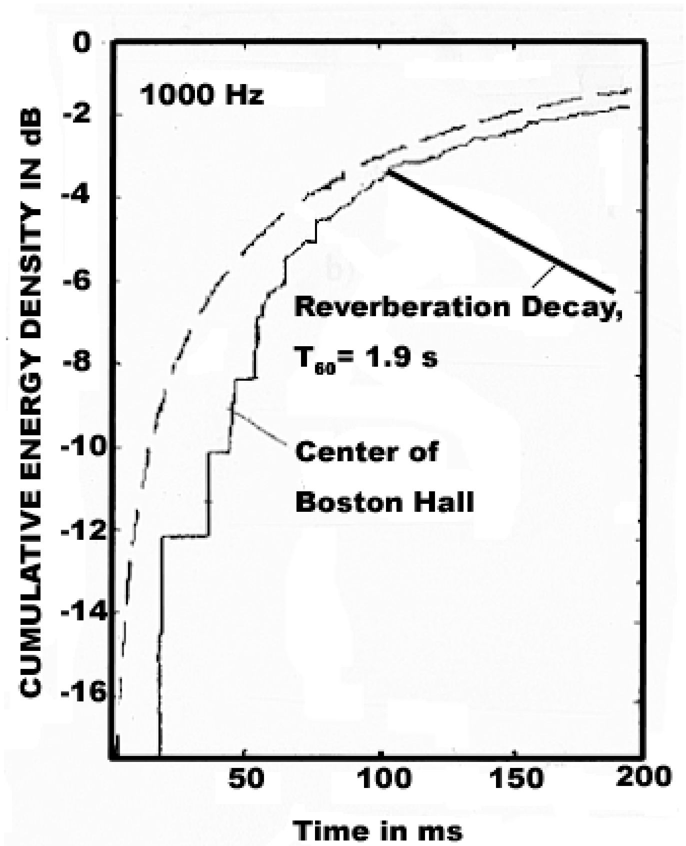
It next compares a hall of different architectural design with a hall highly acclaimed shoebox-shaped hall

and

Concludes with a new calculation that correlates highly with subjective LEV

In my 2004 book, sixty concert halls have been divided into three categories according to subjective ratings by conductors and music critics. Examples are:

		$T_{60(occup)}$	G_{mid} (dB)
Category One:	**Vienna, Grosser Musikvereinssaal**	**2.0**	**6.5**
	Boston, Symphony Hall	**1.9**	**4.2**
	Tokyo Opera City (TOC) Concert Hall	**1.95**	**5.0**
	New York, Carnegie Hall	**1.8**	**-**
	Cardiff, Wales, St. David's Hall	**1.95**	**3.2**
Category Two:	**Cleveland, Severance Hall**	**1.6**	**3.5**
	Los Angeles, Disney Hall	**1.85**	**-**
	Munich, Philharmonie Am Gasteig	**1.8**	**1.9**
	Washington, D.C., JFK Concert Hall	**1.7**	**2.5**
Category Three:	**The rankings and the acoustical data here precede renovations.**		
	London, Royal Festival Hall	**1.45**	**1.9**
	Paris, Salle Pleyel	**1.5**	**3.9**
	Montreal, Salle Wilfrid-Pelletier Hall	**1.65**	**0.1**
	San Francisco, Davies Hall (bass and stage)	**1.85**	**2.2**
	Buffalo, Kleinhans Music Hall	**1.5**	**2.7**



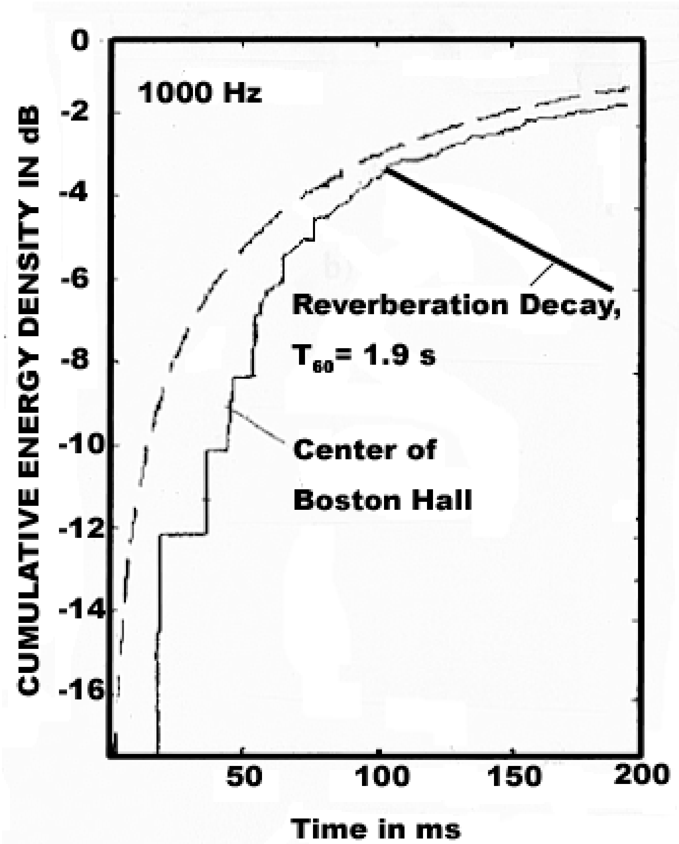
Assume that a violin plays a note 100 ms long with energy in the 1000 Hz band. At a seat in the center of the Boston Hall the cumulative energy will rise as shown by the irregular curve. At 100 ms, the energy will start to decay.

If a second note is sounded at just after 100 ms, at its peak energy it will be heard easily above the previous reverberation. But simply hearing each note is not the only measure of the acoustical quality.

First, the reverberation time T_{60} must go with the music to be performed in the Hall. An RT of 1.9 seconds goes with today's symphonic music repertoire.

Second, the initial-time-delay gap ITDG is important, the time at which the first reflection is heard after the direct sound. For Boston, the ITDG is about 15 ms, and this is about optimum. If greater than about 35 ms, the hall will sound like an arena, with a lack of intimacy. Thus hall size is audible.

Third, there is the law of the first wave front: Before about 100 ms, the azimuth location of the source is possible as heard from the first wave front and this is an important contributor to sound quality.



Fourth, during this 100 ms period, the sound is also broadened—called the apparent source width ASW. The ASW depends on the proportion of the early energy that arrives at the listener <u>laterally</u> and is measured by the Inter-Aural Cross-Correlation Coefficient IACC (microphones at two ears) or the Lateral Fraction function LF (figure-8 microphone). Boston Symphony Hall ranks with the best.

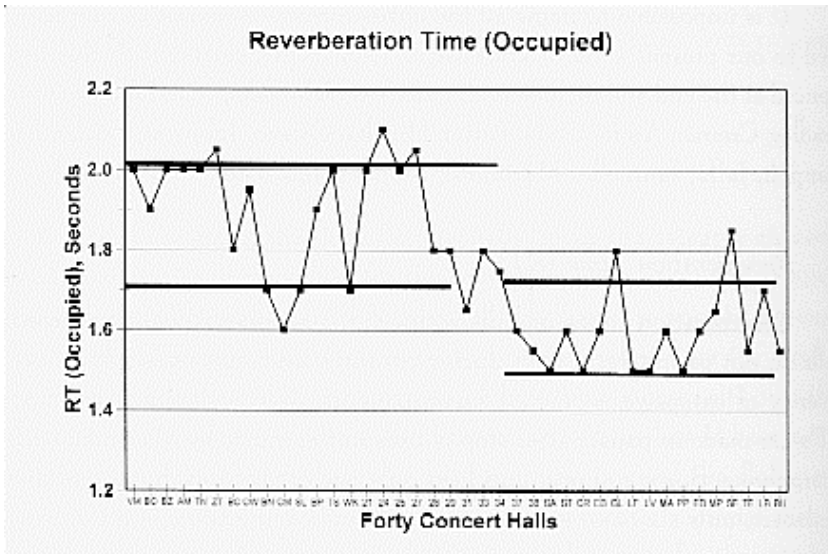
Fifth, after about 100 ms, the listener is enveloped in the sound. Its measurement, LEV, must be large enough for good sound quality. Note that when LEV is achieved, the lateral direction of the source can no longer be observed.

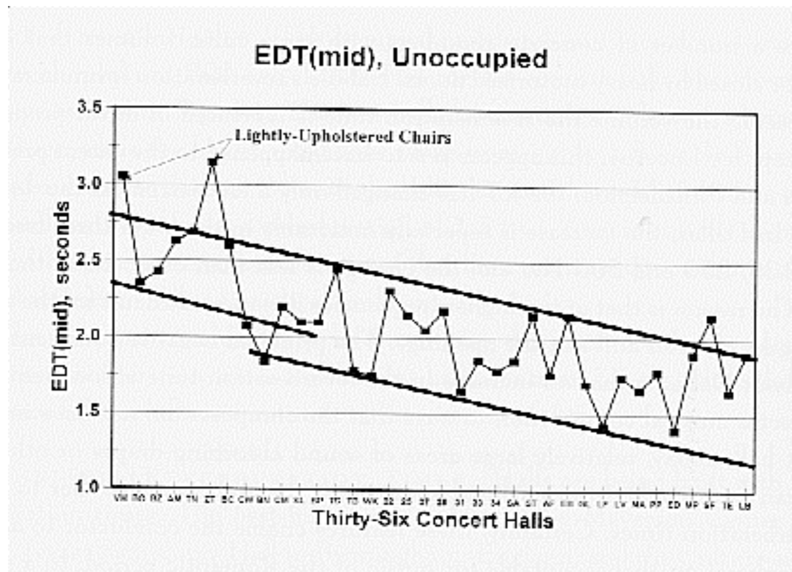
Sixth, Griesinger says that for best sound quality, the energy in the direct sound at the listener's position should be no weaker than about -10 dB below the ultimate level as shown on the above curve. This -10 dB goal holds in Boston for 2/3 of the audience. But, the ITDG is shorter in the balconies and the energy of the earliest reflections directly adds to the energy of the direct sound, hence the remaining 1/3 of the audience is still well served.

Seventh, Texture, which is the number and distribution of early reflections that occur before about 100 ms, is an important factor in acoustical quality.

These are the critical factors for judging acoustical quality of a concert hall, at least as they are known today. Let us see how they apply to halls for which data are available:

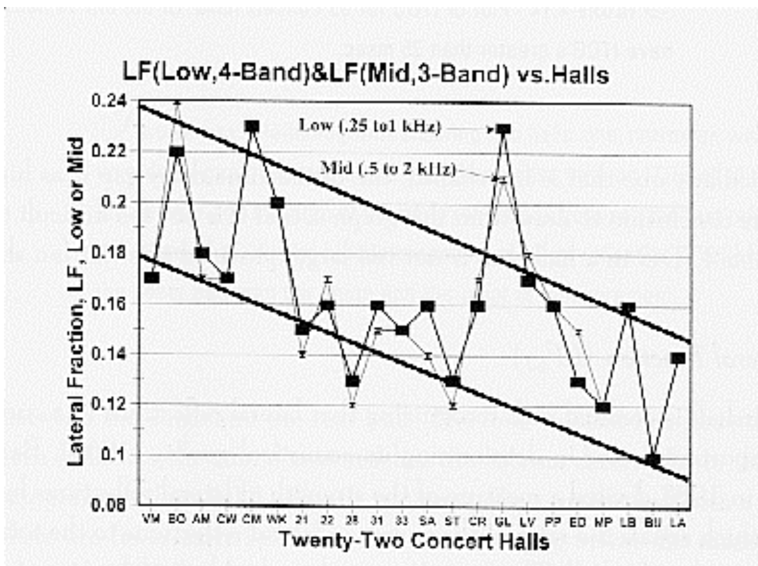
Below, the left graph shows that when occupied reverberation time is plotted against the ranking of the halls according to subjective ratings of acoustical quality, two groupings are found: The best and better halls have occupied reverberation times between 1.7 and 2.0 sec, while those of lower subjective quality have times between 1.5 and 1.7 sec.

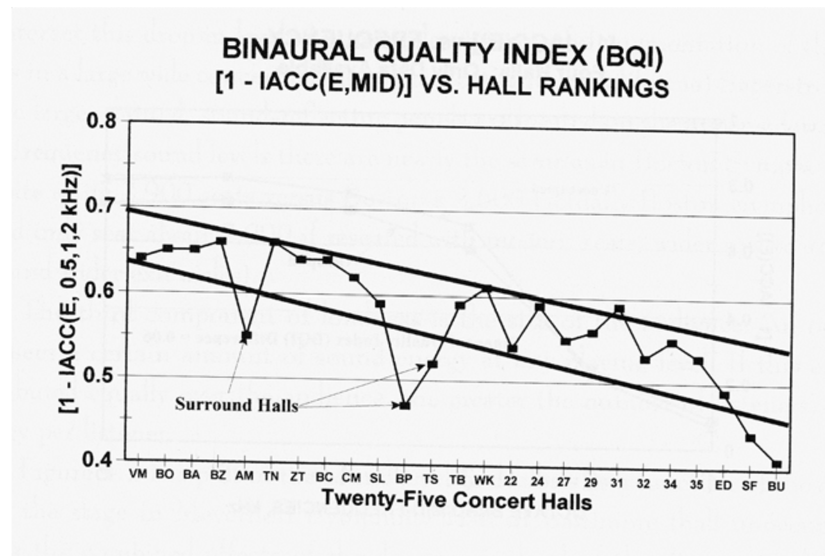




The right hand graph gives the early decay time EDT plotted against the rank ordering of the halls according to acoustical quality. For judging acoustical quality, it appears that the early decay time, EDT (measured with hall unoccupied) is a better measure than reverberation time. Part of the variation in location of points on the EDT graph is due to different degrees of chair sound absorption.

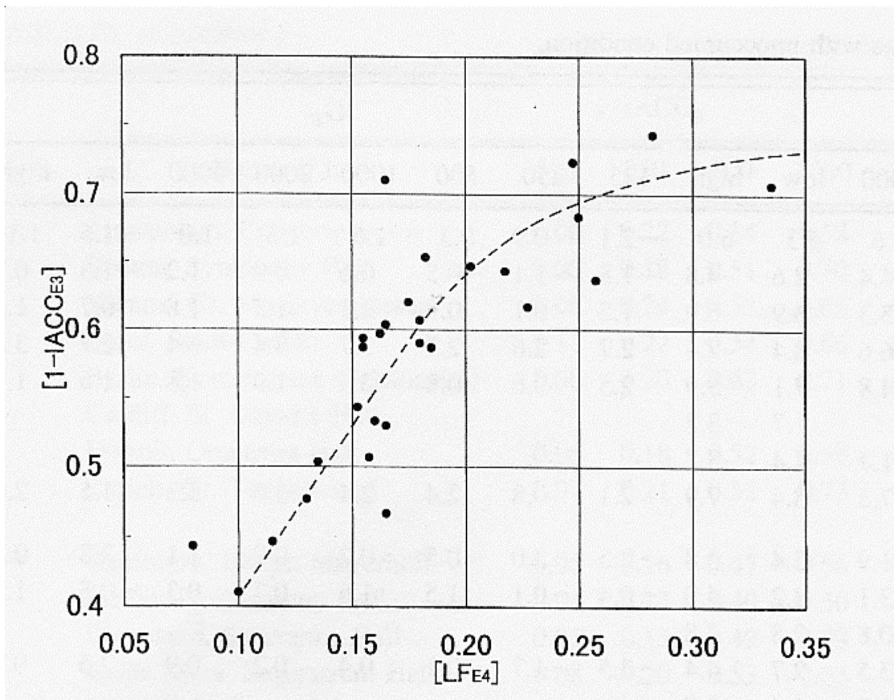
The graph on the left below plots Lateral Fraction, LF_{E4} versus subjective concert hall ratings. Lateral fraction is the ratio of the energy measured with a figure-eight microphone to that measured by a unidirectional microphone. The “E” stands for integration before 80 ms and the “4” means the average of the levels in the four octave bands from 125 to 1000 Hz. Also is plotted (crosses and dotted lines) the LF_{E3} where the “3”means the average of the levels in the three octave bands 500, 1000 and 2000 Hz. The low-bands LF_{E4} and mid-bands LF_{E3} curves are almost identical—this fact is used later.





The graph on the right shows the Binaural Quality Index = $[1 - IACC_{E3}]$ values plotted against the subjective ratings.

This graph is a plot of the data from the graphs on the previous page, i.e., BQI = [1 – $IACC_{E3}$] versus LF_{E4}, showing that for the 28 halls for which data for both are available the two parameters are highly correlated. Part of the scatter is due to the large differences in times in which the data were taken and the fact that a number of laboratories were involved in taking the data.



Important use of this correlation will be made later in this paper.

SABINE AND EYRING EQUATIONS

If we use the Sabine and Eyring equations to predict the same reverberation time

$$\frac{0.161\ V}{S_{tot}\ \alpha_{sab} + 4mV} = T_{60} = \frac{0.161\ V}{S_{tot}\ \{-2.3 \log (1 - \alpha_{ey})\} + 4mV}$$

Then,

$$\alpha_{sab} = -2.3 \log (1 - \alpha_{ey})$$

This means that if α_{sab} is known, α_{ey} is automatically known.

So, $(\alpha_{ey} / \alpha_{sab})$ is known.

Let us designate the audience area, S_T, other not-highly absorbing surfaces, S_R, and any highly absorbing surfaces, $\sum S_i$. Then, give them the Sabine sound absorption coefficients α_T, α_R and α_i, respectively, and the Eyring absorption coefficients $\acute{\alpha}_T$, $\acute{\alpha}_R$ and $\acute{\alpha}_i$, respectively. For both equations, the total hall area is: $S_{tot} = S_T + S_R + \Sigma S_i$. Then, it can be shown,

$$\acute{\alpha}_T = (\alpha_{ey}/\alpha_{sab})\ \alpha_T$$
$$\acute{\alpha}_R = (\alpha_{ey}/\alpha_{sab})\ \alpha_R$$
$$\Sigma\acute{\alpha}_i = (\alpha_{ey}/\alpha_{sab})\ \Sigma\alpha_i$$

What does it mean to say that both equations predict the same T_{60}? Consider T_{60} = 0 first.

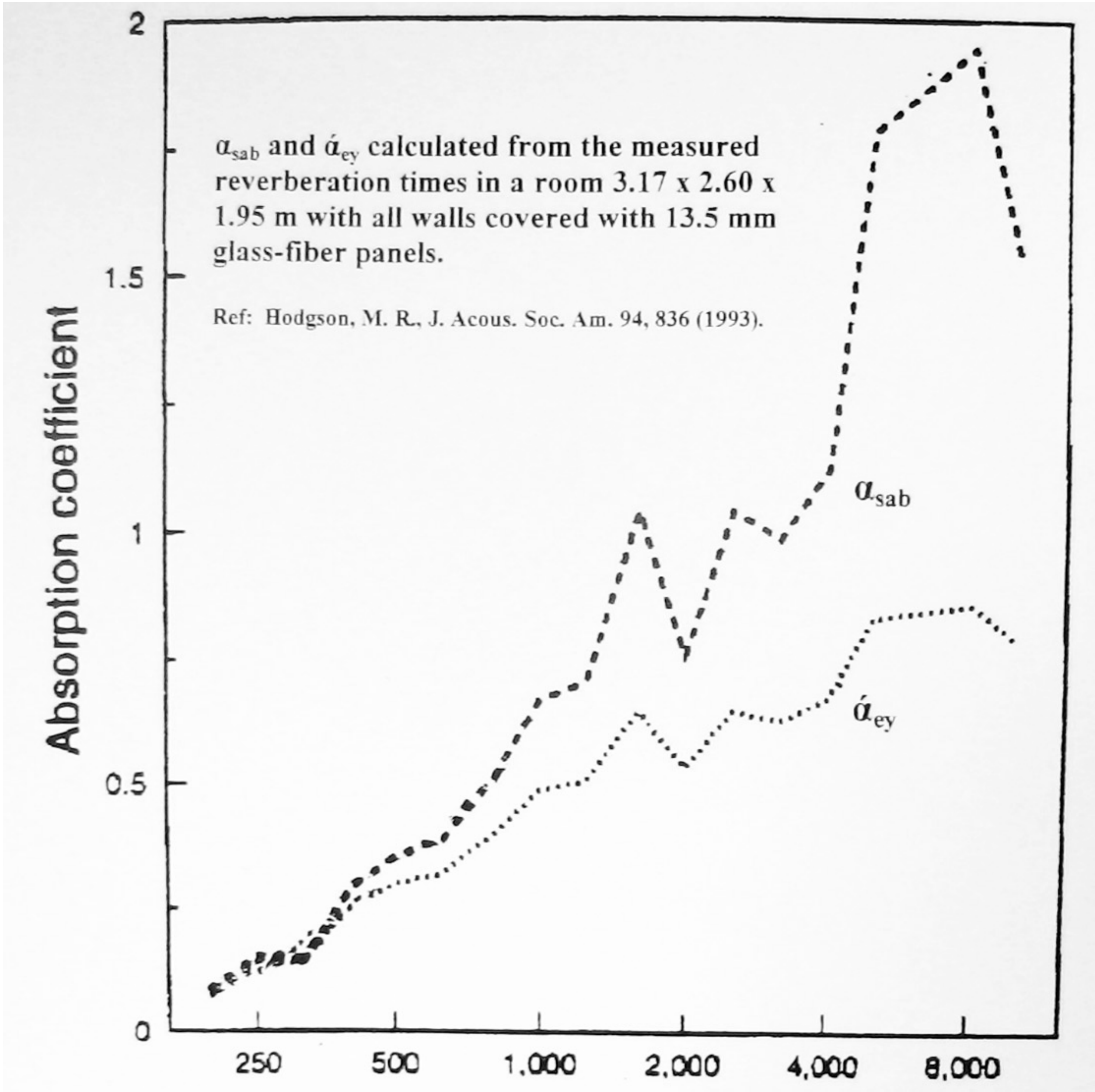
For the Eyring Eq., T_{60} = 0 when the Eyring coefficient is 1.0.

For the Sabine Eq., T_{60} = 0 only if the Sabine coefficient is very large.

This demands that the Sabine absorption coefficient must be allowed to exceed 1.0, and this is my premise. Example:

Consider a *very small* room with all walls equally absorbing: Room: 3.17 x 2.60 x 1.95 m and covered with 13.5 mm glass-fiber panels.

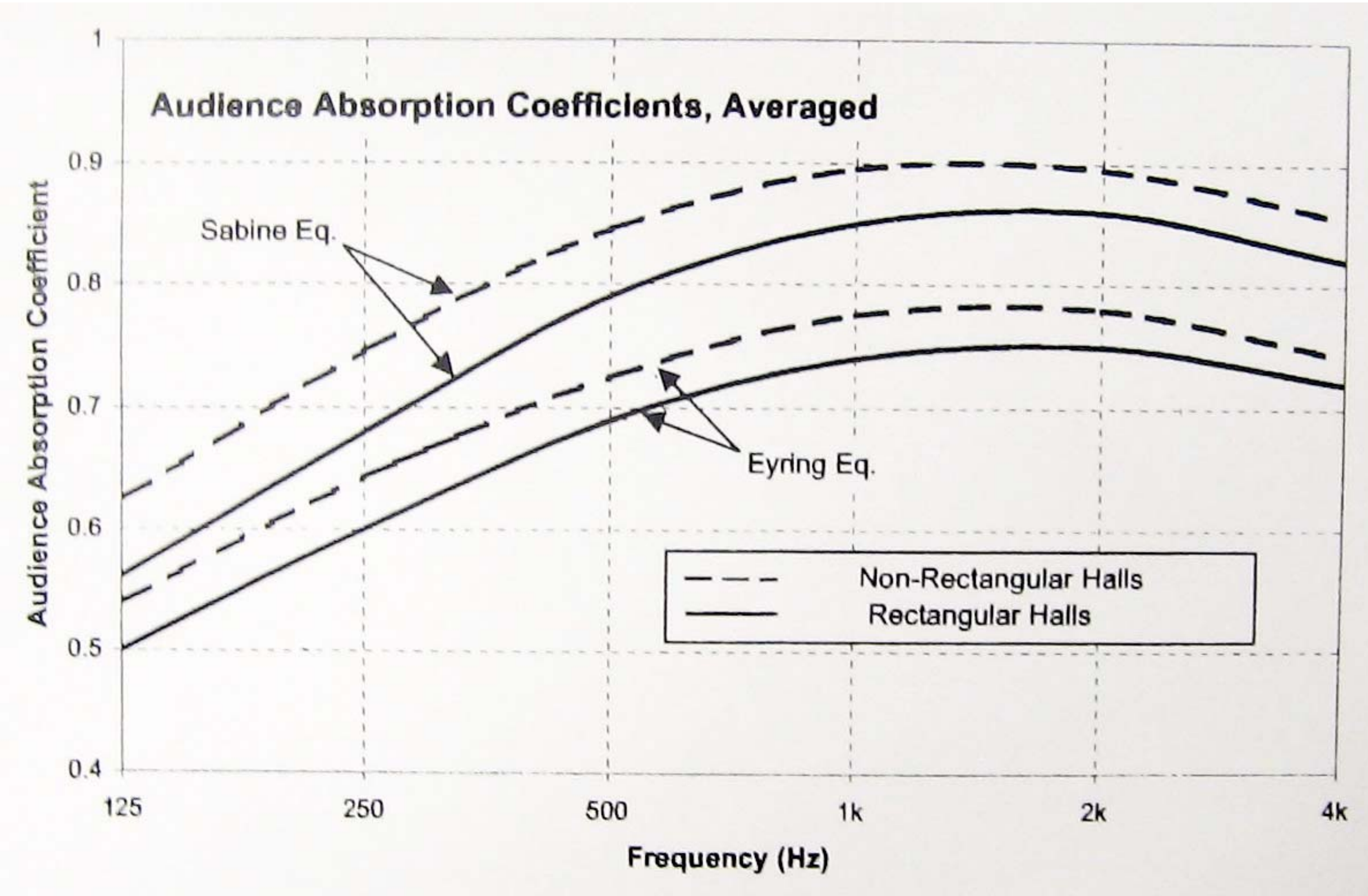
What are the two measured absorption coefficients as a function of frequency?


α_{sab} and $\acute{\alpha}_{ey}$ calculated from the measured reverberation times in a room 3.17 x 2.60 x 1.95 m with all walls covered with 13.5 mm glass-fiber panels.
Ref: Hodgson, M. R., J. Acous. Soc. Am. 94, 836 (1993).
α_{sab}
$\acute{\alpha}_{ey}$
Absorption coefficient
2
1.5
1
0.5
0
250
500
1,000
2,000
4,000
8,000

It is hoped that no one is still calculating reverberation times in a concert hall considering the audience absorption as being proportional to the number of occupants. In repeated papers I have shown, and more recently Barron and Coleman have confirmed, that the absorption of an audience is proportional to the area over which it sits. This difference is serious because, for example, in the Amsterdam Concertgebouw, 1200 people sit over an area of 500 square meters, while in the Munich Philharmonie, only 900 sit over this area. Thus, because the absorption is proportional to area, in the Munich hall each person absorbs 33 percent more sound energy than in Amsterdam. Also, it must be noted that the area of an audience is greater if they are on a slope than would be indicated by the projected area. The sloped area must be used in calculations.

Furthermore, for different halls there is no one audience absorption coefficient if the same reverberation equation is used for prediction in them. The audience in each shape of hall absorbs a different amount of sound energy because of the difference in the way successive sound reflections involve the different surfaces in it. Alternatively, if the same absorption coefficient is to be used, a different reverberation equation must be used for each shape of hall. This has been demonstrated by Joyce, Kuttruff, Hidaka and others.

In the next figure the difference is shown in the audience absorption coefficient for a classical shoebox shaped hall (average of 9 halls) compared to a non-shoebox shaped hall (average of 11 halls). The absorption coefficient for the latter is 6 percent greater.



Audience Absorption Coefficients, Averaged
Audience Absorption Coefficient
Frequency (Hz)
1
0.9
0.8
0.7
0.6
0.5
0.4
125
250
500
1k
2k
4k
Sabine Eq.
Eyring Eq.
Non-Rectangular Halls
Rectangular Halls

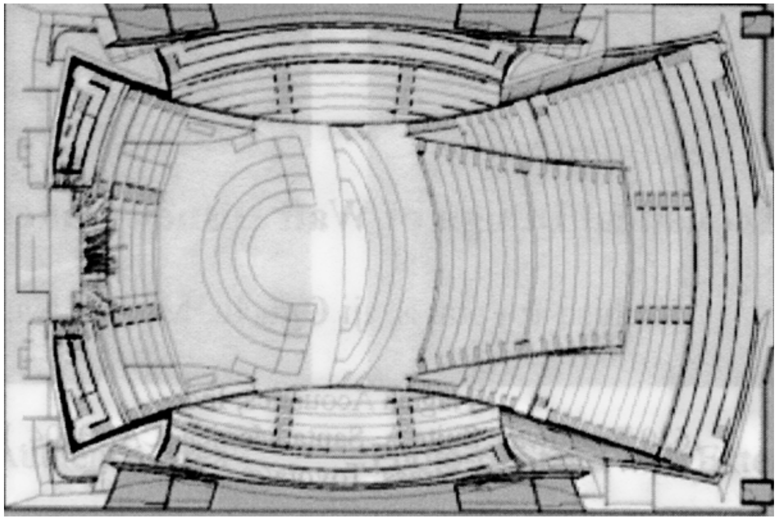
I wish to make some observations on the sound in two halls of quite different shapes,

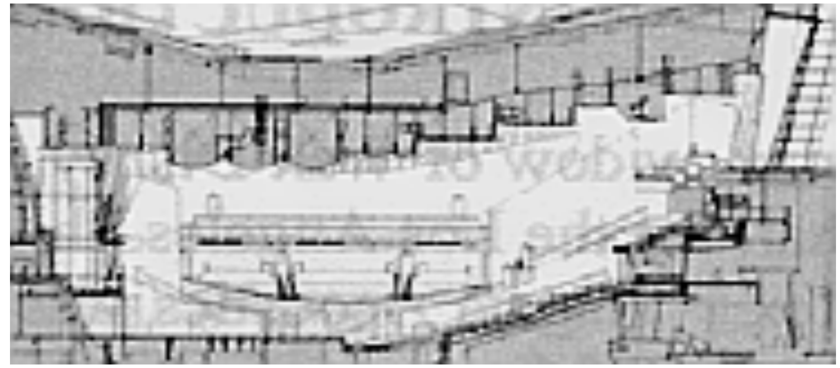
Boston Symphony Hall and Los Angeles Walt Disney Hall.

Boston Symphony Hall opened in 1900. I am often asked why this hall is so successful when so little was then known about concert hall acoustics. The most important decision was made by the owner of the Boston Symphony Orchestra, Henry Lee Higginson, who was also the Chairman of the building committee. He decided, after consultation with conductors and musicians in Europe, that the hall should be shoebox in shape (This assured uniform coverage of the audience). Second, for visual reasons, he stipulated that the 2600 seat hall should be no wider than 75 ft (22.9 m) (This assured adequate ASW, apparent source width). The building committee asked that the hall be fireproof—concrete block and plaster (This assured strong bass). The architect wanted a beautiful hall and asked for niches and statues on the side walls and coffers in the ceiling (This assured a pleasant reverberation time). Sabine, using the equation that he had discovered only 4 months before, calculated the ceiling height which resulted in optimum reverberation time (for today's orchestral repertoire). Finally, in order to keep the length of the hall reasonable, Sabine designed a stage house that did not significantly increase the volume of the hall (The musicians like the sound in it). These decisions led to optimum values for RT, G, Clarity C_{80}, ITDG, IACC, bass response and musicians' satisfaction.

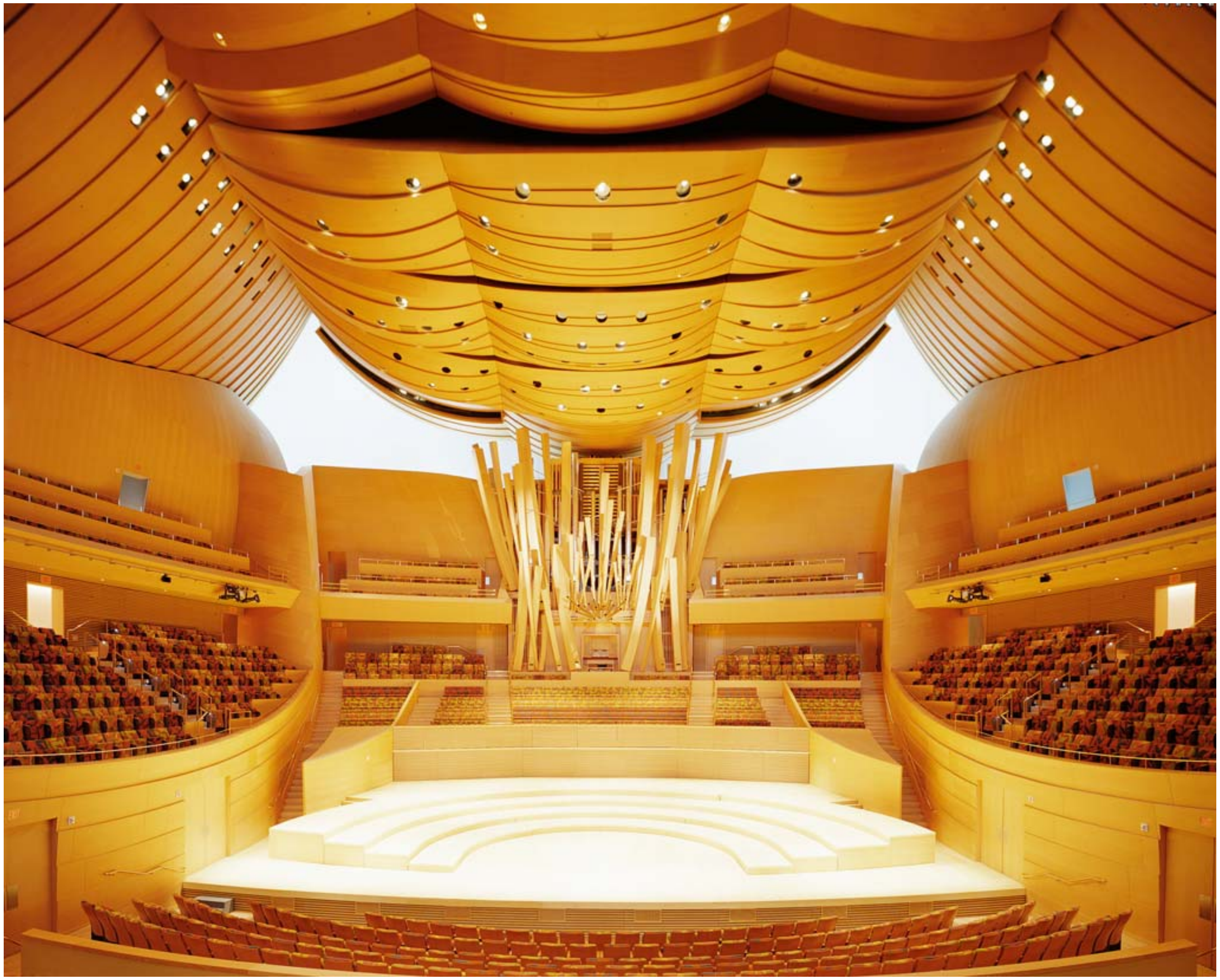
Recent studies in several countries, including England, have shown that the Boston stage is nearly ideal. It has flared vertical side walls, a ceiling that is about 43 feet high, and a stage area that is as small as possible for comfortable seating of the orchestra.

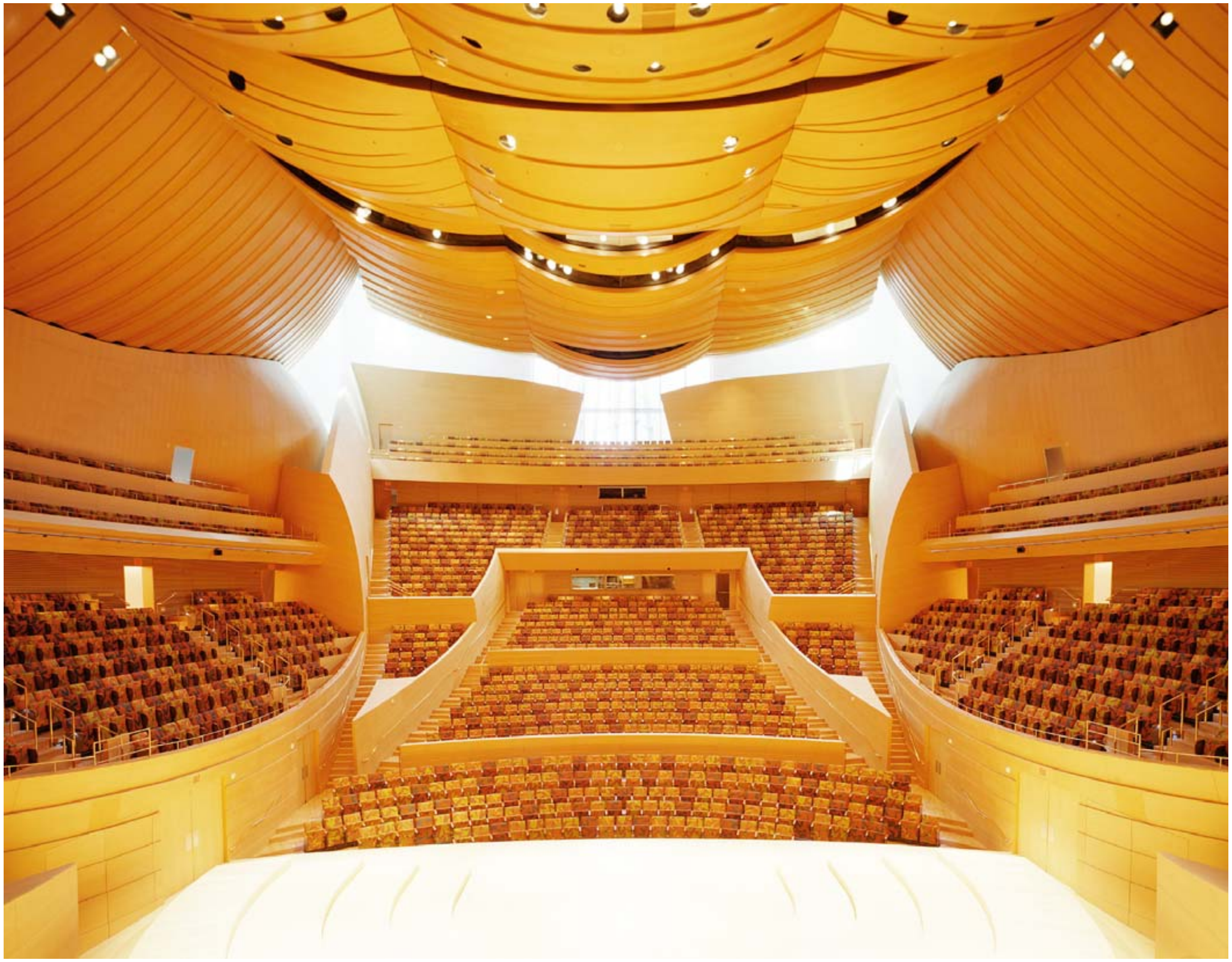
The only published plans for the Walt Disney Hall that I am aware of are as follows:





There are several ways this hall differs from the Boston hall. Most important, the audience surrounds the orchestra. The height of the ceiling above the stage is about 49 ft and the mid-frequency occupied reverberation time is 1.85 s, both near optimum. The average strength G in the hall is about 2 decibels less than in Boston and 4 dB less than than Vienna's Vereinssaal. The principal difference in the sound in it and that in a shoebox hall is in the number and distribution of the lateral reflections at the different seats, which means that the sound is not as uniform as in Boston and Vienna. Also, the orchestra must become accustomed to playing without side and rear walls, which, apparently, the Los Angeles Symphony did after a couple weeks of practice. This means that the players hear each other less well and must pay closer attention to the conductor.





Perceived Loudness at different distances from the stage.

In 2001, Zahorik and Wightman (in an obscure publication) found from listener judgments in a carefully executed experiment, that even though the strengths G in decibels of the music in a concert hall decreases with distance, listeners say there is <u>no change in loudness</u>. Their explanation was that listeners judge the loudness <u>based on the strength of the reverberant field</u>, which does not vary much in a hall.

At a meeting a month ago in Madrid, Barron gave a paper, apparently unaware of the above paper, in which he concluded, "Assessment of subjective loudness indicates that the listeners' <u>loudness</u> judgment is almost <u>independent of distance</u> from the stage, which suggests that listeners are compensating their judgment of loudness <u>on the basis of visual information</u>." Barron even gives a criterion for the strength G by which he says that ideally the sound strength G <u>should</u> decrease with distance from the stage by about the same amount as it decreases in Boston Symphony Hall.

This is an important discovery, even though we do not know for sure whether listeners judge loudness in a hall based on the strength of the reverberant field alone or in combination with vision.

CHAMBER MUSIC HALLS

Hidaka and Nishihara sought general design guidelines for chamber music halls based on studies of 11 European halls and 7 Japanese halls. The occupancy of the former ranged from 336 to 844 and the latter from 252 to 767. If halls with seating over 339 and multi-purpose are excluded, the occupied-hall mid-frequency reverberation times RT range from 1.5 to 1.7 s. Opinions of musicians using halls between 500 and 600 seats were in agreement that those numbers are optimum. For those particular halls, the mid-frequency (unoccupied) clarity factor C_{80} lay in the range (0.2 $\pm$ 1.6) dB. For the European halls, the unoccupied hall-averaged sound strengths at mid-frequencies G_M ranged from 9 to 13 dB and G_L (125/250 Hz) from 9 to 14 dB. In the modern (mostly Japanese) halls these values were 3 and 5 dB less, respectively. The initial-time-delay gaps ITDG's measured at mid-floor were 20 ms or less in the best halls. For the best halls, the Binaural Quality Index's integrated over 80 ms (BQI_{MID} = {1 – $IACC_{MID}$} were more than 0.68 and integrated over 50 ms were more than 0.58.

Next, I wish to present a new formula for calculation of Listener Envelopment, LEV. This method has as its basis a paper presented in the Journal of the Audio Engineering Society Volume 51, September 2003, by Gilbert Soulodre, Michael Lavoie and Scott Norcross of the Communication Research Center in Ottawa. I view this work as very important. The changes that I am going to present are different in detail from their work but are solidly based on their findings. My method makes possible the use of data of the kind that I gave earlier in this lecture and that are tabulated in my 2004 book on Concert Halls and Opera Houses. The following finding is also important:

First, it has been believed until now that the most important component of listener envelopment is the energy arriving from lateral directions a person's ears. But, Furuya, Fujimoto, Wakuda and Nakano found from extensive subjective measurements of listener envelopment LEV that late vertical energy and late energy from behind a listener affect LEV by approximately 40 and 60 percent, respectively, of the late lateral energy. Hence, one has to conclude that total late energy is a better component of LEV than late lateral energy. Soulodre et al confirmed this result in their paper.

In the experiments performed by them a listener was surrounded by the sound from five loudspeakers, one frontal, two ± 30° and two ± 110°. The sound stimulus was a 20 sec segment of anechoic music (Handel's Water Music). Direct sound came from the forward loudspeaker. Early reflections and reverberant sound came from the other loudspeakers. The reverberant sound and some of the early reflections were varied and the strength G and reverberation time RT were varied. The subjects were asked "to rate only their perception of being enveloped or surrounded by the sound."

They measured in octave bands: (A) late lateral energy fraction (LF_L)(measured with figure-eight microphone and integrated after 80 ms), (B) late total energy (G_L), and (C) reverberation time.

Note: They found very little change in perceived LEV for RT's between 1.7 and 2.0 sec, common for concert halls [They and Morimoto et al found that LEV is diminished when the RT is low in any frequency region, whether low, middle or high].

An important conclusion: "The results are fairly independent of how the various octave bands are grouped." They even found slightly higher correlations between the results of their subjects' responses using the 500 and 1000 Hz bands for averaging their measured data than using the four 125-1000 Hz bands. They decided for no particular reason that they would average their results over the four, 125 to 1000 Hz, bands.

As a by-product, they found that for the lower three bands, the transition time between ASW and LEV is substantially longer than the usual 80 ms, but for the two mid-frequency bands it is about 100 ms. Because at mid-frequencies the 100 ms transition time is close enough to the 80 ms value which has been used for nearly all of the data in the literature (and my book), I am using the 500/1000 Hz band average in what follows.

Directly from the Soulodre et all, but with the above modifications, their formula for calculating Listener Envelopment, LEV, which correlated highly with their subjective judgments, becomes,

$$LEV_{calc} = 0.5\ G_{Late,mid} + 10 \log LF_{Late,mid}\ dB$$

G (overall) and the clarity factor C_{80}, which measures the ratio of early to late energy, are published for many halls in the literature and in my book. Obviously, from these two quantities G_{Late} can be determined.

Earlier in this lecture, I showed that [1 – IACC] is highly correlated with LF, hence, [1 – $IACC_{Late}$] can be substituted for LF_{Late}, so that their formula revised to use widely available data becomes,

$$LEV_{calc} = 0.5\ _{GLate,mid} + 10 \log [1 - IACC_{Late,mid}]\ dB$$

$LEV_{calc} = 0.5\ G_{Late,mid} + 10 \log [1 – IACC_{Late,mid}]$ dB

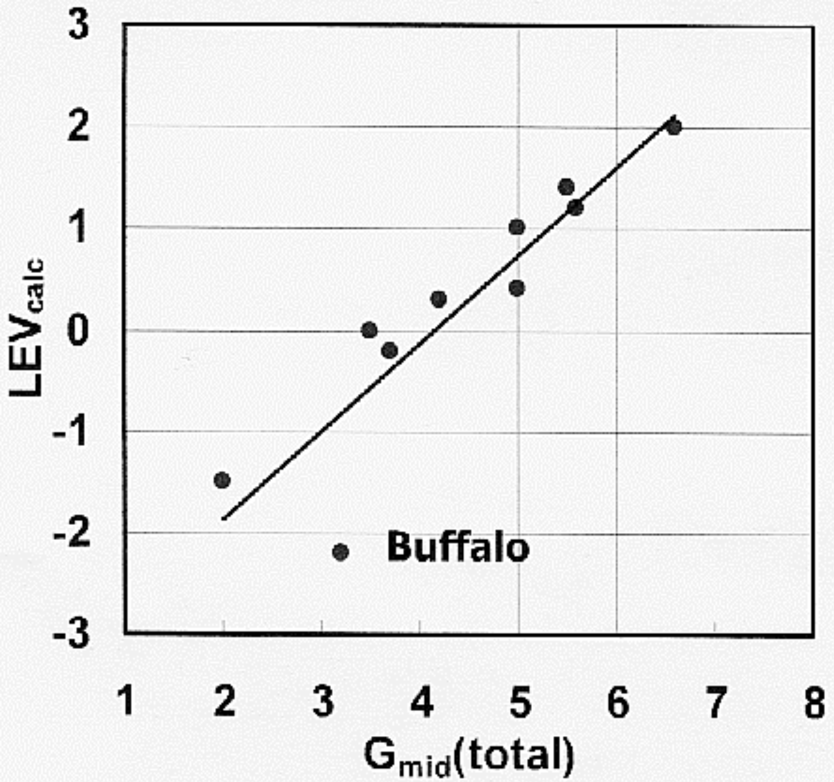
With this formula, the calculated listener envelopment LEV_{calc} for 10 well-known halls is as follows.

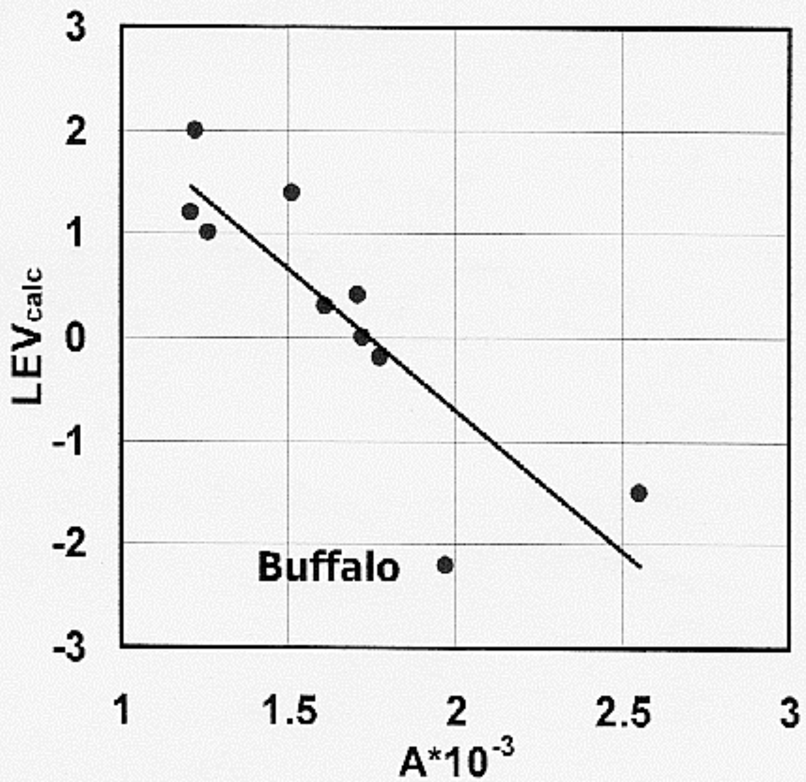
Hall	LEV_{calc}
Vienna, Musikvereinssaal	2.0
Amsterdam, Concertgebouw	1.4
Berlin, Konzerthaus	1.2
Tokyo, TOC Hall	1.0
Tokyo, Suntory Hall	0.4
Boston, Symphony Hall	0.3
Berlin, Philharmonie	-0.2
Baltimore, Symphony Hall	0
Sapporo, Kitara Hall	-1.5
Buffalo, Kleinhans Hall	-2.2

Anyone who has listened to music in these halls will agree that the degree of listener envelopment is greater in the upper group of four halls than in the lower group of four halls. Boston is appreciably lower than Vienna because, as shown in a table earlier, the sound strength G is lower. The famous conductor Herbert von Karajan, whose home hall was the Vienna Musikvereinssaal, said to me in an interview, “The sound in the Vienna hall is so full that the technical attack of instruments—bows and lips—gets lost. Also successive notes merge into each other. I consider Boston Symphony Hall a little better than the Musikvereinssaal.”

A question, “Is this measurement, LEV_{calc} unique, or is it highly correlated with other common measures?” Let us plot LEV_{calc} against:

(A) Total strength G_{mid}, and (B) Total room absorption, $S_{tot}\alpha_{sab}$ (Note: Buffalo has both exceptionally low G_{mid} and low [1 – $IACC_{late}$])





IN SUMMARY

1. Sabine absorption coefficients should be allowed to go above 1.0 and, if so, there is always a definite relation between Eyring and Sabine coefficients.

2. When calculating reverberation times, the sound absorption coefficients that are used must have been determined in rooms of nearly the same shape and size. Audience area and not audience count should be used in determining audience absorption.

3. There is high correlation between measurements of low-frequency lateral refraction LF and mid-frequency Binaural Quality Index [1 – IACC].

4. The lateral direction that the sound is coming from is determined by the direct sound, and this continues up to about 100 ms, at which time the upper limit of the first wave front is reached. Early reflections before about 100 ms act to widen the apparent source width ASW.

5. Envelopment of the listener by LEV occurs only after the upper limit of the first wave front is reached, where the direction of the sound source is no longer apparent .

6. Listeners judge the loudness of an orchestra in a hall to be the same in remote seats as in front seats even though the measured strength G decreases with distance from the stage.

7. Listener envelopment LEV can be calculated by a new formula that includes sound strength G (late), and the late lateral energy as measured by [1 – IACC(late)], where "late" means after about 80 ms.

8. The calculation of LEV can made using available data in the 500 to 2000 Hz octave bands and a transition time of 80 ms.

9. For most halls, The results of the formula for calculating LEV are highly correlated with the overall G (not late) and the total room absorption Stot*αtot except when either, or both, the late lateral energy, BQI = [1 – IACC], or the overall G is weak.