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BEHAVIOR OF LATERAL ENERGY IN SMALL CONCERT HALLS

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ABSTRACT

Lateral efficiency and spatial impression are generally assumed to be closely related to the width of the hall. Achieving desired values of lateral energy is therefore generally not seen as a problem in small halls. Previous research by one of the authors of data for small Finnish halls has however shown that a considerable number of these spaces have low mean lateral efficiency values as measured by the early lateral energy fraction, LF. In this paper the behaviour of lateral energy in small concert halls will be investigated by means of measured data from 28 small halls (<800 seats). In particular, the relationship between LF, the geometry in small halls, and the early sound strength will be investigated. Criteria for LF in light of the greater strength and resultant increase in the “effective spatial impression” found in smaller spaces will be discussed. It will be shown that LF is a design variable, depending upon a hall’s use, whether it be by symphony or recitalist. Small size does not on its own assure sufficiently high LF values, while on the other hand, in some cases lower LF values may be desirable. When deploying variable absorption to control a hall’s loudness, LF must be higher to accommodate the loss in spatial impression due to the decrease in loudness.

INTRODUCTION

The design of small concert halls presents acoustical challenges which differ from those of large halls. For instance, a challenge for large halls is to attain adequate Sound Strength (G) whereas in a small concert hall accommodating a full symphony orchestra, the challenge is to control the loudness. Strategies for controlling G and attaining adequate reverberation have been recently discussed by the authors [1] on the basis of studies and design of small chamber halls in Finland. This discussion included determining the mean value of G considered to be the maximum for performing spaces on the basis of listening experience in halls of known objective acoustical values. Citing opinions of several authorities, the conclusion was that, for large symphonic performance, the mean value of G at mid-frequencies (500 and 1kHz)(unoccupied) should generally be limited to G_o = +5 dB, but should also be greater than +3 dB.

Those familiar with small concert halls ($N_T \leq 800$ seats) know that mean G_o values are found to be in the range of +6 to +12 dB. These smaller halls are also generally found to have high values of early lateral energy, although not always. This paper discusses the magnitude and behavior of early lateral energy (LF) as a function of room design, along with the effects of higher Sound Strength, on spatial impression (SI). It will be seen that the size of the source and/or the dynamic level of the music determines the desired combination of G and LF values. The result in some cases may be that lower than usual LF values may be desirable. The value of subjective SI, as the combination of the effects of G and LF, will be defined here as the effective SI, or ESI.

THE EFFECTS OF LOUDNESS ON SPATIAL IMPRESSION (SI)

Early lateral energy fraction as a measure of SI

Spatial Impression is generally considered to be comprised of two basic perceptual components; these are 1) auditory source width (ASW), a function of the "early" sound field, and 2) listener envelopment (LEV), a function of the "late" sound field. This discussion will address only the effects of the "early" sound field, integrated to 80 msec, on the subjective SI of the space, and SI will be used here to denote the effect of source broadening.

Based upon the pioneering work of Marshall [2] and Barron [3], the objective measure of the early lateral energy fraction (LF) has been accepted as an important measure of the effect of source broadening. Simply stated, LF is the ratio of the sum of the early lateral energy to the sum of the early total energy (for precise definitions, see Ref. [4].)

With LF having been measured for a multitude of halls, subjective evaluation has yielded a range of LF values considered to be preferred for symphonic presentations. These preferences have been determined on the basis of listening in the world's larger, and more famous halls. Various sources therefore list preferred mean values in the range of LF = 20 to 25%. Even for the typically large halls, mean values over 25% are considered to be prone to image shifting and dissipation of the acoustical source image.

Sound Strength as a factor of effective SI (ESI)

It has been known, initially through observation and confirmed through listening simulations, that SI is a function of the source level. This effect was reported by Veneklasen and Hyde [5] where, in an "auditorium synthesis" listening system, the acoustical image was found to focus on the source during quiet passages while it broadened as the passages became louder, creating a feeling of "envelopment" by the sound, and a broadening of the source image.

At around the same time, Keet [6] published a paper showing a clear and definitive relationship between sound level, ASW (in degrees), and what he called the "incoherent lateral energy fraction," being the crosscorrelation function of a binaural signal from a dummy head measurement. Barron has shown [3] a direct linear relationship between Keet's crosscorrelation factor and his units of spatial impression thereby yielding a direct relationship between LF and the change in sound level at ΔLF=1,6%/dB (or ΔLevel/62,5). This translates to a change in LF of approximately 5% for each 3 dB change in level. Barron has since suggested [4] combining LF with level in defining a "degree of source broadening" (DSB) = LF+G(early)/*k*. He and Marshall [6] have also shown that work by Morimoto and Iida [7] yields a value of k=57. Combining the above, the expression DSB=LF+G(early)/60 is suggested. With due respect to Barron, for the purposes of this paper we are using the descriptive term "effective spatial impression" or ESI = LF+G_e/60. The subjective response to the image broadening aspect of SI is therefore proposed as being a factor of both LF and G_e more or less to this degree.

DESCRIPTION OF THE HALLS

Data from 28 Finnish halls are included in this investigation. The halls seat from 350 to 780. From a geometrical point of view in plan, the halls can be divided into 4 groups such as:

- 10 Shoebox shaped or parallel wall
- 10 fan-shaped halls
- 4 non-symmetrical
- 4 "Almost Shoebox" shaped

Of the shoebox halls, three have a proscenium type stage to hall transition. One hall has a projecting ceiling structure over the stage, two of the halls have a vaulted ceiling and the rest have more or less flat ceilings. The widest hall is 17 m wide, (23 m at upper balcony level) and the narrowest is 13,5 (the width at balcony level is 18 m).

The fans walls vary in angle from 7° to 25° outward, with a grand average of 15°. All fans have "projecting" ceiling structures, at least over the stage. These are surfaces which reflect overhead, frontal reflections into the seating. In four of the halls, the proscenium plane is "offset" laterally between the stage and the side walls. In the remainder, the sidewalls are continuous from the stage. Average width is between 18 m and 25 m, with maximum widths between 18 m and 32 m.

The non-symmetrical halls all have one "straight" sidewall whereas the other side wall is fanned outwards. The average width for this sample is between 17 m and 19 m.

The "Almost Shoebox" halls typically are halls with parallel sidewalls in the seating area, but with either a fan shaped transition area between the stage and the auditorium walls, or a large "offset" between the stage and side walls. All of them have more or less "projecting," overhead reflection ceiling surfaces, at least over the stage. The widths of these halls are 16 m to 22 m.

MEASUREMENT RESULTS

The measurements and procedures are described in detail in [1] and [8].

Sound Strength (G) and Early Sound Strength (G_e)

Figure 1 shows the measured Early sound strength G_e as a function of seat-count. As can be seen from Table I, there is low correlation between any of the strength parameters and seat count. However, with the Sibelius Academy as an outlier and the data omitted from the regression, the correlation of G_e becomes significant as seen in the figure. [The Sibelius design creates an early energy situation which is not typical; the side walls are narrow, parallel, large and very smooth, creating a "flutter-echo" effect. In addition, the ceiling at the stage is angled to provide significant early reflections.]

Table I.- Statistics for sound strength parameters

F	G	G_{early}	G_{late}
Average all halls	9,4	5,7	6,8
Standard Deviation	1,81	1,89	1,90
Correlation with average width	-0,33	-0,29	-0,36
Correlation with Seat Count	-0,46	-0,60	-0,27
Correlation with Seat Count, omitting Sibelius Academy	-0,59	-0,75	-0,36

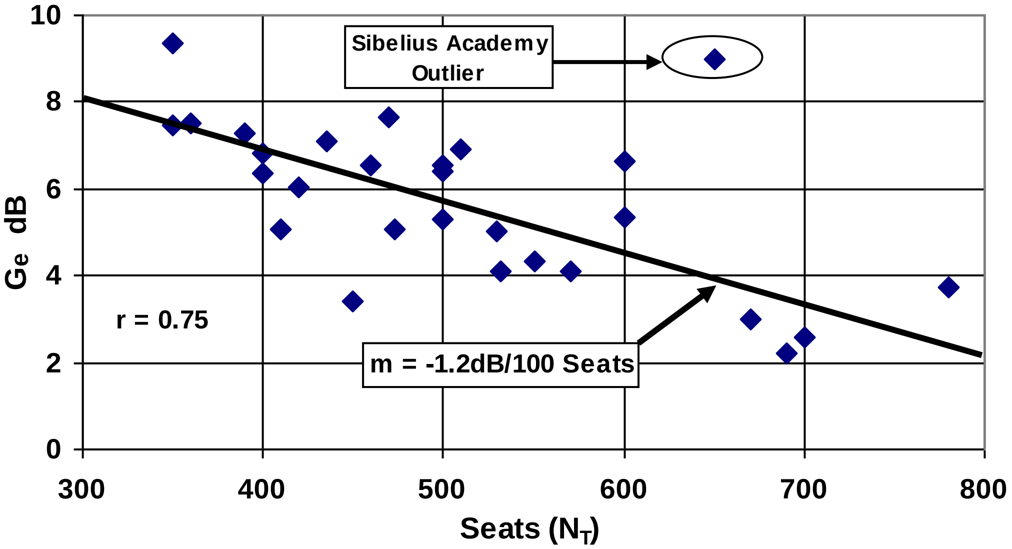

Figure 1: G_e vs seat count for 28 small Finnish halls

As one would expect, there is an inverse correlation between the early sound strength G_e and the number of seats (N_T). Of design interest is the rate of change of G_e with N_T which is shown to be at ≈ 1,2 dB/100 Seats. Notwithstanding any change in LF due to the size of the space, this reduction in G_e produces a reduction in ESI of ≈ 2%. Thus, doubling capacity, say from 400 to 800 seats, could decrease ESI by around 8% by virtue of the reduced early reflected energy. Since greater N_T usually translates to a wider room and therefore on average a lower LF value, increasing the number of seats is seen to decrease both LF, as well as G.

Of the 28 small halls studied, mean G_e ranged from +2,2 to +7,5 dB with an average of +5,7dB. This value, when applied to the equation for ESI given above, yields an average correction factor of +9,5%, which shows that the early energy in small rooms of this size is a major contributor to the overall effective spatial impression. This knowledge provides some design flexibility, using both LF and G_e as design factors. As for the total G in these halls, the mean value range per hall was +6,1 dB to + 12,8 dB with a grand average of G(Ave. 28 Halls) = +9,7 dB. These are significantly high values relative to large concert halls and the effects of such values on spatial impression and hall use are significant as discussed below. The average values in Table I for G(early) and G(late) indicate that among these halls a value of C_{80} ≈ -1.1 dB which is the same value as the arithmetic average of all C_{80} measurements.

Lateral Energy Fraction (LF) as a function of hall width

The behaviour of LF as a function of width was previously reported for small halls [9]. This current analysis has found a significantly greater decrease in LF with width than that reported by Barron [4] in his study of large North American and British Halls. Figure 2 shows the distribution of the values for small halls in this study with a mean width range of 13 m to 25m, and an average of 18 m. All but 5 of the 28 halls in this study are less than 20 m in mean width.

The range in mean widths of Barron's analysis on the other hand was from 13 m to 50 m in the British sample and from 24 m to 58 m in the American hall sample. The regression slopes tell an interesting story; that the greater the mean width of the halls studied, the less the percentage change in hall width from small to large and, therefore, the smaller the drop-off in LF with room width. Note also the significant lower LF values for the larger American halls relative to the smaller British halls studied.

Table II.- Regressions for LF vs Width

Halls Studied	Slope in LF/10 m	Correlation r
13 American halls	-2,6%	-0,65
17 British halls	-3,3%	-0,59
28 Small Finnish halls	-8,9%	-0,57
Finnish halls minus outlier	-12,9%	-0,67

The drop-off rates per 10 m of width increase are shown in Table II below and illustrated in Fig. 2. If we take the widest hall as an outlier, the regression becomes significantly greater at -12,9%/10 m. [The hall in question has large surfaces in the ceiling area reflecting lateral energy to the seats, in addition to coffers. It is an extreme fan from 18 m at the front to 32 m at the back, making the choice of an appropriate "average" width more difficult. In any event, while LF isn't very high, it is significantly higher than a hall of its size and mean width.]

There are significant design implications to be taken from the Table II and Fig. 2 data. Increasing the number of seats of a small hall significantly increases the width, both percentage-wise as well as relative to the increase in height. In fact, increasing the width of a hall while maintaining the same reverberation time essentially maintains a constant ceiling height. The result of diminished lateral reflections relative to frontal reflections is therefore obvious, other design features remaining the same.

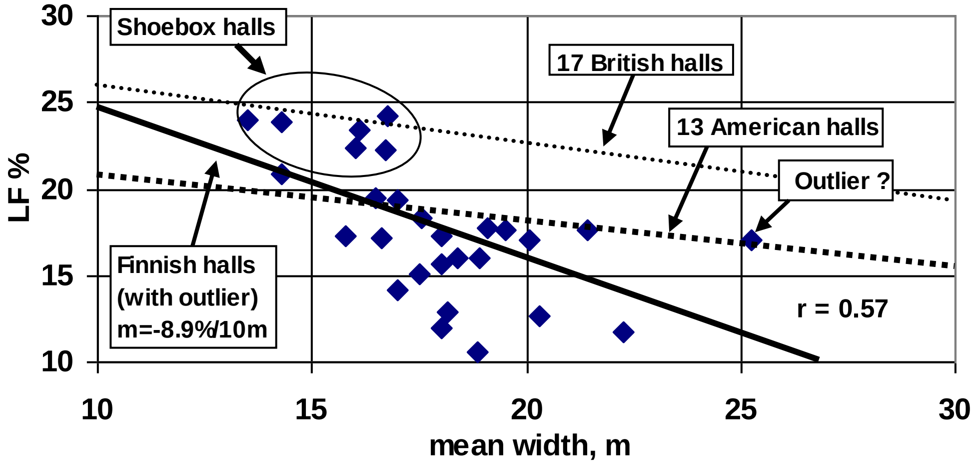

Figure 2: LF vs width for 28 Finnish halls plus Barron's [4] regression lines for larger halls

The impact of changing hall width in small halls is therefore significant. A reduction of ΔLF = 9% or more per 10 m of increased width is significant. Choosing a small hall's width, then, is seen as a significant factor affecting the design process, since a large LF value isn't necessarily always desirable as discussed below.

LF values as a function of hall type and design features

The halls in this study can be divided into 3 groups:

- Group A: LF < 15%
- Group B: 15% > LF < 20%
- Group C: LF ≥ 20%

There are six halls in Group A. Four of these are fan-shaped, and either very wide or with "projecting" ceiling surfaces above the stage. The other two halls are Shoebox but with large proscenium "offsets" at the side walls and with "projecting" ceilings.

There are fifteen halls in the intermediate range Group B. These are generally characterized as having either "very projecting" surfaces above the stage and/or proscenium "offsets" between the stage width and the front of the hall. Most of these can be described as either non-symmetrical or "almost Shoebox." Three of them are Shoebox halls, but with "projecting" surfaces above the stage increasing frontal reflections to the seating.

The seven halls in Group C are all Shoebox in design and, with the exception of the Sibelius Academy discussed above, all have horizontal ceilings and no lateral proscenium "offset." Seen in Fig. 2, these Shoebox halls compare rather well to Barron's regression of British Halls the smaller of which were comprised mostly of the Shoebox design.

Variation of LF within hall types as a function of design features

Having examined the trend of hall design type versus LF ranges and design features, the averages and variation in LF and ESI are given here as a function of hall type. Referring to Table III, the mean LF value varies from 21,7% for the Shoebox design down to 14,6% for fan-shaped halls.

Table III.- LF and ESI as a function of hall type

Hall Type (number)	Mean LF %	Variation in LF %	ESI % (Ave. & Var.)
Shoebox (10)	21,7	24,2 – 17,3	32.3 / 38,9 – 26,7
Non-symmetrical (4)	17,1	18,3 – 15,1	25,3 / 29,3 – 23,9
“Almost” Shoebox (4)	15,1	17,6 – 12,9	23,0 / 24,2 – 19,7
Fan (10)	14,6	17,6 – 10,6	24,6 / 20,2 – 31,6

The variation of LF within a hall type, when the reason for such variations is known, can yield valuable information on how hall design affects LF. For instance, within the Shoebox category, the highest LF values belong to “pure” rectangular halls with no projecting surfaces over the platform. The lowest performing hall in that category is made of glass panels and has structural elements in the proscenium-side wall zone which effectively absorbs some of the sound. In addition, each side wall panel is fanned back at about 5° essentially creating a fan-like, more frontal reflection.

The “almost” Shoebox category halls, while having parallel walls in the seating area, are notable by having “offset” surfaces in transition between the platform and the seating area, in addition to having some “projected” surfaces above the stage. The hall with the lowest LF = 12,9% has a fanned “offset” and a narrow platform (12,7 m), whereas the highest LF hall has a stepped “offset” and a wider platform (15,7 m). Appearing to be “Shoebox” in the seating area, they nevertheless have a lower mean LF value by 6½ %.

There is also significant variation in LF values within the Fan hall category. The higher LF values are attained through the use of articulated surfaces at the side walls intended to provide some lateral reflections. The lowest of these, with LF = 10,6% has a very widely fanned stage in addition to structures in the hall’s sidewalls which amount to providing absorption.

LF, G(total) AND ESI IN 28 FINNISH HALLS

The mean values for LF and G(total) for 28 Finnish halls are plotted in Fig. 3. Taking into account the highly correlated relationship (r = 0.91) between G_e and G(total) for these halls, Fig. 1 also estimates lines of constant ESI. Note that most of the halls with LF<20% have values of ESI in the range 20% to 25%. For these halls, since the strength is seen to range up to G=+10 dB, LF values in the 10% to 15% range are therefore found to be adequate from the point of view of the effective SI. Further, these data would indicate that the halls in the G(total)=+7 to +8 dB range, would perform best with chamber orchestras or less, while those in the +10 dB and greater range would be best suited for smaller groups and recitals. Finally, Shown in comparison, and providing context to our discussion are data points for larger well-known halls with ESI values from 18% to 26%.

Of particular interest are the halls at the top of Fig. 3, which have high values of LF, and mean G(total) values > +10 dB, giving ESI values from 30% to over 35%. These are all shoebox halls. Several are considered to be too loud, and/or reverberant, but work well for smaller ensembles and recitals. In these performance cases, then, where some restraint on the musical forces is applied to the space, no particular excessive SI is observed. Barron [4] reports similarly high ESI values for small British halls, and from data presented by Hidaka and Nishihara [10], even higher ESI results (> 40%) are deduced for European chamber music halls.

The relationships in Fig. 1 show that in balancing G(total) with hall use (symphony to soloist) the choice of LF is actually a key factor of the architectural design, and cannot be simply left to chance.

DISCUSSION AND CONCLUSIONS

Listening experience in these halls tells us that with even high values of G(total) > 10 dB, giving ESI values from 30% to over 35%, the results are subjectively good as long as the dynamic level of the performance is appropriate; that is, they work well for soloists, recitals and small ensemble and choral groups. With high G and high source power, there is an adverse reaction, not because of excessive ESI, but because of the experience of loudness “saturation.”

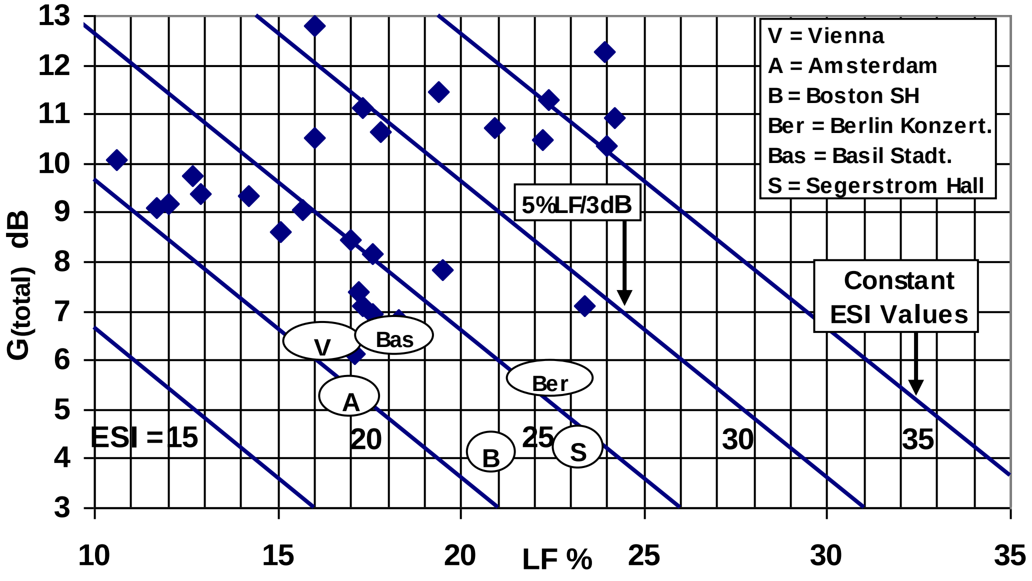

Figure 1: LF vs G(total) with approximate ESI values as a parameter

Controlling G(total) to be commensurate with the performance source output can be achieved with variable absorption, most effectively placed in the platform area, and in the hall’s reverberant field, being careful not to cover surfaces providing early lateral reflections.

In conclusion, this paper has shown that mean LF values between small halls varies a great deal, depending not only hall shape and width, but on other design features such of the transition zone between the platform and the seating. At the sides, where there is an “offset” between the stage walls and the hall’s, especially when this transition is fan-shaped, lower LF values are found. The same is true at the platform ceiling, if panels “project” early frontal energy, of course diminishing LF in the hall.

The authors suggest that ESI values in the range of from 20 to 25% work well for full orchestras as long as the G(total) is controlled to be in the +5 dB range. For smaller ensembles, greater G values are desirable and the increased ESI is acceptable as long as the source power doesn’t create loudness saturation.

Of the halls studied, eleven have resident orchestras with the largest being a 70 piece orchestra, and the smallest a 15 piece chamber group. For pure small ensemble and recital halls in the G(total) = +10 dB range, lower LF values can be tolerated, and the above discussion has given ideas as to the related architectural design correlates. Finally, when using variable acoustics to compensate for larger, louder performances, LF values should be designed in the range of from at least 17 to 20% to allow for good SI at the lower G values. At the same time, that absorption must not cover “lateral surfaces.”

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