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The influence of late arriving energy on spatial impression

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New subjective experiments using sound fields simulated in an anechoic room confirm that spatial impression in concert halls is composed of at least two distinct aspects: apparent source width and listener envelopment. Previously published research has shown that apparent source width is related to the relative level of early lateral reflections. This new work demonstrates that listener envelopment is related to the level, direction of arrival, and temporal distribution of late arriving reflections. It is further shown that increased amounts of listener envelopment decrease the subject's sensitivity to changes in the apparent source width of the sound field. Listener envelopment is related to objective acoustical measures, and the implications for concert hall design are discussed.

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INTRODUCTION

Spaciousness or 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. Most authors have not differentiated between envelopment and apparent source width. Some refer to the sound enveloping the source[1] while others describe the sound enveloping the listener. This paper describes a series of experiments which confirm that there are at least two distinct dimensions to spatial impression, apparent source width (ASW) and listener envelopment (LEV), and that each is related to different aspects of the sound field.

The pioneering work of Keet and Barron related spatial impression to objective measures. Keet[2] found judgments of ASW to relate to short-time cross correlations obtained using a stereo pair of cardioid microphones and a test signal radiated into an auditorium from a single loudspeaker. In more extensive studies, Barron[3] and Barron and Marshall[4] related spatial impression to the relative level of the early arriving lateral sound energy. Although they called the perceived effect "spatial impression," when described in detail they refer to an apparent broadening of the source. The authors' previous work,[5] using simple sound fields consisting of a direct sound and a few early lateral reflections, confirmed that ASW was related to the relative strength of the early lateral reflections. The variation in the subjective judgments of ASW were similarly related to measures of the lateral energy fraction of the early arriving sound (LF_0^{80}), and to the interaural cross correlation of the early sound field ($IACC_0^{80}$). (LF_0^{80} is the lateral energy fraction of the early arriving sound, i.e., the fraction of the sound energy arriving from the side or lateral directions within 80 ms after the direct sound. Similarly, $IACC_0^{80}$ is the interaural cross correlation of sound arriving at the ears of the dummy head between 0 and 80 ms after the direct sound.) However, studies using a binaural simulator indicated that there wee situations where $IACC_0^{80}$ and LF_0^{80} did not predict the same effect.[6]

While in our previous work increased early lateral reflection energy led to increased ASW, it never gave any impression of the listener being enveloped by the sound. However, the results of this paper demonstrate that listener envelopment is detected when there is significant late arriving lateral energy. This distinction between ASW, caused by early lateral energy, and LEV, caused by later arriving lateral energy, has not previously been clearly delineated.

Early studies had tended to relate perceived spatial effects to diffuse reverberation. For example, Kuttruff[7] summarizes early work by Reichardt and Schmidt that related spaciousness to a direct-to-reflected sound level ratio. After the discovery of the importance of early lateral reflections, most work has ignored the effects of later arriving sound on spatial impression.

Morimoto and Pösselt[8] considered reverberant energy and early lateral energy to have equivalent effects on spaciousness. They defined spaciousness as the width of the auditory event. Their experiment forced the subjects to equate the spatial effects of reverberant energy and early reflections. Because the subjects were not asked to consider envelopment, it is not possible to say whether the reverberant energy was perceived as an apparent change in source width or listener envelopment. The experience gained from the new experiments reported in this paper suggest that the details of the sound fields used by Morimoto and Pösselt (reflections only from ±90° and delayed by 50 ms) would have tended to make it more difficult to differentiate between ASW and LEV. Bilsen and Brinkman[9] also showed that reverberation influenced judgments of spaciousness but did not suggest that the effects of reverberation were different from the effects of early lateral reflections.

Morimoto and Maekawa[10] carried out tests that suggested that listeners can discriminate two aspects of spatial impression. These corresponded to what we are calling "apparent source width" and "listener envelopment," and they showed that these subjective dimensions were related to

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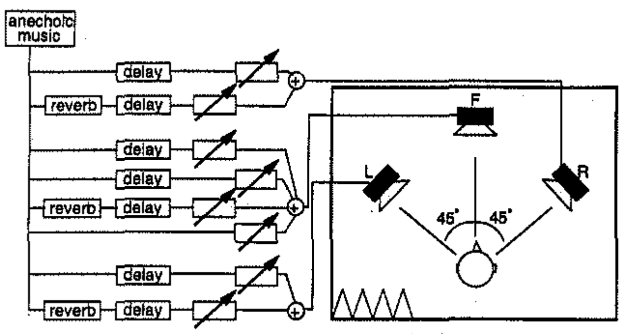

FIG. 1. Experimental setup of the loudspeakers and associated electronics.

$IACC_0^\infty$ and $IACC_{80}^\infty$, respectively (the interaural cross correlations of the total and late arriving sound). However, in their 1989 paper, ASW was usually referred to as spaciousness, and the term "broadening" was used as the more general overall concept. Their work was further clarified in a 1993 paper[11] in which they defined ASW as "the width of a sound image fused temporally and spatially with a direct sound image." They defined envelopment as "the fullness of sound images around a listener." The results reported in this paper confirm these concepts and extend our understanding of them.

After the earlier experiments with simple sound fields, the authors tried various combinations of level, angle of arrival, and time delay of early reflections in an attempt to create listener envelopment. Listener envelopment was only observed when late arriving lateral energy was added to the simulated sound fields.[12] Further, the addition of late arriving lateral energy appeared to reduce the listener's ability to discriminate the effects of early lateral reflections.

I. METHOD

A total of six experiments were conducted using simulated sound fields in an anechoic chamber. Depending upon the experiment, three or five loudspeakers were used to radiate sounds that consisted of a simulated direct sound, delayed early reflections, and later arriving energy. Figure 1 illustrates a typical setup using three loudspeakers. Using programmable digital reverberators and equalizers, the experimental setup allowed independent control of the level and time delay of both the reflections and reverberation sent to each loudspeaker. Separate digital reverberators were used for each loudspeaker to ensure that their outputs were not highly correlated. Experiments were automated and a computer controlled the changes to the sound fields and recorded the subjects' responses.

All tests were in the form of paired comparisons. In most cases, subjects rated the magnitude of the difference between a pair of sound fields. The stimulus used for all of the tests was an anechoic orchestral recording consisting of the first 20 s of Handel's Water Music. The music was repeated continuously throughout each test at an average level of approximately 72 dBA at the listener's position. In each test, all sound fields had the same A-weighted level. Using a small keypad, subjects could toggle between the two sound fields of each pair as many times as they wished until they had decided on their response. After the subject entered a response score using the keypad, the computer controlling the experiment randomly selected the next pair of sound fields.

Tests used between seven and ten subjects and usually included repeated samples of the sound fields. There was always a short practice session before each test to ensure that the subjects were familiar with the requirements of each test and so that they were aware of the range of conditions in that test.

In each experiment, sound fields were set up to have the desired objective parameters using broadband impulse response measurements. The loudspeakers were equalized to have flat responses and no attempt was made to vary acoustical parameters as a function of frequency. All objective measurements of the sound fields were obtained using our auditorium acoustics measurement software, RAMSOFT-II.[13] This system provides octave-band values of a number of room acoustics quantities. Broadband values were obtained by averaging over various octave bands.

TABLE I. Description of the 20 sound fields used in experiment 1. [LF_0^{80} (125–2 kHz) is the mean measured LF_0^{80} averaged over the octaves from 125 to 2 kHz.]

C80 (dB)	LF_0^{80}(125–2 kHz)			
2.5	0.05	0.12	0.20	0.28
3.9	0.05	0.12	0.20	0.28
6.8	0.05	0.12	0.20	0.28
9.6	0.05	0.12	0.20	0.28
30.	0.05	0.12	0.20	0.28

II. EXPERIMENT 1

The first experiment was intended to show how late arriving energy affects a listener's ability to detect changes in early lateral energy. Ten subjects listened to pairs of sound fields and were simply asked to identify the one which they perceived to have greater apparent source width. The sound fields consisted of the 20 combinations of five levels of late arriving energy and four values of early lateral energy, as given in Table I. For a given level of reverberant energy (i.e., one row in Table I), listeners compared all six combinations of the four values of early lateral energy. In this way, each subject effectively provided a ranking of the sound fields according to ASW. This was repeated for all five levels of the reverberant energy. Thus in total, each subject made 30 comparisons.

The structure of the sound fields is illustrated in Fig. 2. The signal from the front loudspeaker (F) contained the direct sound and two early reflections, while the left (L) and right (R) loudspeakers each contributed a single early reflection. As well, a reverberant decay was added to each of the three loudspeakers. The onset of the reverberant energy was delayed by more than 80 ms (relative to the direct sound) so as not to affect the early portion of the sound field. The relative level of early lateral energy, as measured by LF_0^{80}, was altered by varying the distribution of the early reflections between the front and side loudspeakers. This was accomplished while keeping the total level of the early energy,

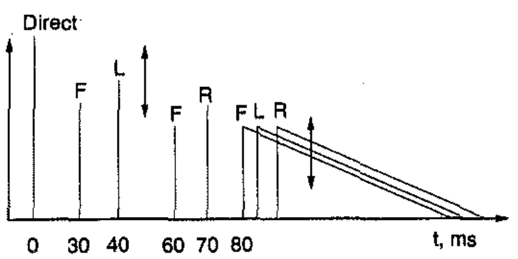

FIG. 2. Symbolic impulse response showing the structure of the sound fields used in experiments 1 and 2 (F=front, L=left, and R=right).

and hence C80, constant. C80 is the early-to-late arriving sound energy ratio in decibels where the limit of the early sound interval is 80 ms.) Varying the level of the reverberant energy, which was equally distributed among the three loudspeakers, produced the five levels of reverberant energy as measured by C80. Because the reverberant energy was equally distributed among the three loudspeakers, there were no changes in the spatial distribution of this energy. The overall sound-pressure level of each sound field was adjusted to 72 dBA. The controlling instrumentation was configured as illustrated in Fig. 1.

The results of the experiment are given in Fig. 3. The number of subjects who made errors in judging the relative width of the sound fields is plotted versus C80. Thus each point is the total number of subjects that made errors over all differences in LF_0^{80} for each C80 value. It should be noted that an error corresponds to choosing the sound field with the smaller LF_0^{80} as the wider of the two. When there was no reverberation (measured C80=30 dB), only one of the ten subjects made an error in correctly selecting the widest of each of the six sound field pairs. However, as the level of reverberant energy increased, the number of subjects who made errors systematically increased. Thus the differences in ASW, caused by changes in early lateral reflection levels, were more difficult to detect in the presence of reverberant energy.

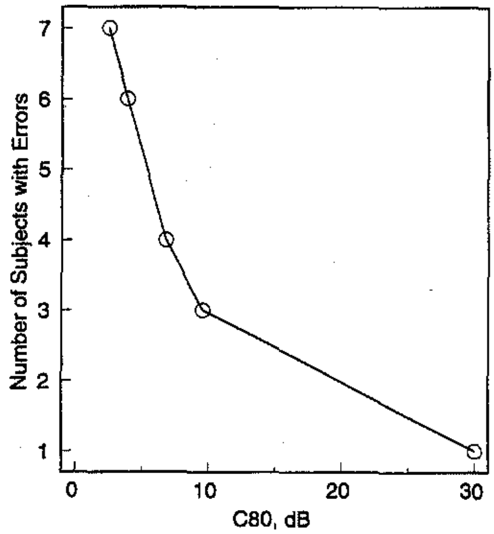

FIG. 3. Number of subjects with errors in selecting the wider sound field vs the level of the late arriving sound energy (total number of subjects was 10).

TABLE II. Description of the 12 sound fields used in experiment 2. [LF_0^{80} (125–2 kHz) is the mean LF_0^{80} averaged over the octaves from 125 to 2 kHz.]

C80 (dB)	LF_0^{80} (125–2 kHz)			
2.5	0.05	0.12	0.20	0.28
6.8	0.05	0.12	0.20	0.28
30.	0.05	0.12	0.20	0.28

III. EXPERIMENT 2

A limitation of the first experiment was that there was no indication of the magnitude of the effect of late arriving sound energy on judgments of ASW. Therefore in the second experiment, subjects were asked to rate the difference in ASW of each pair of sound fields on a five-point scale. A score of one indicated that the two sound fields were "the same" while a score of five indicated that they were "very different."

A subset of 12 sound fields from experiment 1 was used consisting of three levels of C80 by four values of LF_0^{80} as given in Table II below. For each level of C80, subjects compared the six combinations of the four values of LF_0^{80}. Because there were three different C80 values, there were 18 different comparisons. Subjects repeated the comparisons three times. Again, the sound field pairs were presented in random order. Figure 4 shows the mean scores and 95% confidence limits of the eight subjects versus differences in LF_0^{80} between sound fields. To produce this plot, the data were averaged into three groups having δLF_0^{80} values of 0.075, 0.150, and 0.225. An analysis of variance test of these results showed significant main effects ($p<0.001$) of both C80 and the difference in LF_0^{80} values, as well as a significant interaction ($p<0.001$) of thee two objective measures. (Here p is the probability of the result occurring by chance.)

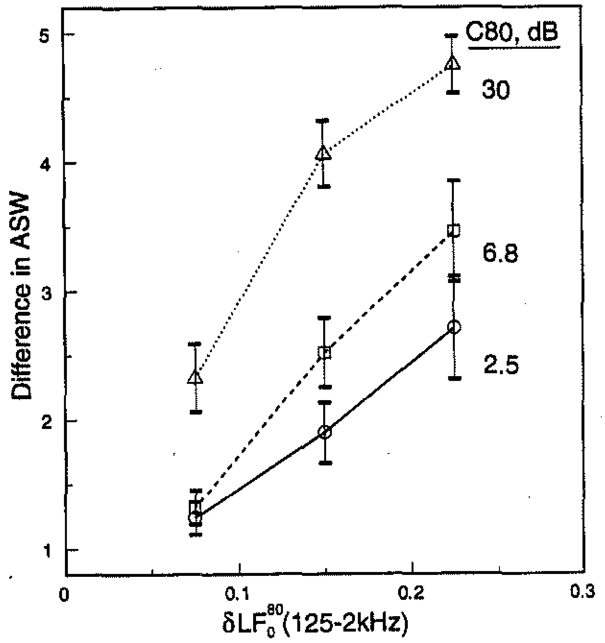

FIG. 4. Mean ratings and 95% confidence limits of the difference in ASW as a function of the change in broadband LF_0^{80} and C80.

That is, the perceived differences in ASW between sound field pairs increased with increasing differences in LF_0^{80}. Furthermore, increased levels of late arriving sound made it more difficult for subjects to detect changes in ASW. The results of this experiment confirm the finding of experiment 1 that differences in early lateral energy (as measured by LF_0^{80} or $IACC_0^{80}$) become increasingly difficult to detect as the level of reverberation (as measured by C80) is increased. With no late arriving energy (measured C80=30 dB), a change in LF_0^{80} of only 0.07 was apparently readily detected. However, with the highest level of late energy (C80=2.5 dB), a 0.24 change in LF_0^{80} resulted in approximately the same subjective ASW score as the 0.07 change in LF_0^{80} without reverberant energy. A change in LF_0^{80} of 0.24 is close to the largest observed difference between real halls, while a change of 0.07 is close to the limit of detectability in nonreverberant conditions. These results suggest that the importance of early lateral reflections may be exaggerated in the results of experiments using simple sound fields without reverberant energy. In realistic sound fields with significant late arriving sound energy, early lateral reflections will be less effective at increasing ASW.

There is evidence in the literature to support the finding that differences in early lateral energy are more difficult to detect under reverberant conditions. Barron (Ref. 3, p. 485) indicated that subjects found his experiment to be more difficult in the presence of reverberation, but it appears that he did not pursue this issue. From the work of Bilsen and Brinkman,[9] one can derive that the threshold for a perceived change in lateral reflections increased in the presence of reverberation. A similar conclusion regarding the threshold of detection of lateral reflections in the presence of reverberation can also be derived from the work of Morimoto and Pösselt.[8] However, neither of these previous studies identified the increased threshold of perception of early lateral reflections in the presence of late arriving energy.

Figure 4 shows that without reverberant energy (measured C80=30 dB), subjects could readily detect a change in LF_0^{80} of 0.07. This suggests that a just-noticeable difference in LF_0^{80} values is less than the 0.07 suggested by Barron and Marshall.[4] This would agree with comments by Morimoto and Pösselt.[8]

IV. EXPERIMENT 3

Informal listening tests indicated that late arriving or reverberant energy seemed to provide a sense of listener envelopment that was not experienced with early reflections alone. The results of the first two experiments demonstrated that the same late arriving sound energy could also modify perceptions of early lateral reflections. The third experiment was intended to investigate the influence of late arriving energy on listener envelopment by varying the level and time of arrival of a gated burst of energy from a digital reverberator.

Figure 5 illustrates the structure of the sound fields used. The direct sound and four early reflections were held constant. The complete reverberant decay of the first two experiments was replaced by a gated burst of energy. The duration of the burst was 70 ms and the level and arrival time of the burst were varied to create the different sound fields of this experiment. The energy of the gated burst was distributed across the three loudspeakers to match the distribution of early energy. In this way, the gated burst did not change the ratio of lateral to nonlateral energy, and shifting the gated burst in time did not change measured values of the lateral energy fraction LF_0^{80} and produced only very small changes (e.g., ±0.03 at 1000 Hz) in the interaural cross correlation $IACC_0^{80}$.

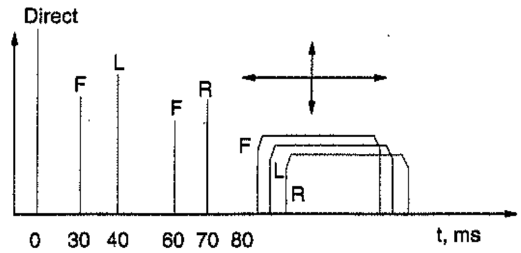

FIG. 5. Symbolic impulse response showing the structure of the sound fields used in experiment 4 (F=front, L=left, and R=right).

Six sound fields were created using combinations of two levels of the burst and three delay times for the start of the burst. The levels of the burst were −6 and −1 dB relative to the early sound energy. The onset times (δt) of the burst were 0, 80, and >100 ms relative to the direct sound. The longest onset time was set to maximum possible before echo disturbance was audible and was therefore different for the two levels of the gated burst. With a 0-ms burst delay, all of the energy of the burst arrived within the first 80 ms after the direct sound. One of the sound fields was used as a reference (C80=6 dB, δt=0 ms), and subjects compared each sound field to this reference. Each pair of sound fields was randomly presented eight times, giving a total of 40 presentations. All sound fields were presented at the same A-weighted level. Subjects were asked to rate the difference in listener envelopment (LEV) between the two sound fields on the same five-point scale used in the previous test. Listener envelopment was described to the subjects as being the sense of feeling surrounded by the sound or immersed in the sound.

The average results for the seven subjects are given in Fig. 6 which shows the perceived change in LEV versus onset time for two levels of the gated burst. An analysis of variance test of these results indicated highly significant main effects ($p<0.001$) of both the burst level and time delay on the subjective responses. Interaction effects were not significant. Listeners indicated feeling enveloped when the gated burst arrived more than 80 ms after the direct sound (i.e., when there was some energy beyond 80 ms). The degree of envelopment increased with the level of the burst and with increasing delay time. The increase in the level and delay time of the burst were, of course, limited by the onset of audible echo disturbance approximately indicated by the shaded area in Fig. 6.

These results indicate that listener envelopment and apparent source width are separate components of spatial impression. That is, previous studies have shown that the ASW is influenced by the relative level of early lateral reflections;

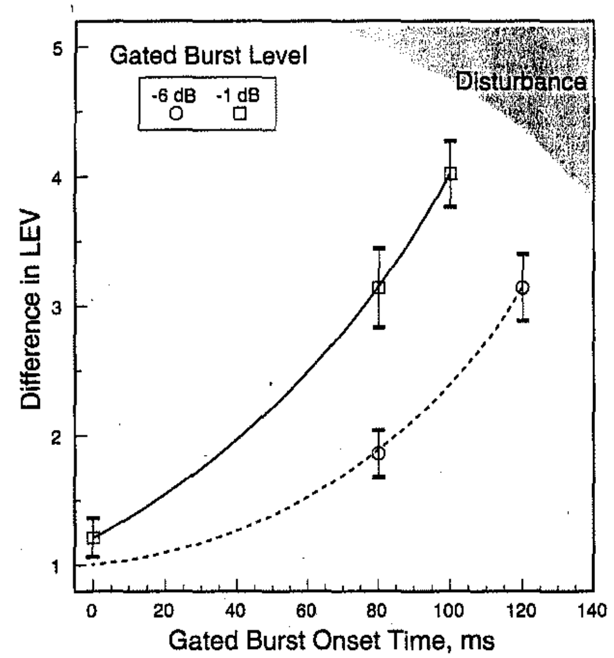

FIG. 6. Mean scores and 95% confidence limits of the difference in LEV as a function of the gated burst level and onset time.

the present results show that LEV is experienced when significant later arriving lateral energy is present.

V. EXPERIMENT 4

The sound fields used in experiment 3 were not completely realistic in that they did not include a complete exponential decay. The fourth experiment was designed to use sound fields with complete exponential decays to further explore the influence of the level and the temporal distribution of the late arriving energy on perceived LEV. By using more realistic sound fields, it was also hoped to relate judgments of LEV to objective auditorium acoustic measures. These relationships with objective measures will be considered in Sec. VIII.

The sound fields used in this experiment were similar to those used in experiment 2 and described in Fig. 2. Again, three loudspeakers were used as illustrated in Fig. 1. The early reflections were held constant and only the level and reverberation time of the reverberant energy were varied. The six sound fields consisted of the combinations of two reverberation time settings and three reverberant levels (expressed in terms of C80). The three broadband C80 values were 1, 4, and 7 dB, and the two reverberation times were 0.5 (low) and 1.5 s (high). Ten subjects rated the difference in LEV of each sound field compared to one reference sound field (C80=7 dB, low RT) on the five-point scale used in the previous experiment. Each of the six sound field pairs was presented four times to subjects in random order.

The average results and 95% confidence limits are shown in Fig. 7. The results show that the differences in perceived LEV increased with both increasing reverberant level (decreasing C80) and with increased RT. An analysis of variance of these results showed highly significant main effects ($p<0.001$) of both the RT and C80. These results confirmed the effect of the level of late arriving energy and showed that the distribution in time of the late arriving energy (RT) influences the perceived LEV.

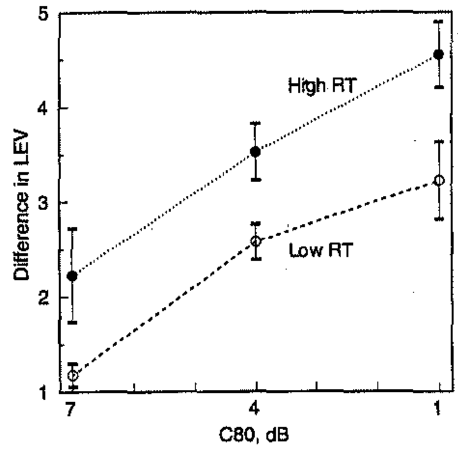

FIG. 7. Mean score and 95% confidence limits of the difference in LEV as a function of the level of the late energy and the RT (low RT=0.5 s, high RT=1.5 s).

VI. EXPERIMENT 5

It was expected that LEV would vary with the angle of arrival of the late sound energy. It is well known that ASW varies with the angle of arrival of individual reflections. Barron[4] showed that judgments of ASW varied with the cosine of the angle of arrival such that reflections arriving from angles of 90° from straight ahead produced the greatest perceived widths. It is not realistic to think of enveloping late energy arriving from a single direction. Thus sound fields were created with late energy distributed over a range of angles that were symmetrical about the direction of the direct sound.

In the previous experiments, three loudspeakers were used, located at 0° and ±45° relative to the listener, as illustrated in Fig. 1. In the fifth experiment, a total of five loudspeakers were used and were located at 0°, ±35°, and ±90° relative to the direct sound source. As illustrated in Fig. 8,

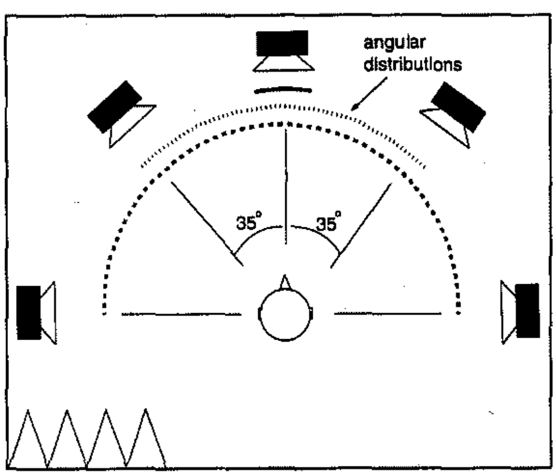

FIG. 8. Experimental setup of loudspeakers and distribution of late arriving sound energy for experiment 5.

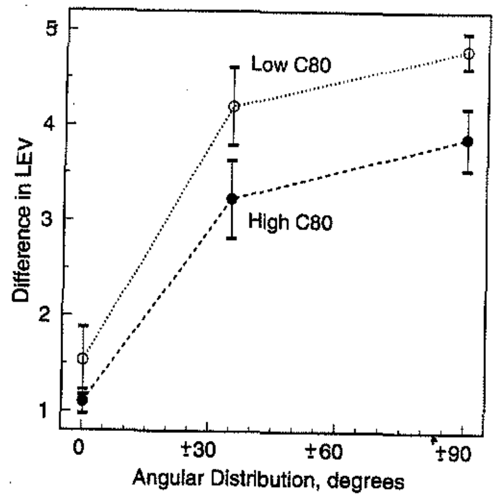

FIG. 9. Mean difference and 95% confidence limits of LEV as a function of the level and the angular distribution of the late arriving sound energy (low C80=1 dB, high C80=6 dB).

this allowed three different angular distributions of the late arriving sound energy: 0° using one loudspeaker, ±35 using three loudspeakers, and ±90° using all five loudspeakers. Informal listening tests suggested that loudspeakers placed symmetrically behind the listener at angles of 180° and ±145° would have similar effects on LEV as those in front of the listener at 0° and ±35°, respectively. Thus the levels of the late energy from the 0° and ±35° loudspeakers were double those from the ±90° loudspeakers to represent the effect of the missing rear speakers. In this way, the angular distribution of late energy in the simulated sound fields was thought to better approximate a diffuse sound field. Distribution of the late energy in this manner also resulted in more natural sounding conditions.

Two different levels of late arriving energy (C80=1 and 6 dB) were used in combination with the three different angular distributions to create a total of six different sound fields. The early reflection patterns did not vary. The six sound fields, repeated three times, were presented to ten subjects in random order and all had the same A-weighted level. As in the previous tests, subjects rated the difference in LEV between each sound field and the reference sound field (0°, C80=6 dB) on a five-point scale.

The mean scores of the perceived differences in LEV and the 95% confidence limits are shown in Fig. 9. An analysis of variance test of these results indicated highly significant main effects ($p<0.001$) of both C80 and angle. Thus LEV was again shown to be related to the level of the late arriving sound energy. However, it is clear from the results of Fig. 9 that this late arriving energy must arrive from the side to produce significant LEV. Similar to Barron's result for ASW,[4] the present results indicate that maximum LEV occurs when late arriving energy from ±90° is included. This is equivalent to minimizing the correlation of the late energy arriving at the listener's ears.

VII. EXPERIMENT 6

The combined results of experiments 3, 4, and 5 indicate that LEV is a different phenomenon than ASW and is related to different objective measures. Specifically, LEV requires the presence of significant late arriving lateral energy while variations in ASW are related to variations in early lateral reflections. Because there is no clearly defined boundary between early and late energy, there are clearly situations where it is difficult to differentiate between an early and a late arriving lateral reflection and the concepts of LEV and ASW must correspondingly overlap. It was also shown in experiments 1 and 2 that increased levels of late arriving sound energy decreased a listener's sensitivity to early lateral reflections. Thus it was sometimes quite difficult to hear differences in ASW when significant levels of reverberant sound were present. The final experiment was intended to confirm that subjects could reliably distinguish between changes in LEV and changes in ASW.

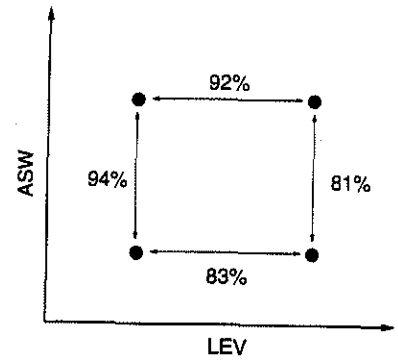

FIG. 10. Percentage of correctly identified sound field pairs having differences in ASW or LEV.

A matrix of four sound fields was used consisting of two levels of ASW and two levels of LEV. Because late energy diminishes our sensitivity to changes in early lateral reflections, the sound fields included significant changes in ASW. The two levels of ASW corresponded to broadband (125–2 kHz) LF_0^{80} values of 0.01 and 0.1. The two levels of LEV corresponded to broadband (125–2 kHz) LF_{80}^{∞} values of 0.1 and 0.6. LF_{80}^{∞} is the fraction of the late arriving lateral energy to the late arriving energy from all directions and with an 80-ms limit to the early sound. This measure is discussed further in Sec. VIII.

A total of nine subjects were asked to identify differences in the sound field pairs as either a change in ASW or a change in LEV. The sound field pairs were presented in random order and were repeated four times.

The results are shown in Fig. 10 as the percentage of correct judgments. As expected, detection of width changes were more difficult for the higher envelopment situation. For the lower ASW situation, changes in LEV were more difficult to detect, probably because they were more frequently confused with width changes. The lowest score of 81% correct corresponds to 29 out of 36 judgments being correct. The probability of this happening by chance is much less than 0.001 and hence these results are highly significant. Overall these results showed that there are two distinctly different aspects to spatial impression, and that subjects could correctly identify each of them. Furthermore, these results confirm that ASW is related to the early energy while LEV is related to the late arriving energy.

VIII. OBJECTIVE MEASURES OF LISTENER ENVELOPMENT

The experiments described above have shown that LEV is influenced by late arriving lateral sound energy. Specifically, the level, temporal distribution, and angle of arrival of the late energy were all shown to influence judgments of listener envelopment. The results of experiment 4 allow us to relate listener envelopment to the level and distribution in time of the late lateral energy. From the results of experiment 5, we can relate perceived LEV to the level and angle of arrival of the late lateral energy.

In each experiment, the sound fields were measured to provide octave-band values of early/late energy ratios, center time, early decay time, reverberation time, relative total sound levels, relative early and late sound levels, several lateral energy fractions, and interaural cross correlations. Interaural cross correlations were obtained using a Brüel & Kjaer head and torso simulator.

The judgments of LEV from experiment 4 were first correlated with each of these octave-band measures. Two measures, early decay time (EDT) and center time (TS), were significantly correlated with LEV in most octave bands. When arithmetic averages over the six octave bands were calculated for these two measures, both correlated with mean LEV scores with a correlation coefficient of 0.97 ($p < 0.001$) for the six sound fields of experiment 4.

Experiment 4 included six sound fields consisting of three levels of C80 by two RT values. The previously mentioned analysis of variance test showed that both the relative level of the late arriving energy (as measured by C80) and RT significantly influenced LEV judgments. The present results show that broadband average EDT or TS values are good predictors of the influence of the temporal distribution of late energy on LEV values. That is, they approximate the combined effect of both the level and reverberation time of the late arriving sound energy.

The combined effects of the angle of arrival and the level of the late arriving sound energy were studied in experiment 5. The LEV scores from this experiment were first correlated with each of the octave-band auditorium acoustics measures. These included some additions to the more common measures. Two new types of lateral energy fraction were included. One, the total lateral fraction LF_0^∞, was the ratio of the lateral to the total energy of the entire impulse response. The other was the lateral energy fraction of the late arriving energy LF_{80}^∞, i.e., the energy arriving more than 80 ms after the direct sound. The other measures included the interaural cross correlations of the early, late, and total sound.

The late lateral energy fraction can be defined as follows:

$$LF_{80}^\infty = \int_{80}^{\infty} p^2(t)\cos^2(\alpha)dt \Big/ \int_{80}^{\infty} p^2(t)dt, \tag{1}$$

where $p(t)$ is the room impulse response and α is the angle between the direction of arrival of a reflection and the line through the ears of a listener facing the source.

As might be expected, measures related to the late sound correlated best with the LEV scores. Averaging over several combinations of octaves generally produced only small changes in correlation coefficients. When measures were averaged over the three octave bands of 250, 500, and 1000 Hz, the correlations with late and total lateral energy fractions and interaural cross correlations tended to be highest. However, the relationships were more linear and the correlations higher when LEV scores were correlated with the logarithm of the lateral energy fraction and interaural correlation measures.

The best correlations were obtained with the logarithms of the LF_0^∞ and $\{1-IACC_0^\infty\}$ values (averaged over the 250-, 500-, and 1000-Hz octaves). For the logarithm of both measures, the correlation coefficient with LEV scores was 0.97 ($p<0.001$). Thus for the six sound fields of experiment 5, these two objective measures equally well described the combined influence of the variations in level and angle of arrival of the late sound energy.

One final objective measure was considered that led to an even higher correlation with LEV scores. This was the relative level of the late arriving lateral sound energy (LG_{80}^∞). That is, it was the relative level of the energy arriving more than 80 ms after the direct sound as picked up by the figure-of-eight microphone with its null pointed towards the direct sound source. The relative level of the late arriving lateral sound energy is defined as follows:

$$LG_{80}^\infty = 10\log\left[\int_{80}^{\infty} p^2(t)\cos^2(\alpha)dt \Big/ \int_{0}^{\infty} p_A^2(t)dt\right], \tag{2}$$

where $p(t)$ is the impulse response of the room and α is the angle between the direction of arrival of the reflection and the line through the two ears of a listener. The symbol $p_A(t)$ represents the response of the same source measured at a distance of 10 m in a free field.

To obtain a single average value of this measure from the six octave values, each octave value was A-weighted and the resultant energies were summed to give a single overall A-weighted late lateral relative level (LG_{80}^∞). Figure 11 is a plot of the LEV scores versus these A-weighted (LG_{80}^∞) values. The associated correlation coefficient was 0.997 ($p<0.001$).

This final result suggests that the combined effects of the angular distribution and the level of the late sound energy on LEV scores are well predicted by the A-weighted level of the late lateral sound. Although the fit with the perceived LEV is very good for this measure, the effects of varied temporal distributions of the late energy were not included in the sound fields used in obtaining this result. Thus it may well be that in real sound fields, measures of the temporal distribution of the sound energy (e.g., EDT) may also be required as was found when analyzing the data from experiment 4. Further studies are required to explore these possibilities.

IX. CONCLUSIONS

It has been confirmed that spaciousness or spatial impression in concert halls has at least two different compo-

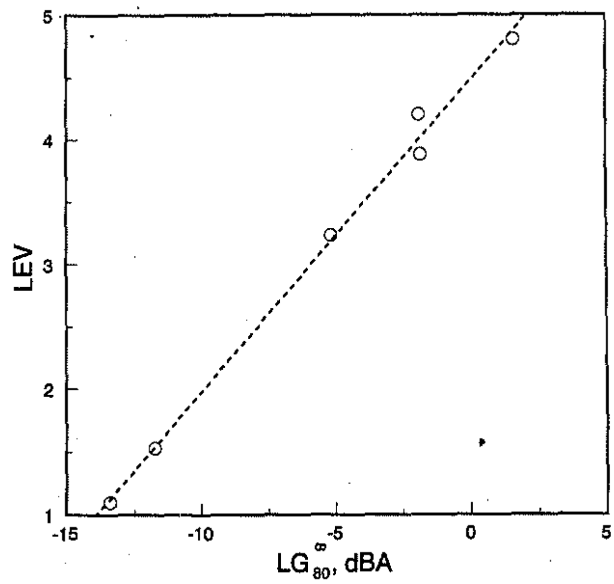

FIG. 11. Mean listener envelopment versus the A-weighted relative late lateral level LG_{80}^{∞} ($R=0.997$, $p<0.001$).

nents: the apparent broadening of the source (ASW) and the degree of listener envelopment (LEV). Subjects can discriminate between the two different phenomena, and each relates to different objective measures of the sound field. While variations in apparent source width have been extensively studied in the past, the clear distinction of listener envelopment as a separate dimension of spatial impression has received very limited previous attention. It has also been shown that higher levels of listener envelopment can reduce our sensitivity to changes in apparent source width. This fact suggests that listener envelopment is an important component of spatial impression for a successful concert hall.

The results of this study show that listener envelopment is affected by the level and the angular and temporal distributions of the late arriving energy.

Apparent source width is influenced by the relative level of early lateral reflections. The lateral energy fraction (LF_0^{80}) that in most measurements sums early lateral energies with a cosine squared directivity pattern, is one objective measure that relates to judgments of ASW in simple simulated sound fields. The present study indicates that listener envelopment is related to the A-weighted late lateral sound level, calculated by summing the late lateral energy with a cosine squared directivity.

For sound fields in which the temporal distributions are similar, the A-weighted late lateral relative level (LG_{80}^{∞}) has been shown to have a very high correlation with perceived listener envelopment.

The difference between ASW and LEV can be explained in terms of well-known properties of human hearing. As Haas[4] and others have shown, sound arriving shortly after the direct sound is integrated or temporally and spatially fused with the direct sound. Thus increasing levels of early lateral reflections increase the apparent level of the direct sound and cause a slight ambiguity in its perceived location. These two effects contribute to the resulting increase in ASW. Later arriving sound is not integrated or temporally and spatially fused with the direct sound, and leads to more spatially distributed effects that appear to envelop the listener.

The result of this study, that later arriving energy reduces our sensitivity to the effects of early lateral reflections, may help to explain several earlier results. Previously, spatial impression was assumed to relate to measures of early lateral reflections such as LF_0^{80}. However, measurements of LF_0^{80} in concert halls have shown relatively small differences between halls and often quite large variations within halls.[15,16] Thus measurements of LF_0^{80} did not appear to explain the high level of spatial impression experienced in some narrow rectangular halls such as the Vienna Musikvereinssaal. Similarly, Barron's subjective survey[17] found a relatively weak correlation between spatial impression and LF_0^{80} measurements. The new results of the present work suggest that these problems may be due to the fact that the LF_0^{80} measure does not relate to the other important component of spatial impression, i.e., LEV.

The new results have considerable practical significance for the design of concert halls. Prior to this new study, increased spaciousness was generally assumed to require strong early lateral reflections. This has led to the introduction in some newer halls of large reflector panels designed to add strong early lateral reflections. Such reflectors can lead to what has been called a directed sound hall,[15] where a large portion of early reflected energy is directed to the audience. This also leads to sound fields with impulse responses that decay more rapidly initially than later in the decay. In these halls, there can be an apparent lack of late arriving or reverberant energy in spite of an adequate reverberation time. Such halls could thus be lacking in both LEV and reverberance.

A hall designed to maximize later arriving lateral energy would ensure a higher degree of envelopment as well as a stronger sense of reverberance. Designs intended to maximize later arriving lateral energy would usually tend to also increase early lateral reflections and the apparent source width. Of course, the converse is not always true. For example, a shoe-box shaped concert 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 later arriving lateral reflections is probably yet another factor that generally ensures the success of shoe-box shaped concert halls.

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[1] W. Kuhl, "Spaciousness (spatial impression) as a component of total room impression," Acustica **40**, 167–181 (1978).
[2] W. de V. Keet, "The influence of early lateral reflections on the spatial impression," Proceedings of the 6th International Congress on Acoustics, paper E-2-4, Tokyo, 1968 (unpublished).
[3] M. Barron, "The subjective effects of first reflections in concert halls: The need for lateral reflections," J. Sound. Vib. **15**, 475–494 (1971).

[4] M. Barron and A. H. Marshall, "Spatial impression due to early lateral reflections in concert halls: The derivation of a physical measure," J. Sound Vib. **77**, 211–232 (1981).
[5] J. S. Bradley, G. A. Soulodre, and N. Popplewell, "Pilot study of simulated spaciousness," J. Acoust. Soc. Am. **93**, 2283 (1993).
[6] G. A. Soulodre, J. S. Bradley, and D. R. Stammen, "Spaciousness judgments of binaurally reproduced sound fields," J. Acoust. Soc. Am. **93**, 2283 (1993).
[7] H. Kuttruff, *Room Acoustics* (Wiley, New York, 1973), p. 196.
[8] M. Morimoto and C. Pösselt, "Contribution of reverberation to auditory spaciousness in concert halls," J. Acoust. Soc. Jpn. **10**, 87–92 (1989).
[9] F. Bilsen and F. Brinkman, "On the perception of spaciousness with artificial head," Proceedings of the 11th International Congress on Acoustics, Paris, 1983 (unpublished), p. 135.
[10] M. Morimoto and Z. Maekawa, "Auditory spaciousness and envelopment," Proceedings of the 13th International Congress on Acoustics, Belgrade, 1989 (unpublished), pp. 215–218.
[11] M. Morimoto and K. Iida, "A new physical measure for psychological evaluation of a sound field; Front/back energy ratio as a measure of envelopment," J. Acoust. Soc. Am. **93**, 2282 (1993).
[12] G. A. Soulodre and J. S. Bradley, "The influence of late arriving energy on concert hall spatial impression," Proceedings of the Sabine Centennial Symposium, Cambridge, MA, 1994 (unpublished), pp. 101–104.
[13] R. E. Halliwell and J. S. Bradley, "RAMSOFT-II: A computer based room acoustics measurement system," J. Acoust Soc. Am. **89**, 1897 (1991).
[14] H. Haas, "Influence of a single echo on the audibility of speech," J. Aud. Eng. Soc. **20**, 146–159 (1972).
[15] J. S. Bradley, "Progress in auditorium acoustics measurements," Proceedings of the Vancouver Symposium on Acoustics and Theatre Planning, Vancouver, 1986 (unpublished), pp. 89–94.
[16] J. S. Bradley, "Comparison of concert hall measurements of spatial impression," J. Acoust. Soc. Am. **96**, 3525–3535 (1994).
[17] M. Barron, "Subjective study of British symphony concert halls," Acustica **66**, 1–14 (1988).