

THE COMPONENTS OF SPATIAL IMPRESSION IN CONCERT HALLS

Gilbert A. Soulodre
McGill University
Montreal, Quebec, H3A 1E3.

John S. Bradley
National Research Council
Ottawa, Ontario, K1A 0R6.

Introduction:

Spatial impression is usually loosely described as the sense of being enveloped by the sound or as an increase in the apparent width of the source. In a previous study by the authors [1], the findings of Barron and Keet [2,3] were verified in experiments using sound fields consisting of a direct sound and a few early reflections. The results confirmed that the apparent width of the source increases with increasing early lateral energy. It was also found however that although a broadening of the source was evident for these simple sound fields, listeners never felt enveloped (surrounded) by the sound. In a series of informal listening tests, it was found that a sense of *listener envelopment* could be obtained by including late arriving or reverberant energy in the sound fields. Furthermore, the addition of reverberant energy was found to reduce the listener's ability to discriminate the effects of early lateral energy. Several subjective experiments were conducted to explore these issues [4,5]. The results indicate that spatial impression has two distinct components: apparent source width (ASW) and listener envelopment (LE).

Method:

All tests were in the form of double-blind paired comparisons using music as the stimulus. Subjects could switch between the two sound fields in a pair for as long as they required in order to make their decision. Two methods were employed to simulate the sound fields used in the experiments: multiple loudspeakers in an anechoic chamber, and reproduction of anechoic music convolved with binaural impulse responses of real concert halls.

Effect of reverberation on ASW:

The first experiment was designed to show how late arriving sound affects a listener's ability to detect changes in the early lateral energy. Subject's listened to pairs of sound fields and rated the difference in ASW on a five-point scale. The sound fields consisted of four distributions of early lateral energy and three levels of reverberant energy, thus giving a total of 12 sound fields. The results, shown in Figure 1, demonstrate that differences in early lateral energy (as measured by ΔLF or $\Delta IACC$) become increasingly difficult to detect as the level of reverberation (as measured by C80) is increased.

This finding was confirmed in a test using the binaural simulator. Ten sound fields of varying early lateral energy were subjectively rated in terms of ASW. The impulse responses used to create the sound fields were

then truncated to eliminate all energy after 80 ms, and the rating was repeated. It was found that changes in ASW were more easily and consistently detected for the truncated sound fields.

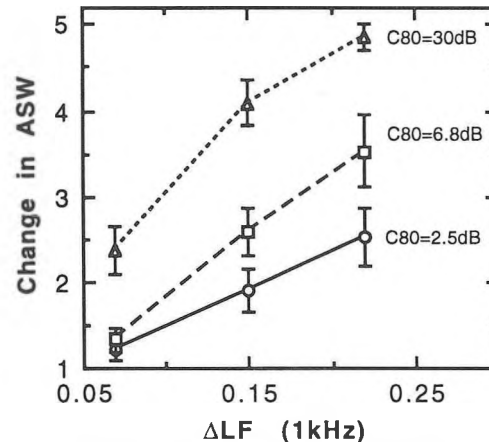


Figure 1. Perceived change in ASW vs. ΔLF with 90% confidence limits.

The degree to which reverberation affects the audibility of changes in ASW can be appreciated when one notices in Figure 1 that a difference in LF of 0.22 with C80=2.5 dB is perceived to be the same as a difference in LF of 0.07 with C80=30 dB. A $\Delta LF=0.22$ approaches the maximum measured in real halls, while a $\Delta LF=0.07$ approaches the limit of detectability under free field conditions.

Listener Envelopment (LE):

Informal listening tests indicated that some late arriving energy was required to produce a sense of listener envelopment. Therefore, a series of subjective experiments were conducted in an anechoic chamber to examine how the temporal distribution, level, and spatial distribution of the late energy affected the perception of listener envelopment.

The temporal distribution of the late energy was found to be important to listener envelopment. Results indicate that some energy must arrive after about 80 ms in order to obtain a sense of LE. LE was also found to be related to reverberation time. Longer RT's provided a greater sense of listener envelopment.

The level of the late energy was found to have a strong effect on LE. Specifically, higher levels of reverberant energy resulted in increased listener envelopment.

The effect of the spatial distribution of the late energy was analogous to the effect found by Barron [2] for early

lateral reflections. Listener Envelopment increased as the late energy from lateral angles increased. The highest degree of listener envelopment was obtained when the late sound included energy from ± 90 degrees.

Predicting Listener Envelopment:

Using the binaural simulation method, a subjective test was conducted in which ten subjects rated ten sound fields according to LE. The findings from the anechoic chamber tests were then used in an attempt to derive a suitable predictor of these subjective results.

A measure of LE must include terms that account for the level and spatial distribution of the energy arriving after 80 ms. As such, it was found that LE was very strongly related to the A-weighted level of the late lateral energy as defined in Equation 1. An A-weighting was used since it was found to correlate best with the perception of loudness in concert halls [6].

$$LG_{80}^{\infty} = \int_{80}^{\infty} p^2(t) \cdot \cos(\alpha) dt / \int_0^{\infty} p_A^2(t) dt \quad (1)$$

where $p(t)$ is the impulse response of the room and α is the angle between the direction of arrival of the reflection and a line through the two ears. The symbol $p_A(t)$ represents the response of the source measured at a distance of 10 m in a free field. The results of the subjective test are plotted against LG_{80}^{∞} in Figure 2.

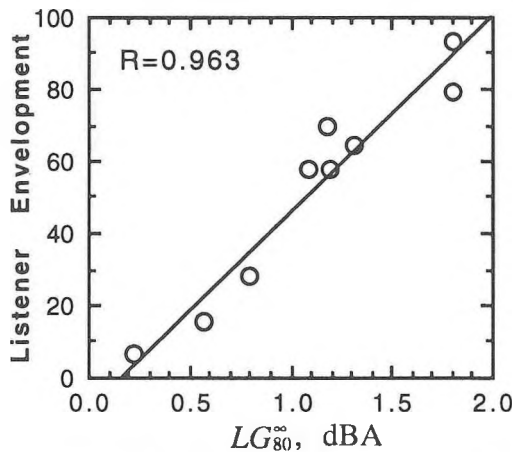


Figure 2. Listener Envelopment vs. LG_{80}^{∞} .

A final experiment was conducted to verify that ASW and LE are indeed separate perceptual phenomena. Four sound fields consisting of two levels of ASW and two levels of LE, were presented to subjects in randomly ordered pairs. The subjects were asked to identify differences in the sound field pairs as either a change in ASW or a change in LE. The results showed that there are two distinctly different aspects to spatial impression, and that subjects could correctly identify them.

The difference between ASW and LE can be explained in terms of the precedence effect. Early reflections will tend to be integrated with the direct sound and will therefore tend to be temporally and spatially fused with

the direct sound. This will increase the apparent level of the direct sound and cause some ambiguity as to its perceived location. The result is an increase in ASW. Later arriving sound however, is not integrated with the direct sound and thus leads to more spatially distributed effects that appear to envelop the listener.

Conclusions:

Spatial impression is composed of two components: apparent source width and listener envelopment. Apparent source width is related to early lateral reflections, while listener envelopment is related to the relative level of the late lateral reflections. It has further been shown that the effects of early lateral reflections are less audible in the presence of reverberation. This suggests that listener envelopment is the more important component of spatial impression.

The new results have considerable significance for the design of concert halls. Prior to this study, increased spaciousness was assumed to require only strong early lateral energy. As a result, some newer halls have introduced large reflector panels specifically to add strong early lateral reflections. This design approach however, does not guarantee that sufficient late lateral energy will result. Conversely, designs intended to maximize later arriving lateral energy will usually tend to also increase early lateral reflections and thus ASW. For example, a shoe-box shaped hall will tend to provide both early and late lateral energy while a fan-shaped hall might include reflector panels to provide early lateral reflections without producing significant late lateral energy. The importance of late lateral energy may be another reason for the success of shoe-box shaped concert halls.

References:

1. Bradley, J.S., Soulodre, G.A., & Popplewell, N., "Pilot study of simulated spaciousness", *J. Acoust. Soc. Am.*, Vol. 93, No. 4, (1993).
2. Barron, M., "The subjective effects of first reflections in concert halls: The need for lateral reflections", *J. Sound Vibr.*, Vol 15, No. 4, pp.475-494 (1971).
3. Keet, W. De V., "The influence of early lateral reflections on spatial impression", *Proc. 6th ICA*, E-2-4, Tokyo (1968).
4. Soulodre, G.A. and Bradley, J.S., "The influence of late arriving energy on concert hall spatial impression", *Proc. Sabine Cent. Symp.*, pp.101-104, Cambridge, MA (1994).
5. Bradley, J.S. and Soulodre, G.A., "The influence of late arriving energy on spatial impression", submitted to the *J. Acoust. Soc. Am.*
6. Soulodre, G.A. and Bradley, J.S., "Subjective evaluation of new room acoustic measures", submitted to the *J. Acoust. Soc. Am.*