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SPATIAL IMPRESSION AND ENVELOPMENT IN CONCERT HALLS

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1. INTRODUCTION

Spatial hearing is one of the fundamental aspects of concert hall listening, which has been studied over the last 40 years. In a way one might see the study as somewhat circular in that the prime concern in the 1960s has become a prime concern now. This paper will seek to discuss some of the history of this study, to record measurements on lateral energy fractions in British concert spaces and to consider the design consequences associated with current proposals for relevant objective measures. The nature of the important spatial effects in concert hall listening is certainly hard to untangle; one recent publication leaves reason to consider that the situation is more complex than the two separate spatial effects currently being considered.

2. ROOM IMPRESSION

In the 1960s it was assumed that spatial perception relied on the reverberant sound. As Kuttruff wrote [1, p.197]: "For a long time it was common belief among acousticians that spaciousness (better called subjective diffuseness) was a direct function of the uniformity of the directional distribution in the sound field: the higher the diffusion, the higher the degree of spaciousness. This belief originated from the fact that many old and highly renowned concert halls are decorated with statuettes, pillars, coffered ceilings and other projections which supposedly reflect the sound rather in a diffuse manner than specularly. It was the introduction of synthetic sound fields as a research tool which led to the insight that the uniformity of the stationary directional distribution is not a primary cause of spaciousness".

The key experiment was conducted in 1967 by Damaske [2] using broadband noise signals which showed that a sense of subjective diffuseness, or being surrounded by sound, could be produced by (incoherent) sound from four principal directions around the listener. In other words the directional acuity of listeners was not very high but "surround sound" was required. The conclusion for design of auditoria was that highly diffusing wall and ceiling surfaces were not essential but that for spatial effects the orientation of surfaces around audience locations should allow sound to arrive from the sides and behind as well as directly from the source.

Another major experiment from the 1960s was made by Reichardt and Schmidt [3] with a simulation system consisting of just direct sound and diffuse reverberation. At the time the spatial effect was called 'Raumeindruck' (room impression) and, by varying the relative levels of direct and reverberant sound, the transition for maximum room impression to zero perceived spatial reverberation could be made.

The conclusion, if one had reviewed the work on spatial effects associated with reverberation in 1970, would probably have been that sound had to arrive from four key directions and that the magnitude of the effect was determined by the ratio of early to reverberant sound.

3. SPATIAL IMPRESSION

The study of spatial perception in auditoria took a sudden change of direction when Marshall [4] suggested that there was an important spatial effect associated with early lateral reflections. He referred to it as "spatial responsiveness", a characteristic of the space in which the music is performed. Experiments with a simulation system [5] showed that reflection delay was of much less importance than lateral reflection level. As an objective measure of what was referred to as spatial impression, the early lateral energy fraction (LF) was proposed:

$$\mathbf{LF} = \int_{0.005}^{0.08} p_F^2(t).dt \Big/ \int_{0}^{0.08} p_O^2(t).dt \ , \qquad (1)$$

where $p_F(t)$ is the pressure measured at the listener position with a figure-of-eight microphone with the null pointing at the source and $p_O(t)$ is the pressure measured with an omni-directional microphone. Time t=0 corresponds to the arrival time of the direct sound. Results for LF in the four octaves between 125 and 1000Hz are averaged to produce a single value.

Between the work on spatial impression in the '70s and the end of the '80s, the main topic of discussion was the relative merits of LF or a second objective measure, based in interaural cross-correlation (ICC). Both measures have their advocates who defend the superiority of their preferred measure, e.g. [6]. Both measures are defined in the 1997 ISO Standard 3382. The early lateral energy fraction was proposed as a practical measure for use in music auditoria. Yet it is clear that spatial impression is caused by differences between the signals at the two ears; a situation with identical reflections from each side has a lateral fraction but produces no spatial effect. In this respect the ICC is superior, but identical signals at the two ears are not significant in practice and can be avoided in measurements in symmetrical halls by not having both the source and receiver on the line of symmetry.

The interaural cross-correlation coefficient is the maximum value of the normalised cross-correlation function in the time interval ±1ms. But whereas the early lateral energy fraction was defined from the start in terms of octave band measurements and microphones with particular directivities, there has been no such unanimity regarding measurement of ICC. There is also the problem with ICC measurements that at low frequencies the ICC hardly varies, whereas there is extensive evidence that low frequencies (including the 125Hz octave) are important for source broadening [5, 7]. Though ICC is closer to the processing mechanism used by our ears, it is certainly not identical and the early lateral energy fraction which presents no problems at low frequencies is probably a more practical measure.

4. ENVELOPMENT

In 1989 Morimoto and Maekawa [8] suggested that at least two subjective spatial effects occurred. They provided evidence that a sense of being enveloped by sound was independent of spaciousness (spatial impression caused by early reflections) and that envelopment was linked to incoherence (a low interaural cross-correlation) of the reverberant sound. Bradley and Soulodre [9, 10] have conducted further subjective experiments into spatial hearing. Their experiments were conducted in an anechoic chamber with a simulation system using five (or three) loudspeakers arranged symmetrically in front or to the side of subjects. They found that sound from behind had no special influence on the subjective effects being studied. The simulations involved direct sound followed by four discrete reflections and then reverberation whose relative level from different directions was varied.

Bradley and Soulodre basically agreed with Morimoto and Maekawa that there were two spatial effects which had in the past often been confused. Bradley and Soulodre called the two effects: source broadening and listener envelopment (LEV). Source broadening can be measured by the perceived apparent source width (ASW). Their experiments showed that ASW is predominantly determined by the early sound, whereas envelopment is governed by the late sound. Most earlier work had concentrated on source broadening, referring to it as spatial impression. The major study by Bradley and Soulodre concerned the objective determinants of envelopment. Just as perceived source broadening is influenced by sound level, so they found sound level also to be significant for LEV.

5. NOMENCLATURE

It will be clear from the above, that many words or expressions have been used for spatial effects in auditoria. Spaciousness, diffuseness and room impression have all been used, the first of these meaning different things to different authors. The proposal here is that spatial impression should refer to spatial effects in general. The two components of spatial impression currently isolated are source broadening and listener envelopment (LEV), as proposed by Bradley and Soulodre. Most publications on spatial effects in auditoria can be interpreted using these two terms, which will therefore be used here.

6. EARLY LATERAL FRACTION AND SOURCE BROADENING

Measurements of the early lateral energy fraction (LF) have been made in 17 British concert halls at an average of 11 microphone positions per hall. Details of the measurements are to be found in [11]; further information about the individual halls is included in [12].

Figure 1 shows the distribution of the 189 individual measured values of LF. The distribution turns out to be "almost certainly not normal" with a mean of 0.19. This mean can be compared with the theoretical value for a diffuse sound field of 0.33; the presence of direct sound obviously reduces the lateral fraction.

In two original publications [4, 13], it was suggested that spatial impression due to early lateral reflections might be influenced by the hall cross-section. Subsequent investigations showed that hall height has very little influence on the hall mean early lateral energy fraction. The best correlation ($r = -0.59$) is with hall width; for the 17 British halls this is shown in Figure 2. But though this is significant at the 2% level, the variation in mean LF is only 0.03 for the substantial change of 10m in the width of a hall. At least as important is the orientation of side wall surfaces, with fan-shape plans performing poorly and reverse-splay plans offering high LF values. This last option can be exploited in "vineyard terrace" type halls.

Also significant for source broadening is the sound level, but there is not agreement about the trade-off between LF and level. Work by Morimoto and Iida [14] leads to the following: Degree of source broadening = LF + (Early level)/60 [11]. A valuable insight into how source broadening may be perceived was provided by Kuhl [15] in 1978. Kuhl suggests that during a musical performance, in which of course the sound level fluctuates, there is a threshold (which can be specified in terms of musical dynamics) for source broadening to occur. In some halls, for example, source broadening can only be perceived with the orchestra playing *fortissimo*, in others *mezzoforte* is sufficient. This dynamic threshold will be determined by the LF and early sound level relative to the source power at the listening seat in question. The situation is summarised in Figure 3. The validity of this approach can be assessed by listeners at concerts.

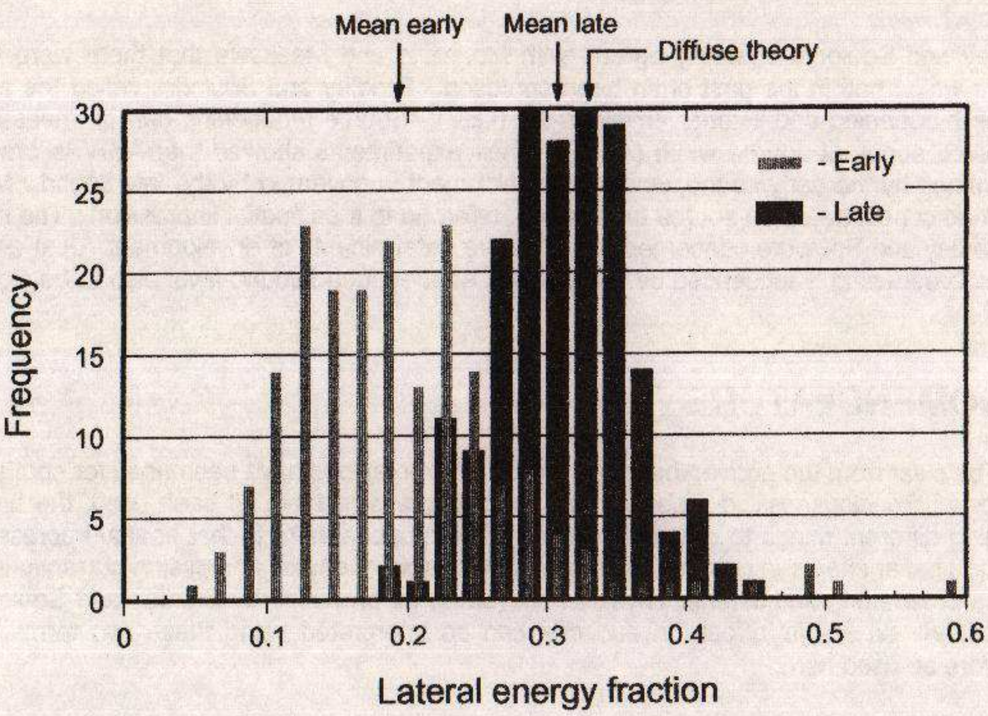

Figure 1. Distributions of the early and late lateral energy fractions measured in 189 receiver locations.

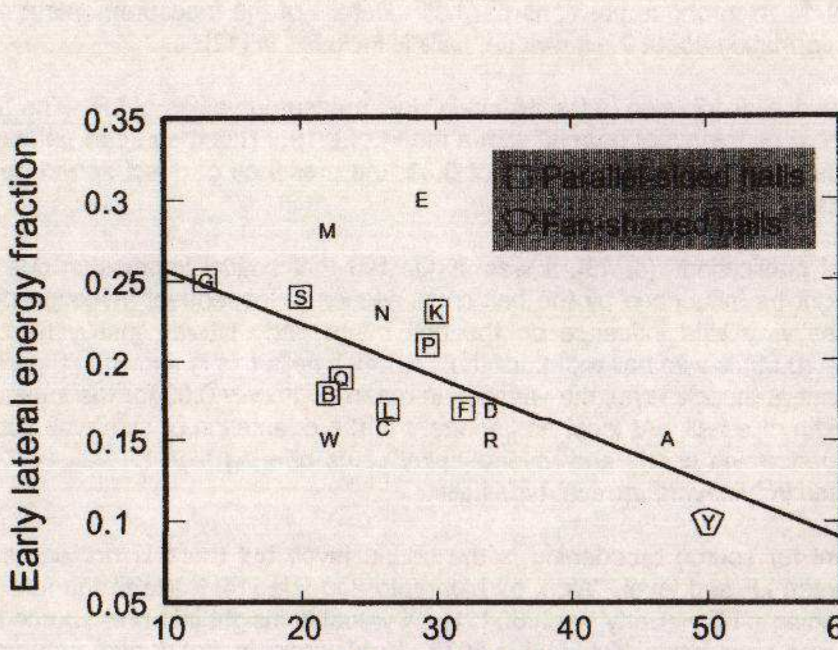

Figure 2. Hall mean early lateral energy fractions as a function of hall width.

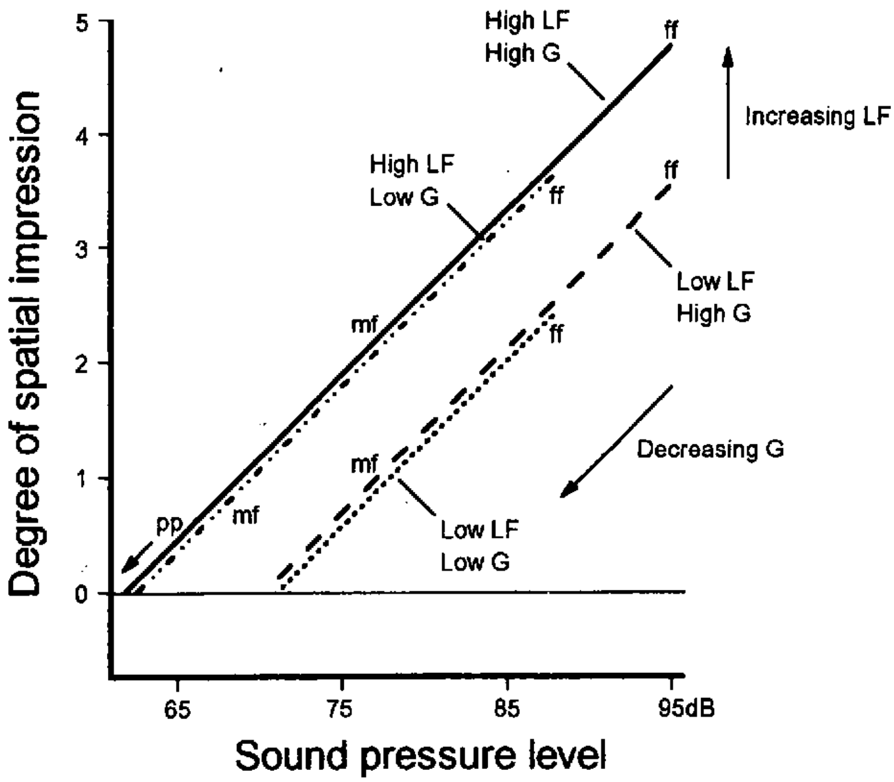

Figure 3. Diagrammatic representation of perceived spatial impression after Kuhl [15]. The relationships for four halls are given with two parameters: LF - lateral fraction and G - strength (or relative total sound level). Music dynamics ff, mf and pp.

7. LATE LATERAL ENERGY FRACTIONS AND ENVELOPMENT

Bradley and Soulodre [9, 10] have proposed the late lateral level (GLL) as a measure of listener envelopment (LEV):

$$\mathrm{GLL} = 10 \log \left\{ \int_{0.08}^{\infty} p_F^2(t).dt \Big/ \int_0^{\infty} p_A^2(t).dt \right\} = \mathrm{LLI} + G_L\,, \quad \mathrm{dB}, \qquad (2)$$

where $p_F(t)$ is as before and $p_A(t)$ is the response to the same source at a distance of 10m in a free field. Time t is measured relative to the arrival time of the direct sound. The late lateral sound level is measured at four octave frequencies (125 - 1000Hz) and averaged.

As shown in equation (2), the late lateral level is calculated by adding the late level (G_L) to the late lateral index (LLI), which is the logarithmic version of the late lateral energy fraction (LLF): LLI=10.log(LLF). The values of these quantities as measured in British halls will be discussed here.

Figure 1 shows the distribution of measured values of the late lateral energy fraction. The scatter is much smaller that it is with the early fraction, the distribution is "highly normal" and the mean value of 0.31 is very close to the theoretical value for a diffuse sound field of 0.33. In other words, as far as this measure is concerned, late sound fields behave much as if they were diffuse, and that there is only a small variation in measured LLF values.

A surprising result emerges if hall mean values of LF are correlated with hall mean LLF values, Figure 4. There is no particularly strong correlation between individual early and late fractions, but when averaged by hall the mean values are correlated with a coefficient of 0.80, significant at the 0.1% level. Halls with a high average early lateral fraction tend to have high mean late fractions. It is interesting to speculate on the possible geometrical reasons for this correlation. But what Figure 4 also shows is the small scatter in measured values of the late lateral energy fraction.

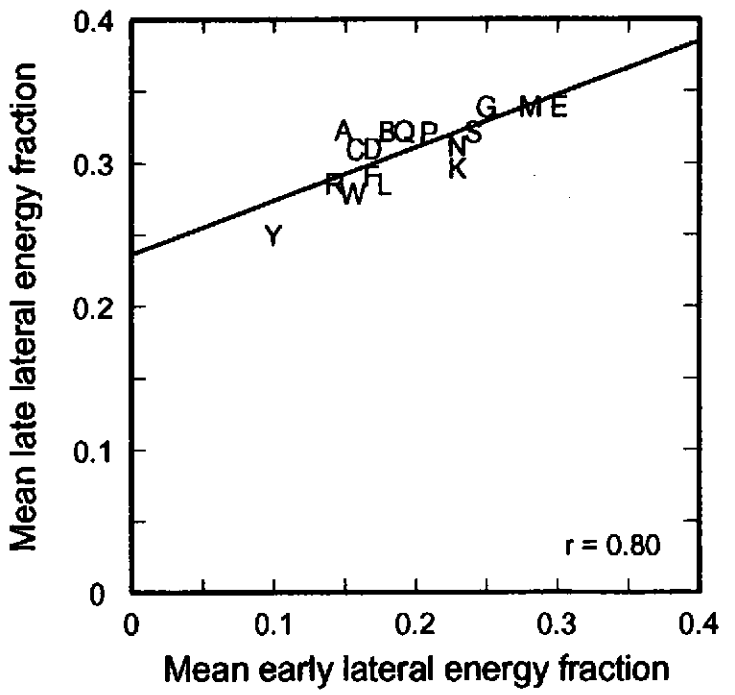

Figure 4. Mean hall late versus mean hall early lateral energy fractions.

Efforts have been made [16], using measured data from British halls, to determine the relative importance of the directional and level components in the proposed measure for LEV, the late lateral level. The standard deviation for measured values of the late lateral index (LLI) was 0.68dB, compared with a standard deviation for the late level (G_L) of 3.27dB. If LLI and G_L are independent of each other, as they prove in fact to be, then the ratio between the two standard deviations gives the relative importance of the two quantities. The result [16] is that the level G_L contributes 83% to the variation of the late lateral level, whereas the late lateral index only contributes towards 17% of the variation.

The late level is thus the dominant determinant of GLL. If one wants to optimise GLL to achieve optimum envelopment, then maximising the late level is the appropriate strategy. To establish the design implications for achieving strong envelopment, we need to establish the main influences on the late level. Revised theory for sound level is useful here [17], since the theoretical values are correlated with measured values of the late level with a coefficient r = 0.89. A correlation with a coefficient of 0.82 is achieved between the late level and the traditional expression for the reflected sound level, which contains T/V, the ratio of the reverberation time to the auditorium volume. But from the Sabine formula this ratio is inversely proportional to the total acoustic absorption.