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Objective measures of listener envelopment

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This paper reports the results of subjective studies to determine objective predictors of perceived listener envelopment in concert halls. Subjects, seated in an anechoic room, were exposed to simulated sound fields that were expected to have varied listener envelopment. As independent variables: the reverberation time, the early-to-late sound ratio, the overall sound level, and the angular distribution of the late-arriving sound levels were varied. All of these factors had statistically significant effects on perceived listener envelopment. The results indicate, however, that the angular distribution of the late arriving sound and the overall level would have the largest effects in real concert halls. Thus listener envelopment depends on having strong lateral reflections arriving at the listener 80 ms or more after the direct sound. Several objective measures correlated significantly with listener envelopment. However, a new measure, the late lateral sound level, as measured using a figure-of-eight microphone, was found to be both conceptually simple and a very good predictor of the perceived listener envelopment of the sound fields in this experiment.

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INTRODUCTION

Subjectively perceived spatial impression or spaciousness in concert halls has been shown to be composed of at least two components: apparent source width (ASW) and listener envelopment (LEV).[1,2] While ASW was extensively studied some time ago,[3,4] LEV has only more recently been investigated. Barron recognized that early reflections and reverberation produced different spatial effects, but his studies focused on ASW. Morimoto and Maekawa[5] considered envelopment, and Morimoto and Iida[6] clearly defined these two principle aspects of spatial impression. However, until very recently the terminology used to describe various aspects of spatial impression has been confused. In his early work, Barron[3,4] usually used the term spatial impression to describe what was really ASW. That is, his subjects rated the apparent width of the sound source. Morimoto and Maekawa[5] described separate source broadening and listener envelopment effects, but referred to the broadening as spatial impression. However, in a more recent paper Morimoto and Iida[6] do use the terms apparent source width and envelopment as we do in this paper.

Our previous work[1,2] demonstrated that while ASW is influenced by the relative level and angle of arrival of early lateral reflections, LEV is related to the level of later arriving lateral energy. Here, later arriving sound refers to reflections arriving at least 80 ms after the direct sound. In addition, stronger levels of later arriving sound were found to diminish the subjects' ability to perceive changes in the ASW of sound fields. The results of six experiments showed that LEV is influenced by the level, direction of arrival, and temporal distribution of later arriving reflections. From one of the six experiments, it was determined that LEV judgments were strongly related to objective measures of late lateral sound levels. That is, the levels of sound arriving from the side 80 ms or more after the direct sound. However, this result was based on a small number of sound fields with quite limited variation of the sound field parameters.

The present experiments were designed to examine more extensively the suitability of various objective acoustical measures as predictors of LEV. Two new experiments each included 27 sound fields from the combinations of three values of each of three different independent variables. The first experiment included sound fields made up of the 27 combinations of three levels of reverberation time, RT, early-to-late sound ratio, C_{80}, and angular distribution of the late arriving sound. The second experiment included sound fields made up of the 27 combinations of three levels of sound level, early-to-late sound ratio, C_{80}, and angular distribution. It was hoped that from this more complete manipulation of the important sound field parameters, objective predictors of LEV judgments could be more reliably determined.

I. METHOD

Two experiments were conducted in which subjects were exposed to simulated sound fields in an anechoic room. Figure 1 illustrates the setup of the loudspeakers in the anechoic room. The level and delay of reflections and reverberation were set by programmable digital equalizers and reverberators. Separate reverberators were used for each loudspeaker to ensure that their outputs were not highly correlated. The setup allowed individual control of the reflections and reverberation for each loudspeaker. Both experiments were automated and a computer controlled the changes to the sound fields and recorded subjects' responses.

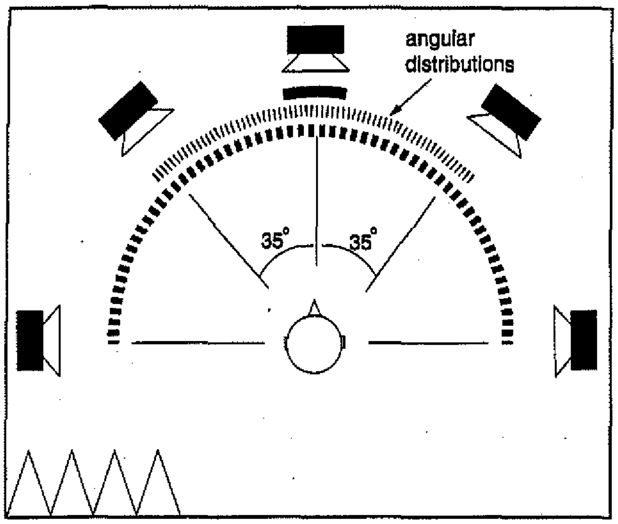

FIG. 1. Experimental setup of loudspeakers and angular distribution of late arriving sound energy.

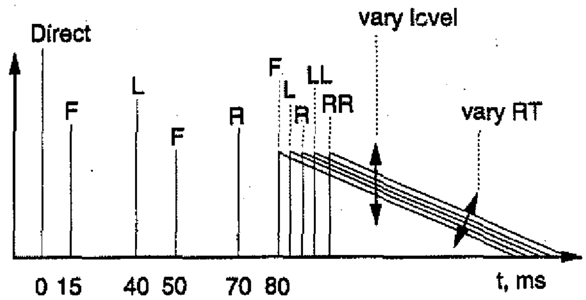

FIG. 2. Symbolic impulse response showing the structure of the sound fields used in Experiment 1. (F=front, L=left, and R=right±35° loudspeakers) (LL=left and RR=right±90° loudspeakers).

Tests were in the form of paired comparisons in which subjects rated the magnitude of the difference of the perceived listener envelopment, LEV, between each pair of sound fields. The first 20 s of the Denon anechoic recording PG 6006 of Handel's Water Music Suite was used as the test stimulus. The music was repeated continuously throughout each test. Subjects could toggle back and forth at will between the two sound fields of each pair, and could take as long as they wanted to make their judgments. Subjects rated the magnitude of the difference in listener envelopment, LEV, using a 5-point response scale. A score of 1 indicated that the two sound fields had the same LEV. A score of 5 indicated the largest expected difference in envelopment. After they entered their estimate of the magnitude of the difference in LEV, the computer controlling the experiment randomly selected the next pair of sound fields. Fourteen subjects were used in the first experiment and 15 subjects in the second experiment. In both tests, subjects experienced each sound field pair twice and the average of their two scores was used in the subsequent analyses. There was a practice session before each test to ensure that subjects were familiar with the requirements of each test and that they were aware of the range of conditions in that test.

Because it had previously been demonstrated that LEV is influenced by later arriving sound,[1,2] only the later arriving sound levels and decay times were varied as part of the experiments. Figure 2 illustrates the structure of the impulse responses that were used in the experiments. The direct sound and the four early reflections were not varied as part of the experiment other than in adjustments to maintain constant overall level. Thus measures of the relative properties of the early sound field such as the lateral energy fraction and the interaural cross-correlation coefficient remained constant.

In experiment 1, three quantities were varied. These were the reverberation time, RT, the ratio of early-to-late sound energy, C_{80}, and the angular distribution of the later arriving sound. Three values of each quantity were used. Thus there were 27 different sound fields consisting of three values of RT, by three values of C_{80}, by three values of angular distribution. Because they were presented with each sound field pair twice, subjects made a total of 54 judgments of sound field pairs. The nominal values of midfrequency (500 and 1000 Hz) RT, C_{80}, and angular distribution are given in Table I. This table shows that the sound fields were representative of a wide range of conditions similar to those found in real rooms. Figure 2 illustrates that C_{80} values were varied by adjusting the relative level of the late arriving sound. RT values were varied by changing the reverberation time setting of the reverberators. The angular distribution of the late arriving energy was varied by radiating reverberant sound from one, three, or five loudspeakers corresponding to the late sound arriving from 0°, ±35°, or ±90°. In varying the angular distribution, the total late sound level was kept constant. The late arriving sound was evenly distributed among the one, three, or five loudspeakers.

Experiment 2 was very similar to experiment 1 except that the overall sound level of the sound fields was varied and RT was kept constant at 1.9 s. Thus there were 27 sound fields consisting of three values of overall level, by three values of C_{80}, by three values of angular distribution. Again, subjects heard each sound field pair twice and thus made a total of 54 judgments. The nominal values of mid-frequency overall level, C_{80}, and angular distribution are given in Table I. As in experiment 1, the sound fields were representative of a wide range of conditions similar to those found in real rooms.

TABLE I. Values of the independent variables at mid-frequencies for the 27 sound fields of each experiment.

	Low	Medium	High
Experiment 1			
RT, s	0.5	1.2	1.9
C_{80}, dB	7.0	4.0	1.0
Angle, degrees	0.	35	90
A-weighted sound level, dB	77	77	77
Experiment 2			
A-weighted sound level, dB	71.	74.	77.
C_{80}, dB	7.0	4.0	1.0
Angle, degrees	0.	35	90
RT, s	1.9	1.9	1.9

TABLE II. Mean LEV scores for each of the 27 sound fields.

	Angular distribution, degrees								
	±90			±35			0		
	C_{80}, dB								
RT, s	1	4	7	1	4	7	1	4	7
				Experiment 1					
0.5	4.32	4.36	3.86	3.07	2.	2.39	1.39	1.18	1.07
1.2	4.79	4.39	3.89	3.57	3.36	2.68	1.54	1.39	1.11
1.9	4.93	4.61	4.14	3.46	3.04	2.75	1.75	1.46	1.11
				Experiment 2					
A-weighted sound level, dB									
71	4.13	3.57	3.37	2.63	2.57	2.37	1.10	1.10	1.03
74	4.30	4.40	3.93	3.40	3.27	3.00	1.60	1.43	1.80
77	4.80	4.73	4.47	3.83	3.67	3.10	2.07	2.17	2.00

Objective measurements of the sound fields were made using our auditorium acoustics measurement software, RAMSoft-II.[7] This system provides octave band values of a number of room acoustic quantities from impulse response measurements using both omni-directional and figure-of-eight pattern microphones. The acoustical quantities considered in these experiments are defined in the Appendix. Note that several of these quantities are new and a new notation has been introduced that indicates the time interval over which each quantity is measured.

The figure-of-eight microphone was positioned with its null pointed toward the location of the source of the direct sound. The responses from this microphone were used to obtain measures of the early and late arriving lateral sound for each of the sound fields.

Binaural impulse responses were also obtained using a Brüel & Kjaer type 4128 head and torso simulator. This allowed the calculation of various interaural cross-correlation measures[8] that are also included in the Appendix.

II. ANALYSIS OF VARIANCE RESULTS

A. Experiment 1

In experiment 1, subjects rated the magnitude of the differences in listener envelopment, LEV, between each of the 27 sound fields and one reference sound field. The reference sound field corresponded to the sound field having the lowest RT, the lowest reverberant level (highest C_{80}), and the minimum angular distribution. The mean scores of the 14 subjects for each of the 27 sound fields are given in Table II. An analysis of variance test, ANOVA, of these results showed that there were highly significant main effects ($p<0.001$) of all three independent variables (RT, C_{80}, and angular distribution). Here p is the probability of these effects occurring by chance. There were no significant two-way or three-way interaction effects.

These results clearly show that all three independent variables (RT, C_{80}, and angular distribution) significantly affect perceived LEV. However, the effects of these three variables are independent and do not interact with or influence each other.

B. Experiment 2

Experiment 2 was similar to experiment 1 except that variations in overall level replaced varied reverberation times. Subjects again rated the magnitude of the differences in listener envelopment, LEV, between each of the 27 sound fields and one reference sound field. The reference sound field corresponded to the sound field having the lowest overall sound level, the highest C_{80}, and the lowest angular distribution. The mean scores of the 15 subjects for each of the 27 sound fields are given in Table II. An analysis of variance test, ANOVA, of these results showed that there were highly significant main effects ($p<0.001$) for all three independent variables (overall sound level, C_{80}, and angular distribution). There were no significant two-way or three-way interaction effects. However, the C_{80} by angular distribution interaction was almost significant ($p<0.06$).

These results clearly show that all three independent variables (overall sound level, C_{80}, and angular distribution) significantly influence perceived LEV. There was a weak (but not quite significant) interaction effect suggesting that C_{80} had more effect for sound fields with greater angular distribution. That is, for sound fields with the late energy distributed over ±90°, varied C_{80} (or relative late sound levels) had the greatest effect on LEV.

III. PRACTICAL IMPORTANCE OF THE RESULTS

The analysis of variance tests give an indication of the statistical significance of the results or the probability of the results occurring by chance. It is also of interest to know how large a change in each independent variable is required to obtain a substantial change in LEV responses and whether such differences are likely to be found in real concert halls. Because there are no interaction effects, it is possible to consider the average effect of each independent variable by averaging responses over all other variables. For example, the average effect of RT can be considered by averaging responses to the nine combinations of C_{80} and angular distribution for each of the three values of RT.

The average scores at each of the three levels of each independent variable are given in Table III for both experisuggests that a 15-dB change in A-weighted sound (from 66 to 81 dB) level would have approximately the same effect on LEV scores as the maximum change in angular distribution in this experiment.

Thus both overall level and angular distribution will have large effects on the differences in perceived LEV experienced in actual concert halls. It is likely that the relative late levels (as measured by C_{80}) will have smaller influences on perceived LEV, and that possible changes in RT values will have even smaller effects. Thus to obtain a sufficient degree of LEV, it is more important to have higher sound levels and particularly higher late sound levels than it is to obtain longer reverberation times. Furthermore, the late energy must arrive from lateral directions.

IV. OBJECTIVE PREDICTORS OF LEV

The results of the two subjective experiments indicate that listener envelopment in real rooms is primarily controlled by two independent components: level and spatial or angular distribution. Therefore, a suitable objective predictor for LEV must in some way account for both components.

To test various predictors of LEV scores, octave band values of a number of modern room acoustics measures were correlated with LEV scores. The Appendix defines the acoustical quantities that were included in these analyses. The patterns of the resulting correlation coefficients were quite similar for the data of experiments 1 and 2.

Because LEV is influenced by the late arriving lateral sound, we did not expect measures based on only the early sound (the first 80 ms after the direct sound) to be related to LEV scores. This was indeed demonstrated to be the case in that values of: LF_0^{80}, G_0^{80}, LG_0^{80}, and $IACC_0^{80}$ were not significantly related to LEV scores.

As a first step toward establishing a suitable objective measure of LEV, acoustical measures that are influenced by later arriving sound, but which contain no directional information were considered. These measures could only account for the level and temporal distribution components of LEV, and ignored the spatial distribution component. Since the spatial distribution was found to be such an important factor in creating the sense of listener envelopment, it was expected that these measures would be only weakly related to LEV scores. The analysis showed that the measures: C_{80}, TS, G_0^{∞}, G_{80}^{∞}, EDT, and RT, were indeed only weakly related to LEV scores. (Correlation coefficients mostly between 0.45 and 0.7, $p<0.01$ in some octave bands.) These measures give some indication of how much late sound energy is present but no indication of the angular distribution of the late sound.

In order to account for the spatial distribution component of LEV, measures which reflect the directional characteristics of the late arriving sound were considered. Varying the spatial distribution of the late sound, of course, produces related changes in the correlation of the energy arriving at the listener's ears. Therefore, LF_{80}^{∞}, LF_0^{∞}, $IACC_{80}^{\infty}$, and $IACC_0^{\infty}$ were examined as potential predictors of LEV. Since the spatial distribution was found to be very important to the sense of listener envelopment, it was expected that these measures would correlate quite well with LEV scores. This was confirmed and each of these measures was found to be strongly correlated with LEV scores in all six octave bands (correlation coefficients 0.8 or larger, $p<0.001$ or better).

None of the objective measures examined so far have accounted for both the level and spatial distribution components of LEV. It would be possible to in some way combine a measure which accounts for the relative level of the late sound with one of the measures which reflects the spatial distribution component. For example, one might attempt to combine G_{80}^{∞} with $IACC_{80}^{\infty}$ or LF_{80}^{∞}, in order to account for the two main components of LEV. A more appealing approach, is to find a single measure which accounts for both the level and spatial distribution components of LEV. One such measure is the relative level of the late lateral energy, LG_{80}^{∞} as defined in Eq. (1).

$$LG_{80}^{\infty}=10\ \log\left\{\int_{.08}^{\infty}p_F^2(t)dt \bigg/ \int_0^{\infty}p_A^2(t)dt\right\},\quad \text{dB}, \tag{1}$$

where the various symbols are defined in the Appendix and $p_F(t)$, is the instantaneous lateral sound pressure, as measured with a figure-of-eight microphone and $p_A(t)$ is the response of the same source at a distance of 10 m in a free-field. When tested as a predictor of LEV scores, LG_{80}^{∞} measures were most strongly correlated with LEV scores in both experiments. Therefore, LG_{80}^{∞} appears to be a very good objective measure of LEV since it accounts for both the level and the spatial distribution components.

Because there has been little previous work on listener envelopment in concert halls, it was not clear how octave band measures should be optimally combined to best produce single number predictors of LEV. In a previous experiment[1,2] using sound fields consisting of the six combinations of two values of RT and three values of angular distribution, an A-weighted sum of relative late lateral sound levels was found to successfully predict LEV scores. In previous studies of spatial impression, low-frequency components have usually been found to be of particular subjective importance.[4,10–13] For example, it is usually suggested that lateral energy fraction measures should be averaged over the four octave bands from 125 to 1000 Hz.[14] Because there has been no previous study to specifically examine the question of the relative importance of different frequency components on listener envelopment, several combinations of octave band measures were tried.

For each of the five quantities related to the directional properties of the late arriving sound, five different combinations of octave band measures were considered as well as an A-weighted sum of all six octave bands. The five quantities were LG_{80}^{∞}, LF_{80}^{∞}, LF_0^{∞}, $IACC_{80}^{\infty}$, and $IACC_0^{\infty}$. The various octave-band sums of these five measures were then correlated with the LEV scores. The resulting correlation coefficients are given in Table IV. Good correlations were obtained for all of the octave band combinations. The highest correlation with LEV scores ($r=0.99$) was obtained for LG_{80}^{∞} values summed over the lowest four octaves (125 to 1000 Hz). Essentially the same high correlation was obtained from the data of both experiments 1 and 2. Figures 5 and 6 show plots of the relationship between LEV scores for the two

TABLE IV. Correlations of multiband acoustical measures with LEV scores.

Measure	3 mid	4 mid	4 low	5 low	6 bands	A weighted
			Eperiment 1			
LG_{80}^{∞}	0.9625	0.9661	0.9907	0.9834	0.9596	0.9380
LF_{80}^{∞}	0.9353	0.9386	0.9281	0.9394	0.9540	
LF_{0}^{∞}	0.9693	0.9722	0.8948	0.9082	0.9221	
$IACC_{80}^{\infty}$	−0.9043	−0.9353	−0.9565	−0.9405	−0.9333	
$IACC_{0}^{\infty}$	−0.9423	−0.9488	−0.9481	−0.9502	−0.9434	
			Experiment 2			
LG_{80}^{∞}	0.9622	0.9667	0.9902	0.9856	0.9642	0.9440
LF_{80}^{∞}	0.9012	0.9023	0.8883	0.8985	0.9109	
LF_{0}^{∞}	0.9244	0.9265	0.8469	0.8604	0.8730	
$IACC_{80}^{\infty}$	−0.8713	−0.8936	−0.9096	−0.8985	−0.8919	
$IACC_{0}^{\infty}$	−0.8932	−0.8976	−0.8906	−0.8980	−0.9019	

Column group heading: Bands included (spans 3 mid through A weighted).

3 mid=500, 1000, 2000 Hz.
4 mid=250, 500, 1000, 2000 Hz.
4 low=125, 250, 500, 1000 Hz.
5 low=125, 250, 500, 1000, 2000 Hz.
6 bands=125, 250, 500, 1000, 2000, 4000 Hz.
($p<0.001$ for all correlations in this table.)

experiments and the LG_{80}^{∞} values summed over the lower four octave bands.

While the LG_{80}^{∞} values from the low four octave sums correlate most strongly with LEV values, a number of other combinations produce quite high correlation coefficients. Many of the differences between correlation coefficients are quite small and these differences may not be statistically significant.

LG_{80}^{∞} values correlate equally strongly with the LEV scores from both experiments, but there are differences for the other measures. In experiment 1, values of LF_{80}^{∞}, LF_{0}^{∞}, $IACC_{80}^{\infty}$, and $IACC_{0}^{\infty}$ correlate more strongly with LEV values than is found for the corresponding data of experiment 2. These four measures are not influenced by sound level and so do not reflect the effects of the changes in overall level that were part of experiment 2 and which have an important effect on the resulting LEV scores. If experiment 2 had included a larger range of sound levels, the correlations with these measures would have been even lower. Thus there is a strong argument that LG_{80}^{∞} would best predict expected lis-

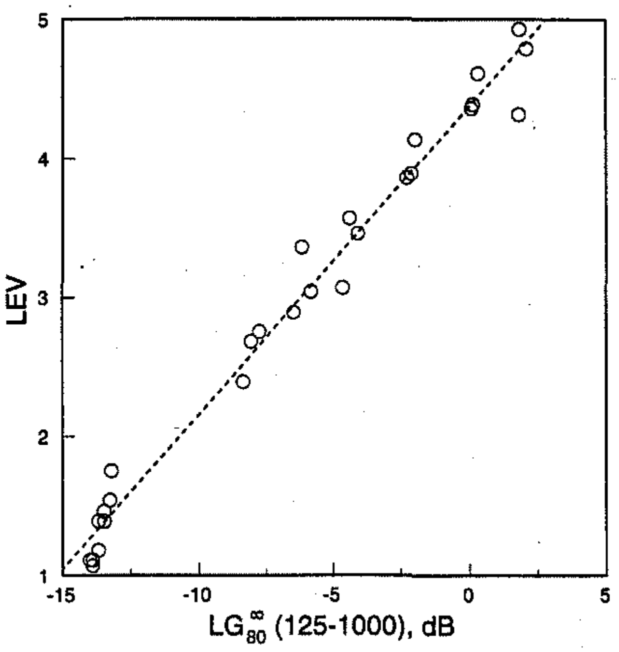

FIG. 5. Mean LEV scores from experiment 1 plotted versus late lateral sound levels, LG_{80}^{∞} (averaged over the four lower octave bands) (correlation coefficient $r=0.99$).

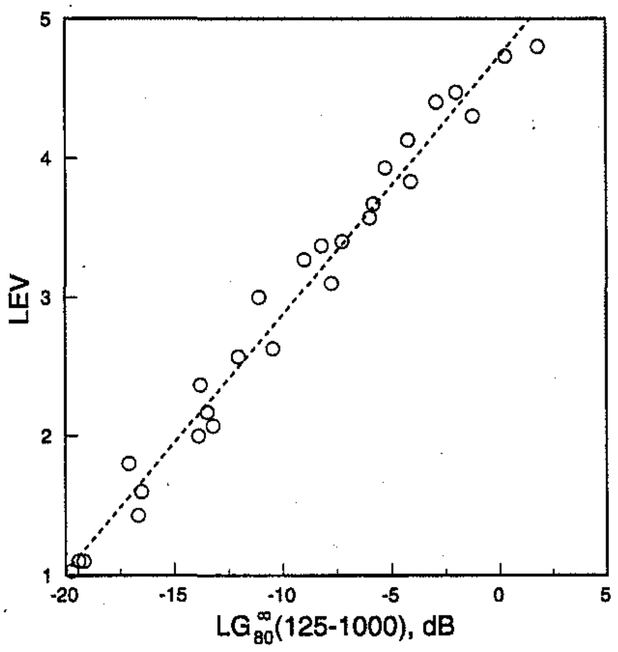

FIG. 6. Mean LEV scores from experiment 2 plotted versus late lateral sound levels, LG_{80}^{∞} (averaged over the four lower octave bands) (correlation coefficient $r=0.99$).

tener envelopment in the full range of conditions to be expected in real concert halls.

Although these experiments were not designed to specifically investigate the question of the relative importance of various frequency bands, they suggest that the low- and mid-frequencies are most important for adequate listener envelopment.

Since the completion of these experiments, measurements at 80 locations in 15 different auditoria have been reprocessed to estimate $LG_{80}^{\infty}(125-1000)$ values. These new results show $LG_{80}^{\infty}(125-1000)$ values to range from -14.4 to $+0.8$ dB. Thus the range of $LG_{80}^{\infty}(125-1000)$ values included in experiment 1 and shown in Fig. 5 are quite representative of conditions in real halls.

V. CONCLUSIONS

The present results confirm previous findings[1,2] that listener envelopment is influenced by the level, direction of arrival, and the temporal distribution of later arriving reflections. Listener envelopment is one of at least two components of spatial impression. LEV may be the more important component of spatial impression because changes in ASW were masked by the late energy. The converse has not been reported.

These new results support suggestions concerning the subjective importance of the reverberant level. However, it is now known that the direction of arrival of the reverberant sound is also important. One can assume that the new results contribute to explaining the acoustical success of narrow rectangular concert halls which are presumed to have relatively high levels of late lateral energy.

From these more extensive new tests, the angle of arrival and the level of the late lateral sound energy were concluded to have the largest influence on perceived listener envelopment in real concert halls. The balance between early and late arriving sound energy was of less importance, but is more important than realistic variations in reverberation time.

A new measure, the late lateral sound level, LG_{80}^{∞}, best predicted listener envelopment scores in these experiments. LG_{80}^{∞} values, summed for the lower four octaves (125 to 1000 Hz), gave the highest correlations with LEV scores. Other measures (LF_{80}^{∞}, LF_{0}^{∞}, $IACC_{80}^{\infty}$, and $IACC_{0}^{\infty}$) influenced solely by the angular distribution of the late sound, were also quite strongly related to LEV scores. These correlations are expected to be weaker if larger variations in sound levels are included, because these measures are not influenced by overall sound levels.

The relative late lateral sound level, LG_{80}^{∞} is proposed as a conceptually simple measure that best predicts listener envelopment. It is also simple to measure and to predict from computer models. The present results suggest that octave band values for the four octaves from 125 to 1000 Hz should be summed for best results. Subsequent studies may be required to further fine tune this measure and specifically to more thoroughly investigate optimum combinations of various frequency bands.

ACKNOWLEDGMENTS

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APPENDIX: DEFINITION OF ACOUSTICAL MEASURES

A number of modern room acoustics quantities were included in the analyses of this paper. They are defined in this appendix. All are obtained from impulse response measurements. In many cases, new notation has been introduced in this paper, to describe measures related to early, and late time periods. In this work, "early" refers to the first 80 ms after the direct sound. However, the new notation specifically describes the time interval over which the quantity is measured.

C_{80} is an early/late sound ratio with an 80 ms early time limit. It is related to subjective judgments of clarity or the balance between clarity and reverberance and is calculated as follows from the impulse response obtained using an omnidirectional microphone.

$$C_{80}=10\log\left\{\int_0^{.080}p^2(t)dt \Big/ \int_{.080}^{\infty}p^2(t)dt\right\},\quad \text{dB.} \tag{A1}$$

The center time, TS, is the center of gravity of the impulse response. It is related to subjective judgments of clarity and is calculated as follows from the impulse response obtained using an omnidirectional microphone,

$$TS=\int_0^{\infty}tp^2(t)dt \Big/ \int_0^{\infty}p^2(t)dt,\quad \text{dB.} \tag{A2}$$

Early decay time, EDT, is the 60-dB decay time measured by a straight line fit to the first 10 dB of the decay curve from a reverse integrated Schroeder decay curve. EDT values relate to judgments of reverberance.

Reverberation times, RT, were calculated as the 60-dB decay time obtained from straight line fits to the reverse integrated Schroeder decay curves between -5 and -30 dB.

The relative sound level $G_{t_1}^{t_2}$ (sometimes referred to as strength) is a measure of the amplification of sound levels at particular locations in halls. Increased $G_{t_1}^{t_2}$ values will lead to louder sounds. The $G_{t_1}^{t_2}$ values are calculated from the impulse response obtained using an omnidirectional microphone as follows,

$$G_{t_1}^{t_2}=10\log\left\{\int_{t_1}^{t_2}p^2(t)dt \Big/ \int_0^{\infty}p_A^2(t)dt\right\},\quad \text{dB,} \tag{A3}$$

where $p(t)$ is the instantaneous pressure response measured with an omnidirectional microphone, and $p_A(t)$ is the response of the same source at a distance of 10 m in a free field.

The total relative sound level, G_0^{∞} is defined as when $t_1=0$ and $t_2=\infty$ s. The early relative sound level G_0^{80} is defined as when $t_1=0$ and $t_2=0.08$ s. The late relative sound levels G_{80}^{∞} is defined as when $t_1=0.08$ and $t_2=\infty$ s. Similarly, relative levels of the lateral sound can also be calculated as follows,

$$\mathrm{LG}_{t_1}^{t_2}=10\ \log\left\{\int_{t_1}^{t_2} p_F^2(t)dt \Big/ \int_0^{\infty} p_A^2(t)dt\right\},\quad \mathrm{dB}, \tag{A4}$$

where $p_F(t)$ is the instantaneous pressure response of the lateral sound obtained from a figure-of-eight microphone with its directional null pointed towards the source. For LG_0^{∞} the total relative lateral level, $t_1=0$ and $t_2=\infty$ s. For LG_0^{80}, the early relative lateral level, $t_1=0$ and $t_2=80$ s. For $\mathrm{LG}_{80}^{\infty}$, the late relative lateral level, $t_1=80$ and $t_2=\infty$ s.

In a similar manner, lateral energy fractions can be defined for the early, late and total impulse response parts.

$$\mathrm{LF}_{t_1}^{t_2}=\int_{t_1}^{t_2} p_L^2(t)dt \Big/ \int_{t_1}^{t_2} p^2(t)dt. \tag{A5}$$

The lateral energy fraction of the total impulse response, LF_0^{∞}, would correspond to $t_1=0$ and $t_2=\infty$ s. The lateral energy fraction of the early sound, LF_0^{80} would correspond to $t_1=0$ and $t_2=0.08$ s. (In many cases, $t_1=0.005$ has been used in the integration of the lateral energy to further diminish the effect of the direct sound on the lateral response.) The lateral energy fraction of the late sound, $\mathrm{LF}_{80}^{\infty}$, would correspond to $t_1=0.08$ and $t_2=\infty$ s.

The interaural cross correlation is defined as the maximum absolute value of the cross correlation function for $|\tau|\leq 1$ ms. The cross-correlation function is given by

$$\Phi_{LR}=\frac{1/(t_2-t_1)\int_{t_1}^{t_2} p_L(t)p_R(t+\tau)dt}{\sqrt{\Phi_{LL}(0)\Phi_{RR}(0)}}, \tag{A6}$$

where $p_L(t)$ and $p_R(t)$ are the instantaneous pressure responses at the left and right ears respectively of a dummy head.

The interaural cross correlation of the early sound, IACC_0^{80} is obtained by integrating Eq. (A6) from $t=0$ to $t=0.08$ s. The interaural cross correlation of the total sound, IACC_0^{∞}, is obtained by integrating Eq. (A6) from $t=0$ to $t=\infty$ s. The interaural cross correlation of the late sound, $\mathrm{IACC}_{80}^{\infty}$ is obtained by integrating Eq. (A6) from $t=0.080$ to $t=\infty$ s.

[1] J. S. Bradley and G. A. Soulodre, "The Influence of Late Arriving Energy on Spatial Impression," J. Acoust. Soc. Am. **97**, 2263–2291 (1995).

[2] G. A. Soulodre and J. S. Bradley, "The Influence of Late Arriving Energy on Concert Hall Spatial Impression," in *Proceedings of the Sabine Centennial Symposium*, Cambridge, MA (Acoustical Society of America, Woodbury, NY, 1994), pp. 101–104.

[3] M. Barron, "The Subjective Effects of First Reflections in Concert Halls: The Need for Lateral Reflections," J. Sound Vib. **15** (4), 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** (2), 211–232 (1981).

[5] M. Morimoto and Z. Maekawa, "Auditory Spaciousness and Envelopment," *Proceedings 13th International Congress on Acoustics* Belgrade, 1989 (Sava Centar, Belgrade), Vol. 2, pp. 215–218.

[6] 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 (A) (1993).

[7] R. E. Halliwell and J. S. Bradley, "RAMSoft-II: A Computer Based Room Acoustics Measurement System," J. Acoust. Soc. Am. **89**, 1897 (A) (1991).

[8] J. S. Bradley, "Comparison of Concert Hall Measurements of Spatial Impression," J. Acoust. Soc. Am. **96**, 3525–3535 (1994).

[9] J. S. Bradley, "Data from 13 North American Concert Halls," National Research Council, IRC Internal Report No. 668 (July 1994).

[10] J. S. Bradley, G. A. Soulodre, and N. Popplewell, "Pilot Study of Simulated Spaciousness," J. Acoust. Soc. Am. **93**, 2283 (1993).

[11] M. Morimoto, K. Iida, K. Sakagami, and A. H. Marshall, "Physical Measures of Auditory Source Width (ASW): Part 1. "Discussion of the Competing Measures, Degree of Interaural Cross Correlation (ICC) and Lateral Fraction (Lf), as Measures of ASW (Auditory Source Width)," in *Proceedings of Sabine Centennial Symposium*, Cambridge, MA (Acoustical Society of America, Woodbury, NY, 1994), pp. 109–112.

[12] M. Morimoto, K. Iida, K. Sakagami, and A. H. Marshall, "Physical Measures of Auditory Source Width (ASW): Part 2. "Comparison Between Various Physical Measures and ASW (Auditory Source Width)," in *Proceedings of Sabine Centennial Symposium*, Cambridge, MA (Acoustical Society of America, Woodbury, NY, 1994), pp. 113–116.

[13] G. A. Soulodre, J. S. Bradley, and D. R. Stammen, "Spaciousness Judgments of Binaurally Reproduced Sound Fields," J. Acoust. Soc. Am. **93**, 2283 (1993).

[14] M. Barron, "Auditorium Acoustics and Architectural Design" (E & FN Spon, an imprint of Chapman and Hall, London, 1993), p. 61.