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Listener Envelopment LEV, Strength G and Reverberation Time RT in Concert Halls

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ABSTRACT

This paper presents listener envelopment LEV calculations and low-frequency strength G and reverberation time RT measurements in shoebox and non-shoebox concert halls. Soulodre and coworkers have determined the response of listeners exposed to direct sound, early reflections and reverberant sound in answer to the question “rate only your perception of being enveloped or surrounded by the sound.” They developed a formula for calculation of LEV that correlated highly with their subjective judgments which included strength factor G_{late} and lateral fraction LF_{late}—data that are not available in the literature. An alternate formula is devised here that makes use of overall strength factor G, clarity factor C_{80} and Binaural Quality Index BQI_{late} where BQI equals [1-$IACC_{late}$], all factors that are available. Calculations of LEV for 21 concert halls are made and correlated with overall strength factor G. Measurements of the relation between Strength G and Reverberation time RT at 125 Hz made in shoebox and non-shoebox halls are presented from data supplied by Hidaka and coworkers. In shoebox halls, the correlation between the two is high, as would be expected from Sabine/Eyring derivations, but in non-shoebox halls there is almost no correlation. The reasons for this result are discussed. Also, G in audience areas in front of the orchestra in shoebox concert halls is about 3 dB higher at all frequencies than that in non-shoebox halls.

INTRODUCTION

The sound arriving at a listener’s ears following a note played on the performing stage is comprised of three parts: direct sound, early reflections, and reverberant sound.[1] The direct sound is primarily heard in the initial-time-delay gap. In the best halls, such as Amsterdam’s Concertgebouw and Boston Symphony Hall, the gap is less than 25 ms. In lesser quality halls, the range is from 25 to 35 ms. Beyond 35 ms, a hall takes on an “arena” sound. From the direct sound, the azimuth position of the source on stage can be perceived, the onsets of the sound are heard, and successive notes are clearly separated from each other. The direct sound also conveys a sense of listener’s closeness to the source.

The listener next hears the early reflections from the walls, ceiling and stage enclosure. If these reflections arrive from lateral directions, the source is subjectively broadened, called apparent source width ASW, giving the sound a fuller and more robust character. This subjective effect is also called spaciousness.

The reverberant sound is all the sound that arrives at a listener’s ears 80 to 100 ms after the direct sound and which is heard within the reverberation time—usually less than 2.2 sec. Listener envelopment LEV is the degree to which the reverberant sound seems to surround the listener—to come from all directions. In the best halls, sound waves are free to travel around the overhead spaces, front, sides and rear of the upper sidewalls giving to the listener the feeling of being immersed in the sound. Until the study discussed below there has been no way to quantify LEV.

CALCULATION OF LISTENER ENVELOPMENT, LEV

Gilbert Soulodre, Michael Lavoie and Scott Norcross of the Communication Research Center in Ottawa, Canada,[2] set out to quantify LEV. In their experiments a listener was surrounded by the sound from five loudspeakers, one frontal, two ± 30^0 and two ± 110^0. The sound stimulus was a 20 sec segment of anechoic music (Handel’s Water Music). Direct sound came from the forward loudspeaker and early reflections and reverberant sound came from the others. The reverberant sound and some of the early reflections were varied as well as the strength G and reverberation time RT. 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.

Prior to about year 2000 most researchers reported that the most important component of listener envelopment is the late energy arriving at a person's ears from lateral directions. Recently, Furuya, Fujimoto, Wakuda and Nakano[3] found from extensive subjective measurements of listener envelopment LEV that late vertical energy and late energy from behind, respectively, affect LEV by approximately 40 and 60 percent of late lateral energy. Soulodre et al's study found that total late energy is a better component of LEV than late lateral energy. Because late lateral energy values have not been published for most concert halls and because there is conflicting evidence as to which is better, total late energy is used in this paper.

Also, the Soulodre study found very little change in perceived LEV for reverberation times between 1.7 and 2.0 sec, a range found in most concert halls [But it must be noted that they and Morimoto et al[4] found that LEV is diminished when the RT is low in any frequency region, whether low, middle or high]. Thus, the derivation that follows is valid only for this range of reverberation times.

Another important Soulodre et al conclusion is that, "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 bands for averaging their measured data than using the four 125-1000 Hz bands. They averaged their results over the four lower bands, saying only that they wanted to use a larger number of bands. For the 500 and 1000 Hz bands they learned that the transition time between ASW and LEV is at about 100 ms. This happy finding is close enough to the 80 ms value which has been used for nearly all of the data in the literature[1] that we can use the published data.

Soulodre et al devised a formula for calculating Listener Envelopment, LEV that correlates highly with their subjective judgments. With the above modifications it is,

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

Here G late is the strength of the reverberant sound and LF late is the late energy coming from lateral reflections. Mid means measurements made at mid-frequencies.

But, $G_{late,mid}$ and $LF_{late,mid}$ are numerical quantities not available in the literature. Instead, the overall strength G and the clarity factor C_{80}, which measures the ratio of early to late energy, are available From these two factors, the late strength factor G_{late} is found from

$$G_{Late} = G - 10 \log(1 + \log^{-1} C_{80}/10)$$

Also, the quantity [1 – IACC] has been shown to be highly correlated with LF, hence, [1 – $IACC_{Late}$] can be substituted for LF_{Late}. With these changes their formula can be revised to use widely available data[i][1]

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

The results calculated for 22 halls using this formula are given in Table 1.

Table 1. Calculated LEV for 22 concert halls.

Name of Hall	LEV Calc	G(mid) Europe
Zurich, Groser Tonhallesaal	2.42	7.4
Vienna, GMVS	2.04	6.7
Basel, Stadt-Casino	1.90	6.9
Amsterdam, Concertgebouw	1.42	5.5
Berlin, Konzerthaus	1.24	5.7
Tokyo, TOC Concert Hall	1.03	5.0
Vienna, Konzerthaus	0.91	5.0
Tokyo, Suntory Hall	0.44	5.0
Boston, Symphony Hall	0.35	4.2
Kyoto, Concert Hall	0.11	4.3
Lenox,Tanglewood Music Shed	0.06	4.0
Baltimore, Symphony Hall	-0.02	3.5
Munich, Phnilharmonie	-0.11	3.2
Costa Mesa, Orange County	-0.12	3.9
Berlin, Philharmonie	-0.15	3.7
Tokyo, Met. Arts Space	-0.45	3.0
Tokyo, Bunka Kaikan	-0.54	3.0
Tokyo, Orchard Hall	-1.09	1.8
Sapporo, "Kitara" Hall	-1.46	2.1
Salt Lake City, Abramavel Hall	-1.48	1.4
Buffalo, Kleinhans Hall	-2.16	3.2
Tokyo, H-Auditorium	-2.60	1.3

It is immediately apparent that the calculated LEV is highly correlated with G, overall, at mid-frequencies, except for the Buffalo Kleinhans Hall. In this hall, the quantity [1–$IACC_{Late,mid}$] is significantly smaller than in the other halls. There is almost no correlation between LEV and reverberation time.

[This author has attended concerts in all but two halls (Sapporo and Tokyo-H). Certainly, the sound in the upper halls of Table 1 is much more enveloping than it is in the lowest halls.]

Bass Perception: G and RT

Bradley and Soulodre set out to determine to what extent reverberation time and strength factor at low frequencies determines the perception of bass in concert halls[5] In their experiments, ten listeners rated their perception of strength of bass content in music samples where the sound strength G and reverberation times in the low frequency bands were systematically varied. The musical composition used in the tests was an anechoic recording of Handel’s water music.

The sound fields in their experiment were presented initially with only the first 80 ms of the musical samples, i.e. G_{80}, so as to eliminate the effects of reverberation time. In Figs. 1 and 2 the frequency responses are shown for both G_{80} and RT. The ranges for G_{80} and RT chosen are similar to the maxima found in actual concert halls.

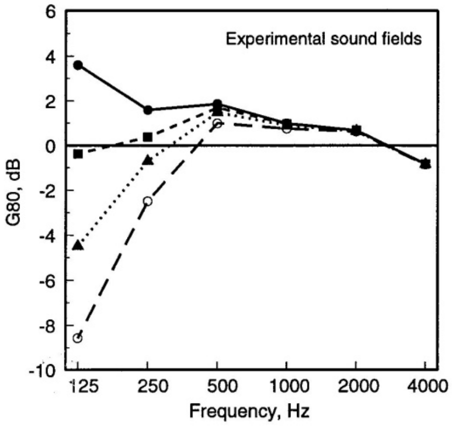

Fig. 1. Frequency responses of early sound levels (G_{80}) of experimental sound fields.

The subjects rated each musical presentation on a scale from 1 to 5. The results of the tests are given in Fig. 3. It is seen that the perceived bass level increases almost linearly with an increase of strength G in the lowest frequency band (125 Hz). On the other hand, the effect of the very large change in the reverberation times is seen to be negligible.

In another experiment they showed that late sound levels also increase the perception of bass sounds and that the perception for both is always greater in the lowest frequency band (125 Hz) then in the next higher band (250 Hz). They also found that the direction of arrival of low frequency sounds had small effect on the assessment of bass content in the sounds.

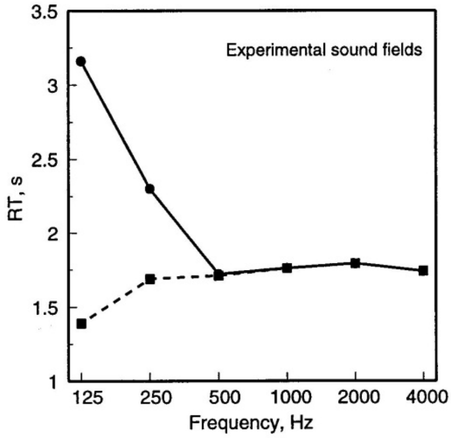

Fig. 2. Frequency response of reverberation times (RT) of experimental sound fields.

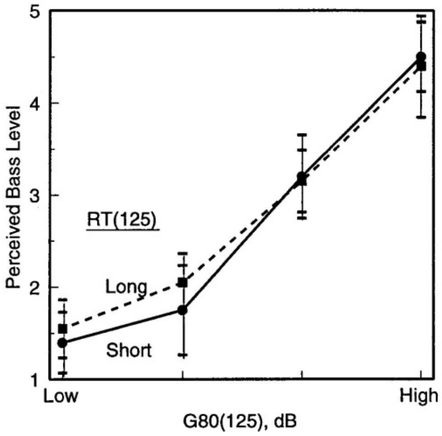

Fig. 3. Mean subjective response versus early low frequency sound level ($G_{80,125}$) for long and short 125 Hz reverberation time (RT).

Relation between G and RT in 125 Hz band.

The result in Fig. 3, which shows that G and reverberation time are not tightly tied together is surprising because from simple Sabine theory knowing one should give you the means for calculating the other.

Takayuki Hidaka and Noriko Nishihara at the Takenaka R & D Institute in Chiba, Japan, sent this author data which shows that an increase in G is accompanied by an increase in RT in shoebox shaped halls, but not in non-shoebox halls (See Figs. 4 and 5).

The reason for the differences in Figs. 4 and 5 between the two shapes of halls is clear. In the shoebox halls, the wall areas above the top balcony are large and are free of sound absorbing materials. Thus, the direct and early sound that reaches these areas joins into the reverberant sound without loss. This type of sound field is the basis for the Sabine/Eyring theory and according to that theory the strength G increases as the reverberation time increases.

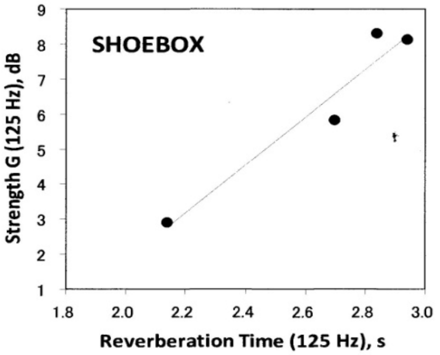

Fig. 4. Relation between strength G at 125 Hz and reverberation time (RT) at 125 Hz for shoebox shaped concert halls, unoccupied. The data are for Berlin Konzerthaus, Boston, Amsterdam, and Vienna Musikvereinssaal. (The correlation coefficient R = 0.80).

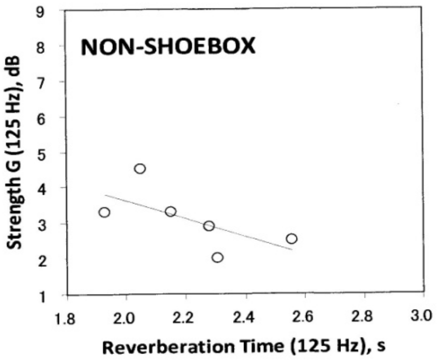

Fig. 5. Relation between strength G at 125 Hz and reverberation time (RT) at 125 Hz for non-shoebox shaped concert halls, unoccupied. The data are for Berlin Philharmonie, San Francisco Davies Hall, Sapporo Kitara Hall, Tokyo Suntory Hall, Tokyo Bunka Kaikan Hall, and Costa Mesa, Orange County Performing Arts Center (The correlation coefficient R = 0.12).

In all of the non-shoebox halls, the audience seating extends nearly to the ceiling on one or more of the four sidewall surfaces. Thus, energy is removed there before the reverberant field is established and G is reduced independently of the reverberation time. From the standpoint of G, this is equivalent to the orchestra reducing its output.

The reverberation time in all of the halls is determined primarily by the ratio of the volume to the total absorption in the room and is not dependent on whether one or more of the upper walls is covered by audience seating.

Let us now look at the average differences in strength G between the two types of halls. But, first, in Fig. 4, the hall with the lowest G and RT is Boston. The low values in the unoccupied hall at 125 Hz are caused by the absorption of the plywood on which the main floor seats are placed. But, with audience, 158 kg/m^2 are added, and, when occupied the G and RT are about the same in this frequency band as they are for the next highest hall. Hence, one can assume that in Fig. 4, the value for Boston would be about 6 if this weight on the wooden floor were present when unoccupied.

The average differences in strength G for the shoebox halls is about 7 (assuming the correction for Boston) and that for the non-shoebox halls is about 3. The reason: In the SB halls the orchestra is at one end of the hall and all the sound is radiated out into the audience in front. In the non-SB halls, the sound is radiated in all directions and a reduction of 3 to 4 dB would be expected in the radiation to the front. The measured difference for G at mid-frequencies in the two types of halls is also about 3 dB.

SUMMARY

1. 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. Data for LEV$_{calc}$ are averaged in the 500 to 2000 Hz octave bands. For most halls, calculations of LEV are highly correlated with overall strength G (not late).

2. In shoebox halls, the increase in strength G (125 Hz) is highly correlated with the increase in reverberation time (125 Hz). In the non-shoebox halls the correlation is almost zero. The reason: Because one or more of the upper side walls in the non-shoebox halls is all or nearly all covered by seated audience areas, direct and early sound radiated from the orchestra is absorbed before it can enter the reverberant sound field. In these halls, increases in RT and G are not highly correlated.

2. The strength G in shoebox concert halls is about 3 dB higher than that in non-shoebox halls

because of the position of the orchestra in relation to the audience. In the SB halls, the orchestra is at one end of the hall and all the sound is radiated to the audience in front. By comparison, in the non-shoebox halls, the orchestra sound is radiated in all directions and 3 to 4 dB less radiation is to the audience areas in the front. Also, with the same reverberation times, the early G(125 HZ) is higher in shoebox halls than in non-shoebox halls, which means the bass sounds are further augmented in the former.

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