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A Comparison of Three Classical Concert Halls

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Résumé

L'auteur présente les valeurs de nouvelles grandeurs de l'acoustique des auditoriums obtenues grâce à des mesures effectuées dans trois célèbres salles de concert classique, le Concertgebouw d'Amsterdam, le Grosser Musikvereinssaal de Vienne et le Symphony Hall de Boston. Les mesures par bandes d'octave ont porté sur : le temps de réverbération, le temps d'affaiblissement initial (EDT), la force ou le niveau du son, le rapport son initial-son subséquent, et la fraction d'énergie latérale. L'auteur fait état des valeurs moyennes des salles pour ce qui est des conditions mesurées en inoccupation, ainsi que des valeurs estimatives en occupation. Il examine en détail les variations observées au niveau des critères selon le positionnement du système source-récepteur. Les résultats aident à définir l'éventail des conditions d'une bonne acoustique dans les salles de concert, et ils montrent de façon précise certaines des différences qui existent entre les salles étudiées.

A comparison of three classical concert halls

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Values of newer auditorium acoustics quantities are presented for measurements in three well-known classical concert halls: the Amsterdam Concertgebouw, the Vienna Grosser Musikvereinssaal, and the Boston Symphony Hall. The measured octave band quantities included reverberation time, early decay time, sound strength or level, early/late sound ratios, and lateral energy fractions. Hall average values from the measured unoccupied conditions are presented as well as estimated occupied values. The variation of parameters with both source and receiver position is examined in detail. The results help to define the range of conditions that are to be expected in good concert halls, and reveal some of the detailed differences among these halls.

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INTRODUCTION

Over the past 20 years, concert hall acoustics research has made considerable progress. A review of this literature[1] has led the author to agree with several others that only four or five parameters are necessary to explain a large part of the variance in subjective preference judgments of hall acoustics.[2,3] Jordan[4] has suggested a list of important acoustical parameters and several authors[5–7] have reported measurements of these newer parameters in halls. There have been some very notable suggestions for the use of other auditorium acoustics measures,[8] but it is not the purpose of this paper to question their validity or to review all the various recent studies in this field. The purpose of this paper is to present the results of measurements, in three well-known concert halls, of a group of five newer objective measures that are widely considered to be related to the principal subjective aspects of concert hall acoustics.

Before these new parameters can be used to assess and understand conditions in halls, considerable practical experience is needed measuring these quantities in a variety of types of halls. We have worked on this problem over a number of years: developing improved and more efficient measuring systems,[9,10] making measurements in a number of halls,[6,11] and considering the accuracy and repeatability of these parameters.[12] Gade has published measurements in 21 Danish halls[13] and more recently a number of other European halls[7] using a quite different measurement system. Barron has made measurements in a number of British halls[14] using yet another measurement technique.[15]

There is still a considerable need for further practical information to help us measure and interpret these quantities in halls. There are a number of questions that require answers. What are typical expected values of the various parameters in particular types of halls? How much within hall variation is to be expected in particular situations? How do values of the acoustical parameters relate to the geometry and materials of the concert hall? Also, what are ideal values of each parameter, and what values are found in our best concert halls? This paper attempts to respond to these questions and to answer the latter by presenting detailed measurement results from three well-known classical halls.

It is always difficult to obtain agreement as to which halls are considered to have excellent acoustical characteristics, and informal opinions can be very unreliable assessments of acoustical conditions. Therefore, this paper presents detailed measurement results from three halls that are almost universally accepted as among the best concert halls in the world. These are the Amsterdam Concertgebouw, the Vienna Grosser Musikvereinssal, and the Boston Symphony Hall. Beranek[16] has suggested that the Vienna and Boston halls are the best and second best halls in the world, respectively. Certainly few would dispute that all three are excellent concert halls, and therefore that the more that we can learn about them, the better we will understand what constitutes a good concert hall.

Unfortunately there is very little comparable quantitative objective acoustical data for concert halls, and in particular for these three. Where reverberation time values are available, there are often discrepancies between different sets of measurements in the same hall and no details as to the measurement technique. Beranek's well-known book, *Music, Acoustics and Architecture*,[17] contains a wealth of information concerning the architectural details of many well-known halls, but the only acoustical data are reverberation times from a variety of older measurements. Unfortunately this book predates the discovery of the importance of the various newer acoustical parameters, and values of these quantities are only now becoming available.

The purpose of this paper is to attempt to provide a comprehensive objective characterization of three very good classical concert halls. It is hoped that this will help to better define what constitutes a good concert hall and will lead to a better understanding of acoustical conditions in these halls. Where there are differences among the measurements in the three halls, it is in general not possible to say which is a better or more desirable result because there is no comparable subjective data.

I. MEASUREMENT PROCEDURES

Measurements in all three halls were made with our RAMSoft[10] measurement system using a specially modified and calibrated blank pistol as the impulsive source. The measurement system consists of a program running on an IBM PC compatible portable computer interfaced to a Norwegian Electronics type 830 two-channel real time analyzer. The values of 12 different parameters in each of six octave bands are obtained while *in situ* at each position in the hall.

The 0.38-calibre blank pistol was modified so that it is a good approximation to an ideal omnidirectional source,[18] and black powder blanks are used to ensure that there is adequate energy in all the octave bands from 125 to at least 4000 Hz.

The real time analyzer is used to capture, ensemble average, and filter the pulse responses, which are then transferred digitally to the computer. Decay times are calculated from least-squares fits to portions of the decay curves obtained by the Schroeder backward integration technique.[19] Both the classical reverberation time RT, measured over the decay from -5 to -35 dB, and the early decay time EDT, measured over the first 10 dB of the decay, are measured.

Early/late arriving sound energy ratios, $C36$, $C50$, and $C80$ with 36, 50, and 80 ms early time intervals, are calculated. $C80$ values are calculated as follows:

$$C80 = 10 \log\left[\left(\int_0^{0.08} p^2(t)\,dt\right) \times\left(\int_{0.08}^{\infty} p^2(t)\,dt\right)^{-1}\right], \quad \text{dB}, \qquad (1)$$

where $p(t)$ is the measured pulse response in the auditorium. Other early/late ratios are calculated in a similar manner, but with different early time limits.

The overall strength G is calculated as the ratio of the total measured energy in the pulse response to the energy from the same source at a distance of 10 m in a free field as given in the following equation:

$$G = 10 \log\left[\left(\int_0^{\infty} p^2(t)\right)\left(\int_0^{\infty} p_A^2(t)\,dt\right)^{-1}\right], \quad \text{dB}, \qquad (2)$$

where $p_A(t)$ is the response of the source at a distance of 10 m in a free field.

The program calculates two versions of the lateral energy fraction LF, which is the ratio of the lateral energy received by a figure-of-eight pattern microphone to the energy measured by an omnidirectional microphone over the first 80 ms of the pulse response. The sensitive lobes of the figure-of-eight microphone were pointed at the side walls so that the null in the directional sensitivity was directed toward a center stage source position. Thus LF values are calculated as follows:

$$\text{LF} = \left(\int_0^{0.08} p_L^2(t)\,dt\right)\left(\int_0^{0.08} p^2(t)\,dt\right)^{-1}, \qquad (3)$$

where $p_L(t)$ is the lateral response from the figure-of-eight microphone. The first integration is sometimes started from 0.005 s rather than 0.0 s. Both variations of LF were calculated and the differences were very small (0.01 or less in the 500-Hz octave band). Only LF values corresponding to Eq. (3) are included in this paper.

Values of the background noise levels, the center time,[2] and useful/detrimental sound ratios[6] that are related to speech intelligibility were also obtained but are not discussed in this paper.

In this paper, octave band values of only five of these parameters are presented because others are either less commonly used or are usually highly correlated with one of these five parameters. These are RT, EDT, G, $C80$, and LF. While RT is related to other physical properties of spaces, EDT values are related to subjective judgments of reverberance. G values relate to how loud a given sound source will be in a particular space and hence to the dynamic range that is possible during musical performances. $C80$ values relate to perceived clarity or the balance between clarity and reverberance, and LF values are related to the subjective sense of spatial impression or envelopment. In this paper, some further parameters are calculated from these five basic parameters to explore in more detail the strength of the sound arriving in the early and late parts of the impulse responses.

In each hall, measurements were made at all the combinations of three source positions and between 10 and 14 receiver positions distributed over all audience seating areas. Each measurement was calculated from an ensemble average of four pulse responses. Measurements in the Amsterdam and Vienna halls were made at the same time and at some of the same positions as measurements by A. C. Gade.[7] Thus it was possible to confirm that the two different measurement systems produced very similar results.

The architectural details of the halls are not included here, but have been well documented by Beranek.[17] For those completely unfamiliar with these halls, they are all classical rectangular or shoe-box-shaped halls with very small side balconies and slightly larger rear balconies. The Boston hall has the most seats and has two balconies. The Vienna hall is narrower than the others, has fewer seats, and has a rear gallery above the rear balcony. The Amsterdam hall is the widest and has only one balcony level.

II. MEAN UNOCCUPIED VALUES

Mean values of the five basic parameters are first presented. It should be noted that these values and most results in this paper are for the unoccupied conditions that existed during the measurements. Because the seating in these halls is only lightly upholstered, considerable changes would be expected with the presence of an audience. However, most measurements of halls are made under unoccupied conditions and hence such data are most useful for comparison purposes.

Figure 1(a) shows the overall hall average RT values for the three halls. The Vienna hall, although smaller in volume than the other two halls, is seen to have larger RT values at most frequencies. [The (b) part of this and several subsequent graphs shows the spatial standard deviations of the values. These standard deviations give some indication of the significance of the differences between the mean values in part (a) of these graphs and are discussed further in Sec. IV.]

The hall average EDT values are compared in Fig. 2(a) and these results are quite similar to those of Fig. 1(a). A comparison of the results of Figs. 1(a) and 2(a) shows that the difference between mean EDT and mean RT values is

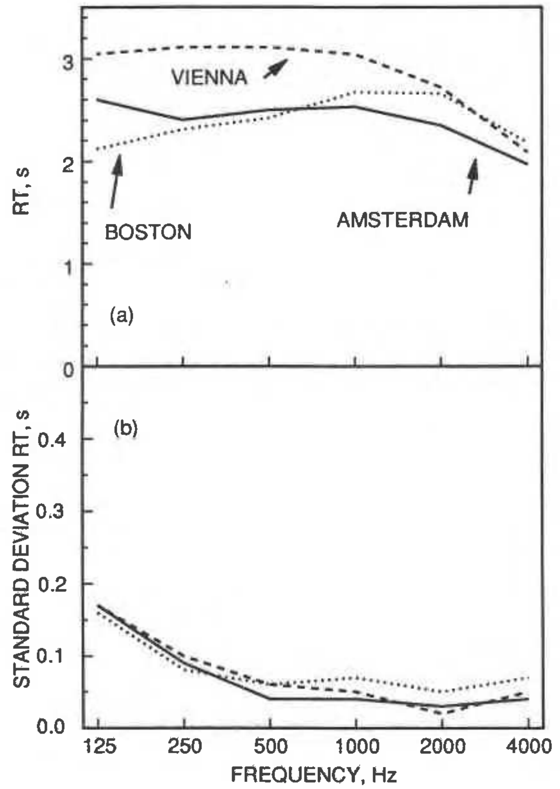

FIG. 1. (a) Hall average and (b) spatial standard deviation of measured RT values versus octave band frequency for each hall.

greatest in the Boston hall. Even in this hall, these differences are quite small and are a maximum of about 0.1 s in midfrequency bands. Some more modern halls have larger differences between EDT and RT values.[6]

Figure 3(a) compares hall average G values. Here again, the Vienna hall has the largest values and this is at least partly because of the related larger RT values and smaller volume.

Surprisingly, the Boston hall mean G values are different from the other two halls in that they are lower by up to approximately 4 dB at lower frequencies. This difference in G values is not reflected in a similar magnitude difference in RT values. Later analyses in this paper will attempt to suggest a cause for this difference.

Hall average $C80$ values are compared in Fig. 4(a). There is a tendency for $C80$ values to be related to RT values, and the Vienna hall with the largest RT values tends to have the lowest $C80$ values. However, the Amsterdam hall has $C80$ values that are quite similar to those of the more reverberant Vienna hall. Even though the Boston hall has similar RT values to the Amsterdam hall, $C80$ values are higher in the Boston hall at frequencies from 125 to 500 Hz.

The hall average LF values are presented in Fig. 5(a). In this figure, the Boston hall unexpectedly has the highest LF values. It is often assumed that narrower halls will have stronger early lateral energy and that LF values would correspondingly be larger. Gade[13] found a correlation between the mean width and mean LF values for 21 Danish halls. Thus it is surprising that the Boston hall has the highest LF

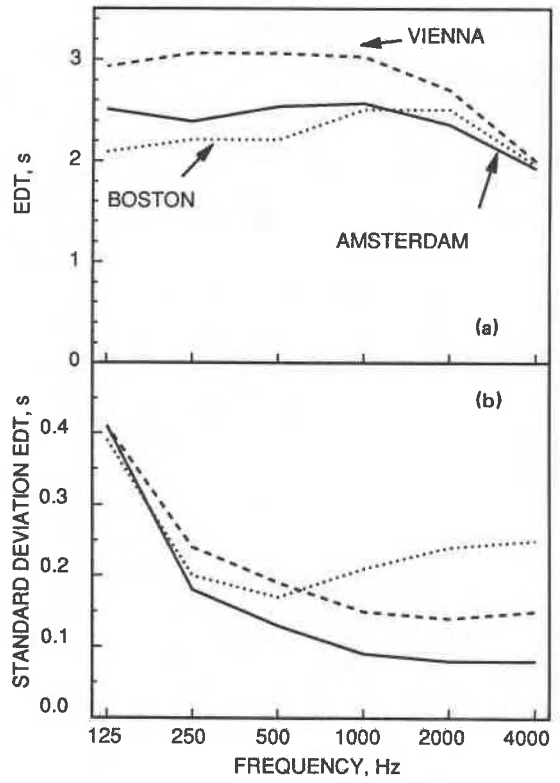

FIG. 2. (a) Hall average and (b) spatial standard deviation of measured EDT values versus octave band frequency for each hall.

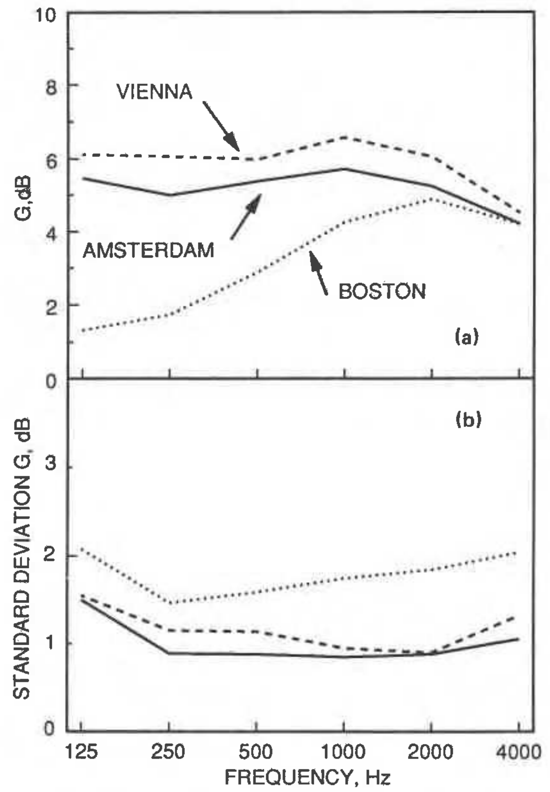

FIG. 3. (a) Hall average and (b) spatial standard deviation of measured G values versus octave band frequency for each hall.

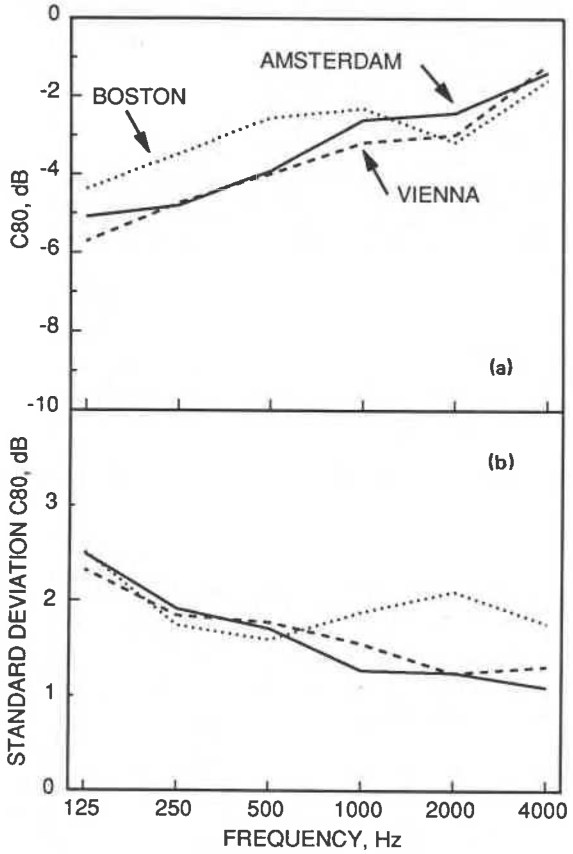

FIG. 4. (a) Hall average and (b) spatial standard deviation of measured $C80$ values versus octave band frequency for each hall.

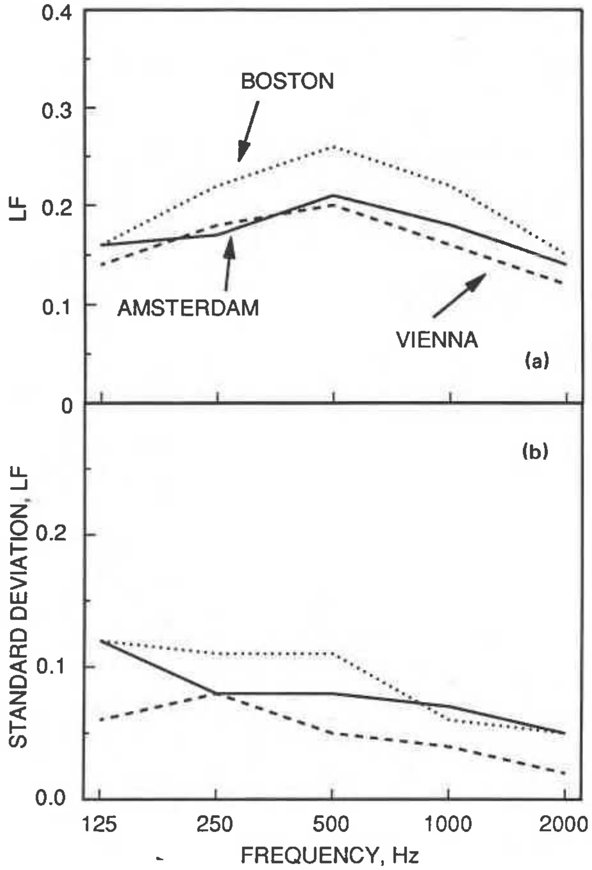

FIG. 5. (a) Hall average and (b) spatial standard deviation of measured LF values versus octave band frequency for each hall.

values and that the Vienna hall that is the narrowest has similar LF values to the Amsterdam hall that is the widest of the three.

While there are many general similarities among the hall average results from the three halls, there are some noteworthy differences. The Vienna hall is most reverberant and, in the Boston hall, the EDT values are a little lower than RT values at midfrequencies. The G values at lower and midfrequencies are lower in the Boston hall, but the LF values in this hall are higher than the other two halls. There are small differences in $C80$ values such that the Boston hall has higher values at lower and midfrequencies.

The interhall differences shown in Figs. 1–5 were tested to determine whether they were statistically significant. First, two-way analyses of variance were carried out for each acoustical parameter and in each octave band, with the hall and the source–receiver distance as the independent variables. This type of analysis determines whether the differences between group means are significant relative to the amount of variance within each group. In almost all of the cases (25 out of 30) there is a statistically significant effect of the hall on the mean values. The exceptions are the 4000-Hz octave band EDT, G, and $C80$ values as well as the 2000-Hz $C80$ values and the 125-Hz LF values. For most octave band mean values, except for RT values, there are also significant source–receiver distance effects as well as some interaction effects. These will be considered in more detail in subsequent sections of this paper.

While these analyses of variance results demonstrate that in general there are significant differences between halls, they do not confirm whether particular differences between a pair of halls are statistically significant. Therefore, further analyses were carried out comparing mean values for each pair of halls. The differences in mean octave band RT values shown in Fig. 1 are all statistically significant. Although some of these differences are very small, the means are quite accurate because there is very little within-hall variation of RT values. The differences between pairs of mean octave band EDT values are all statistically significant except at 4000 Hz, where only one of the three pairs of differences is significant. The differences between pairs of mean octave band G values shown in Fig. 3 are all significant except at 4000 Hz, and the 2000-Hz difference between the Amsterdam and Boston halls.

Only the larger differences between the pairs of octave band $C80$ and LF values are statistically significant. For $C80$ values, only 6 of the 18 pairs of differences are statistically significant. Only 8 of the 18 pairs of differences between LF values are statistically significant.

Overall, most of the between-hall differences shown in Figs. 1–5 are statistically significant. For RT, EDT, and G values, almost all of the differences are significant with only a few exceptions at higher frequencies. For the $C80$ and LF values, only some of the larger differences are statistically significant. For these latter two parameters, it is not always possible to be sure that there are real differences between halls because of the larger within-hall variation of these parameters. While many of the differences between halls are statistically significant, it is usually not possible to say whether these differences are subjectively important.

III. MEAN OCCUPIED VALUES

It is of obvious interest to compare expected values of the acoustical parameters for occupied conditions in each hall. Measurements were not made for occupied conditions and therefore the expected effect of an audience must be calculated. As a starting point, RT values for both occupied and unoccupied conditions are required. RT values for unoccupied conditions have been presented in Sec. II above. RT values for occupied conditions are available,[17] but their accuracy is not known. Various old RT data for unoccupied conditions do not agree well with each other nor with the new measurements presented here. The present results do agree with the modern results of Gade.[7] The older results of occupied conditions suggest that the effect of the audience is quite different in these apparently similar halls. It was therefore concluded that individual older data sets could not be considered to be completely reliable and hence were not used to estimate occupied conditions.

Beranek[17] presents both occupied and unoccupied RT values for a number of halls. Schultz[20] has fitted linear regression lines to this data so that the average effect of adding an audience can be easily calculated. These equations were used here to estimate the audience effect on RT values without the unknown irregularities of particular older data sets. Schultz's equations are included in the Appendix because they are not readily available to readers.

It should be mentioned that on average Schultz's equations relate to more absorptive seats than those found in the present three halls. Thus they are not ideal for the present purpose and would tend to underestimate the effects of an audience, but they were considered to be the best approach available.

The presence of an audience is not expected to change the details of particular early reflections, but only to vary the level of the later arriving sound energy. It is therefore assumed that the effect of the audience on other parameters is simply related to the changes in reverberation time that result when an audience is present. This is similar to the approach taken by Barron,[3] but with a number of differences.

Estimated occupied RT values were calculated by subtracting Schultz's predicted changes in RT values from the measured RT values in each octave band. Thus

$$\mathrm{RT}_o = \mathrm{RT} - \mathrm{DT}, \quad \mathrm{s}, \tag{4}$$

where RT is the measured unoccupied reverberation time, RT_o is the estimated occupied reverberation time, and DT is Schultz's estimated change in RT values from the equations in the Appendix. EDT values were assumed to vary in proportion to the change in RT values as assumed by Barron.[3] Thus estimated occupied EDT values were obtained as follows:

$$\mathrm{EDT}_o = \mathrm{EDT}\ \{\mathrm{RT}_o/\mathrm{RT}\}, \quad \mathrm{s}, \tag{5}$$

where again here and below the "o" subscript signifies occupied values.

According to simple diffuse field theory, reverberant sound levels would vary as ten times the logarithm of the ratio of the reverberation times. Barron has pointed out that this is not correct in concert halls[14] and has proposed his revised theory that more closely predicts measured values. He has estimated the audience effect on G values using his revised theory.[3] The change to G values predicted by Barron's revised theory can be closely approximated by 16 times the logarithm of the ratio of the RT values for RT values from 0.7 to 4.0 s. Thus, in this paper, the estimated effect of an audience on G values was calculated as follows:

$$G_o = G - 16 \log\{\mathrm{RT}/\mathrm{RT}_o\}, \quad \mathrm{dB}. \tag{6}$$

This variation of G values with reverberation time was verified by comparing it with a plot of mean G values versus mean RT values for data from 11 different large halls.

Barron calculated the effect of an audience on $C80$ values again using his revised theory. In an earlier paper,[5] measured $C80$ values were found to vary approximately as 13 times the logarithm of the corresponding RT values. This relationship was found to agree very closely with Barron's revised theory and hence was used to calculate the effect of the audience on $C80$ values as follows:

$$C80_o = C80 + 13 \log\{\mathrm{RT}/\mathrm{RT}_o\}, \quad \mathrm{dB}. \tag{7}$$

Because LF values depend only on early arriving sound energy, they were assumed to not be greatly changed by the presence of an audience. Although these estimates of the effect of the audience on each parameter involve some uncertainty, they are thought to be the best possible with the available information. Because the same procedures are applied to all three halls and because the absorptive properties of the seating in the three halls appeared to be similar, the results should at least provide valid comparisons among the halls for expected occupied conditions.

Figure 6 compares expected hall average occupied RT values for the three halls. The values are of course lower than

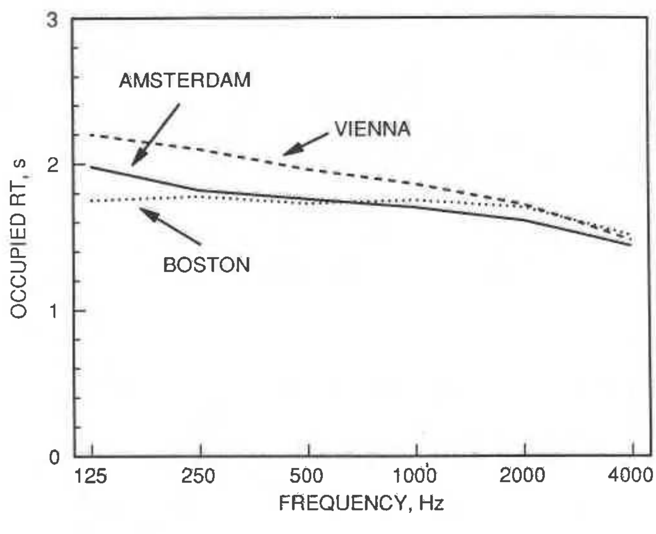

FIG. 6. Estimated hall average occupied RT values versus octave band frequency for each hall.

the unoccupied values of Fig. 1(a), and the occupied estimates for the three halls are more similar to each other than were the unoccupied values. Thus, when occupied, the three halls would be expected to have very similar RT values, with the values in the Vienna hall being a little larger at frequencies up to 1000 Hz.

The estimated hall average occupied EDT values in Fig. 7 show a quite similar pattern. For these occupied EDT values, the Vienna hall again has the highest values and the Boston hall is slightly lower than the Amsterdam hall for frequencies up to 1000 Hz. The midfrequency occupied EDT values for all three halls are approximately in the range 1.8–2.0 s. The perception of reverberance in these halls would on average be expected to parallel these EDT values.

Figure 8 compares expected occupied hall average G values for the three halls. These calculated results suggest that the strength of the sound in the Amsterdam and Vienna halls would be very similar but that it would be weaker in the Boston hall and particularly so at lower frequencies. All occupied G values are 0 dB or greater.

The calculated hall average occupied $C80$ values for the three halls are compared in Fig. 9. Differences among the results are quite small but $C80$ values in the Boston hall are slightly higher for octave bands up to 1000 Hz. Results in the Amsterdam hall are slightly lower than for the Vienna hall in the 250- and 500-Hz octave bands. Almost all $C80$ values are below 0 dB and midfrequency values range approximately from 0 to -2 dB.

In general, the calculated occupied values indicate that the three halls are very similar in their acoustical properties. Of the three halls, the Boston hall is most different with somewhat lower G values and higher LF values than the other two halls.

IV. WITHIN-HALL VARIATIONS

A simple measure of the spatial variation in a hall is the standard deviation of values about the hall average value. This standard deviation includes both the seat-to-seat variation caused by moving the receiver as well as the variation caused by varying the source position. Such spatial standard deviation values are first presented to give an overview of spatial variations before considering the individual effects of source and receiver position.

Figure 1(b) compares the spatial standard deviation of measured RT values in the three halls. The three halls have quite similar results and, above the lowest two octave bands, the standard deviations are well below 0.1 s. Thus RT values vary very little throughout these spaces. The spatial standard deviations in this and subsequent figures also give an indication of the significance of the differences between the mean values in part (a) of the figure.

The characteristic shape of the curves of Fig. 1(b) is to be expected in reverberant rooms, and Davy[21] has shown theoretically that the spatial standard deviation of RT values can be predicted to have this shape. As an example, Fig. 10 compares the measured and predicted results from Davy's

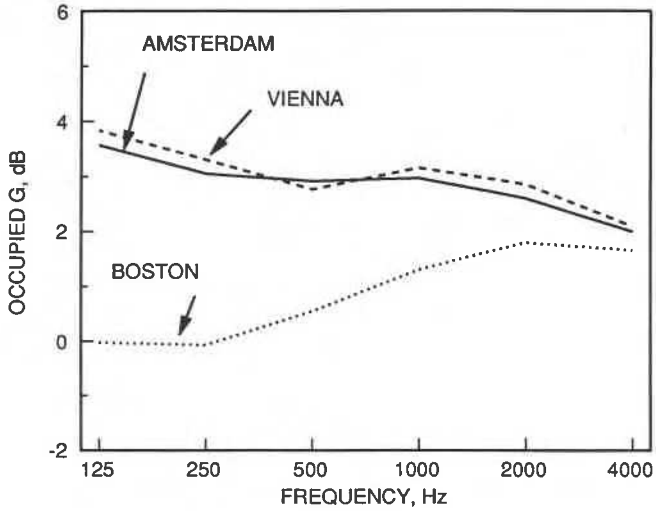

FIG. 8. Estimated hall average occupied G values versus octave band frequency for each hall.

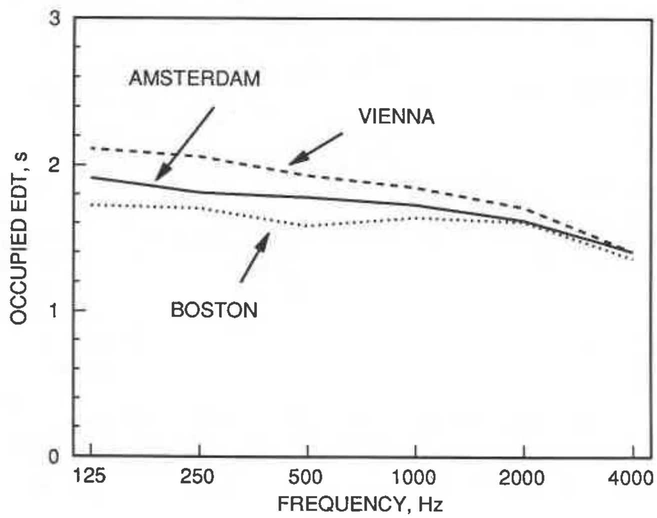

FIG. 7. Estimated hall average occupied EDT values versus octave band frequency for each hall.

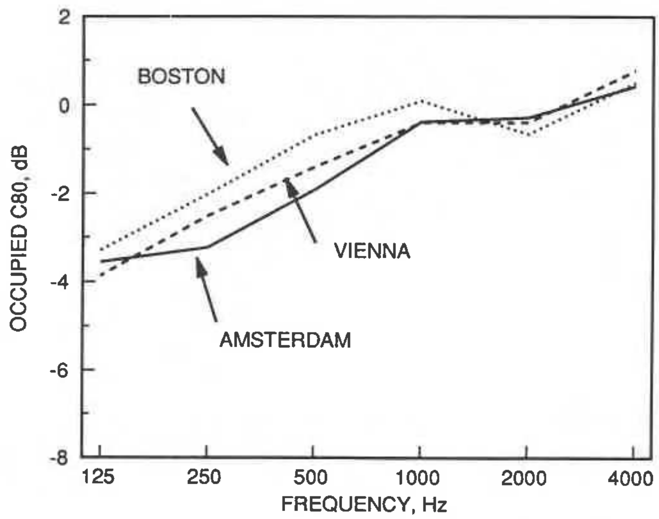

FIG. 9. Estimated hall average occupied $C80$ values versus octave band frequency for each hall.

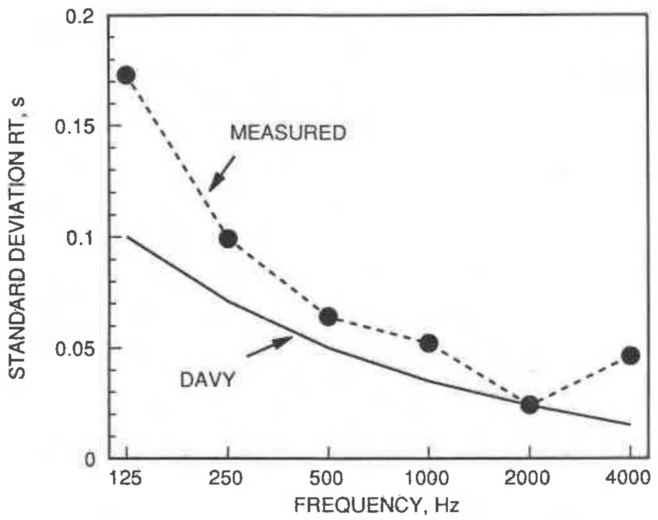

FIG. 10. Comparison of measured spatial octave band standard deviations of RT values in the Vienna hall and predictions by Davy.[21]

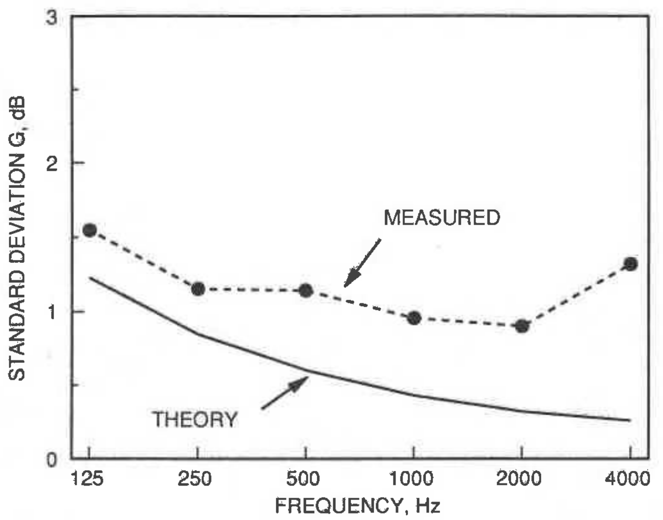

FIG. 11. Comparison of measured spatial octave band standard deviations of G values in the Vienna hall and diffuse field predictions by Lubman.[22]

theory with the Vienna hall results. In this hall, there is no systematic variation of these values with source–receiver distance. Although not shown, measured and predicted spatial standard deviation values in the other halls were quite similar and again Davy's theory predicted the characteristic increase in spatial standard deviation with decreasing octave band frequency.

The comparison of the spatial standard deviations of measured EDT values in Fig. 2(b) presents a different pattern than that found for the RT values. All of the standard deviations are larger than for RT values and the Boston hall standard deviation values deviate from those of the other two halls at frequencies of 1000 Hz and higher. For these high-frequency octave bands, the Boston hall has the largest variation in EDT values while the Amsterdam hall is most homogeneous. Because the spatial variation of EDT values is greater than for RT values, the perception of reverberance will vary more from seat to seat than indicated by RT values.

Figure 3(b) compares spatial standard deviations of G values in the three halls. The Amsterdam and Vienna halls have similar spatial standard deviation values that are approximately 1 dB at frequencies above 125 Hz. The spatial variation of G values in the Boston hall is larger and tends to increase with frequency above 250 Hz.

Lubman[22] has shown how to calculate the expected value of the spatial variance of pressure squared values in an ideal diffuse sound field. Chu[23] has demonstrated how to extend this to calculating the spatial standard deviation of sound levels in such an ideal sound field. In Fig. 11, the measured spatial standard deviations of G values in the Vienna hall are compared with these theoretical predictions. Results for the Vienna hall were used because they had very little systematic variation with source–receiver distance. The theoretical standard deviations increase with decreasing measurement bandwidth and decreasing reverberation time. Thus the predicted standard deviations increase with decreasing octave band frequency due to the decreasing bandwidth of these filters. While one would not expect a concert hall to be an ideal diffuse sound field, the measured spatial standard deviations are reasonably close to predictions at lower frequencies and deviate increasingly with increasing frequency. Thus this hall behaves increasingly less like a diffuse sound field as frequency increases. This is partly due to the increasing effect of air absorption, but also due to conditions simply not being ideally diffuse. The theoretical calculations can at least be considered as a lower bound for concert halls and, the more they deviate from this lower bound, the less they behave like a diffuse sound field in this particular respect. Comparison of the Amsterdam hall results with theoretical predictions gave slightly better agreement than that found in Fig. 11, and comparisons for the Boston hall results indicated somewhat less agreement.

The spatial standard deviations of measured $C80$ values are shown in Fig. 4(b). For this parameter, the results from the three halls are more similar. From 125 to 500 Hz, the three halls have almost identical spatial variation of $C80$ values. At the higher octave band frequencies, the Boston hall results indicate a little larger spatial variation in these values.

Figure 5(b) plots the spatial standard deviations of LF values. There is a trend such that the Vienna hall has the least variation in this quantity and the Boston hall the largest variation. However, the results are a little irregular and vary somewhat with frequency. It is interesting to note that the spatial variations of LF values are quite large when compared to the mean values of this quantity in each hall. In some cases, the spatial standard deviation of LF values is as much as 50% of the mean value. By comparison, the spatial variation of RT values is much smaller and is typically only a few percent of the hall mean values at midfrequencies.

Although there are some differences among the halls, which may be attributable to the details of each hall, the spatial variations in these halls show remarkable similarities. In the case of RT values, these spatial variations were shown to agree quite well with theoretical predictions based on the details of the measurement procedure. It is probable that the similarities among the halls indicate that the spatial variations of the other parameters are similarly limited by the basic physics of the situation. Larger spatial variations have been found in other halls[11] and this additional spatial variation is probably due to specific inadequacies of these other halls.

V. EFFECT OF SOURCE POSITION

Although the spatial standard deviation can be used as a convenient single figure of merit concerning the spatial variation within a hall, it is of interest to examine the separate effects of the source and receiver positions. This section considers the influence of source position. Mean octave band values of each parameter were calculated by averaging the results at each receiver position for each of the three source positions.

For RT and EDT values, there was very little effect of source position. RT values were essentially the same for all three source positions in all of the halls. A similar pattern existed for EDT values except for some small differences for 125-Hz results. Thus, in all three halls, mean RT and EDT values were essentially independent of the source position.

Small variations of mean *G* values with source position were observed. In the Amsterdam hall, the source-averaged *G* values were almost 1 dB lower in all six octave bands for source position S3 than for the other two source positions. This source position was located toward the rear of the orchestra and toward stage right. The average source–receiver distance for S3, which is 23.3 m, was larger than for the other positions, which were 17.8 and 19.0 m. Thus it appears that the slightly lower levels for this source position may be due to the receivers being on average a little farther from the source. When the early and late arriving sound energy was considered separately for these source-average values, the early and late arriving sound energy was considered separately for these source-average values, the early energies showed the largest effect of source position. Calculated *G*80 values, which are the *G* values of the energy arriving within 80 ms after the direct sound, were approximately 1 dB lower for source position S3. The *G*(late) values, which are the *G* values for the sound energy arriving more than 80 ms after the direct sound, exhibited only a very small effect of source position. Thus the small source position effect on the total *G* values in the Amsterdam hall is probably due to the different average source–receiver distances that most influence the early arriving sound energy. There was no evidence of a source–receiver distance effect in the other halls. Perhaps it is evident in the Amsterdam hall because of its greater width that would relate to weaker side wall reflections, or due to the lack of stage rear wall reflections.

In the Vienna hall, differences in source-averaged values were very small. For the source position that was in the middle of the stage left side of the orchestra, mean values were approximately 0.3 dB higher at lower frequencies with smaller differences at higher frequencies. The cause of these small differences was investigated further and the effects were again largest for the early arriving sound energy. The slightly higher average levels for this source position were due to a less obscured view of receivers in the side balcony on the opposite side of the hall and in the side loge under the side balcony. The view of these microphones from the other two source positions was partially blocked by the railing in front of these seats.

The source-averaged *G* values for the Boston hall were almost identical for all three source positions. There were no risers on the Boston stage when measurements were made. Thus all three source positions were the same height above the stage floor. The risers on the stages of the other two halls led to a variation in source height that had some influence on the screening of the direct sound by railings.

Source-averaged *C*80 values, like RT and EDT values, did not vary significantly with source position in any of the halls. There were only small effects at 125 Hz in some cases.

LF values did exhibit some effect of source position. In the Amsterdam hall, the source position in the center of the stage left side of the orchestra produced on average higher LF values. For this source position, LF values were larger by as much as 0.06 with the greatest differences at 500 Hz. Presumably this position was better situated to direct lateral reflections to the various receiver positions.

Differences among the source-averaged LF values for the Vienna hall were very small and did not follow any particular pattern.

The source position effects on LF values for the Boston hall were larger than in the other two halls. For source position S2, LF values were approximately 0.1 greater than for the other source positions in the 250- and 500-Hz octave bands. Smaller differences occurred at higher frequencies. In this hall, source position S1 was center stage and S2 and S3 were stage left and stage right, respectively. The stage left source position produced higher LF values at the receivers, which in this case were all on the other side of the hall. Thus, in this hall, there is a tendency for sources to direct early lateral energy preferentially to seats on the opposite side of the hall. This is thought to be due to the shape of the angled side walls of the orchestra enclosure that is unique to this hall. The other two halls do not have any specific orchestra enclosure. In the Boston hall, the side walls of the stage and the ceiling over the stage are angled to direct more energy out to the audience and, as might be expected, this appears to effect the early reflections in this hall.

In general, the effects of source position in these three halls are very small, and this is probably one of many factors that influence the general perception that these are good halls. RT, EDT, and *C*80 values are not significantly influenced by the position of the source. The small differences in *G* values appear to relate to the geometry of source and receiver positions but are probably of little practical consequence. The source-dependent effects on LF values suggest the influence of the shape of the orchestra enclosure in the Boston hall.

VI. EFFECT OF RECEIVER POSITION

The effect of receiver position was first examined by plotting 1-kHz octave band results versus source–receiver distance in each hall. These plots showed the more important midfrequency effects. RT values showed virtually no variation with source–receiver distance in these three halls.

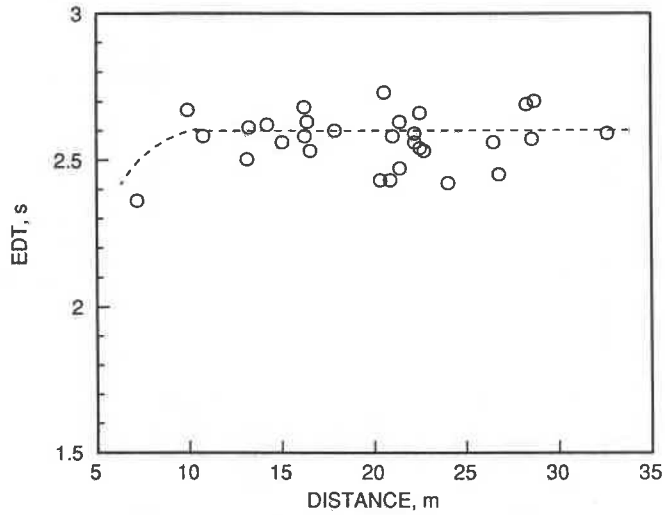

FIG. 12. Measured 1-kHz EDT values versus source–receiver distance in the Amsterdam hall. The dashed line is drawn so that the horizontal portion follows the mean 1-kHz RT value.

However, there were source–receiver distance effects on EDT values that were different for each hall.

Figure 12 plots 1-kHz EDT values versus source–receiver distance in the Amsterdam hall. Here, the EDT values do not indicate any systematic variation with distance. The dashed line in this figure was drawn to follow the mean constant trend with distance of the RT values in this hall. The initial curvature was added to parallel the results in the subsequent two plots.

Figure 13 plots 1-kHz EDT values versus source–receiver distance in the Vienna hall. Again, the dashed line was drawn to follow the approximate mean trend of the measured values and to level off at the mean RT value at larger distances. There is a more obvious trend for these EDT values to increase with increasing source–receiver distance in this hall to at least a distance of about 20 m. It is also seen that the EDT values for seats in the balcony and gallery are larger than for other seats and are larger than the RT values at these same seats.

The 1-kHz EDT values are plotted versus source–receiver distance for the Boston hall in Fig. 14. In this hall, there is an even more obvious increase of EDT values with source–receiver distance than in the other two halls. EDT values increase in value up to a distance of approximately 30 m. Again, the dashed line has been drawn to follow the mean trend and to level off at the mean value of RT for this hall. This hall is unique among the three in that it has a significant number of seats under a balcony. The results of Fig. 14 show that EDT values tend to be lower at seats that are under the balcony.

The amount of variation of EDT values with source–receiver distance varies among these three halls. This is thought to be due to the variation in the concentration of early energy at the front of these halls. There is a stronger concentration of early energy at the front of the Vienna hall because it is narrower and this leads to stronger lateral reflections at these closer seats. A similar but stronger concentration of early energy occurs at the front of the Boston hall due to the shape of the orchestra enclosure that directs energy to these seats. The effect is minimal or absent in the Amsterdam hall because of its greater width, lack of a specific orchestra enclosure, and possibly due to the presence of audience seating behind the orchestra.

The variations in $C80$ values with source–receiver distance paralleled those for EDT values, except the effects were inverted. Thus, where EDT values increase with increasing source–receiver distance, $C80$ values decrease with increasing distance. There was in some cases more scatter in the $C80$ results due to more irregular results at a few seats such as side balcony seats, where in some situations the direct sound was partially screened by a railing.

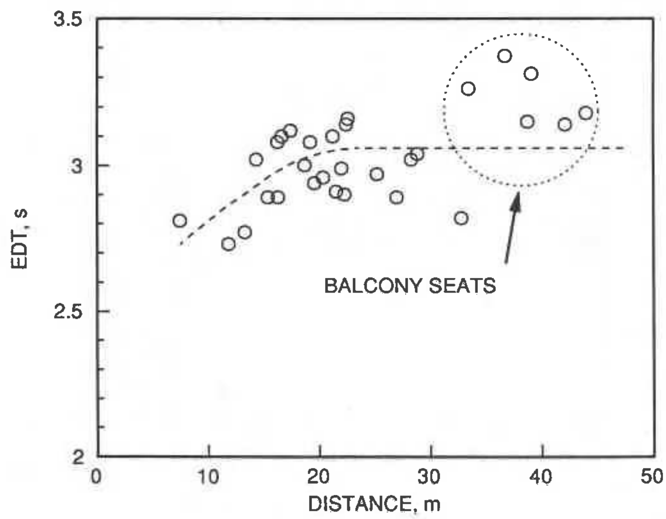

FIG. 13. Measured 1-kHz EDT values versus source–receiver distance in the Vienna hall. The dashed line is drawn so that the horizontal portion follows the mean 1-kHz RT value.

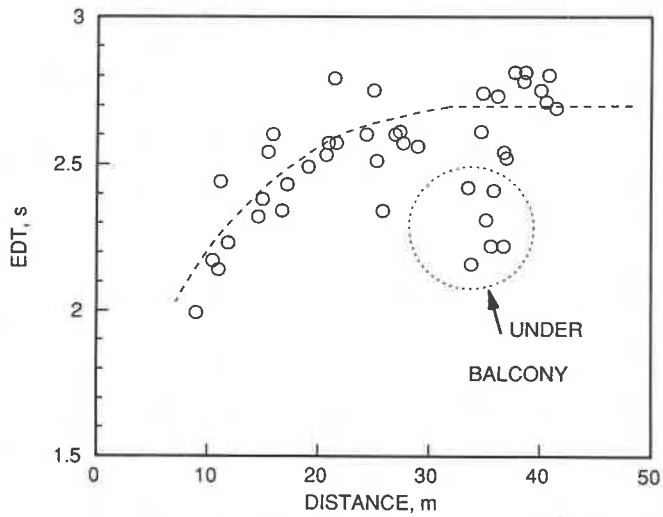

FIG. 14. Measured 1-kHz EDT values versus source–receiver distance in the Boston hall. The dashed line is drawn so that the horizontal portion follows the mean 1-kHz RT value.

VII. LEVEL DECREASE WITH SOURCE–RECEIVER DISTANCE

The variation of 1-kHz G values with source–receiver distance is illustrated in Fig. 15. To permit clear comparisons among the results for the three halls, only the best fit regression lines to the measured data are shown. The equations of these regression lines are included in Table I. The actual data points indicated reasonably linear trends with no indication of unusual effects for seats either in or under balconies. In all three halls, G values decrease with increasing source–receiver distance. The slopes of these lines vary from -0.6, for the Vienna hall, to -1.6 dB/10 m for the Boston hall. Larger variations of G values with distance have been reported. Barron[14] found slopes as steep as -2 dB/10 m and Bradley[11] reported values as great as -2.6 dB/10 m. While the Boston and Amsterdam results exhibit somewhat similar trends, G values at the farthest seats in the two longer halls, Vienna and Boston, are different by more than 3 dB. Thus the farthest seats in the Vienna hall would receive a louder sound than seats at a similar distance in the Boston hall.

The variation of G values with distance was explored further by considering the early and late components of the G values as well as separately considering the early lateral energy. Figure 16 compares the regression lines fitted to the $G80$ values that include sound energy arriving up to 80 ms after the direct sound. The equations of these regression lines are also found in Table I. The Boston hall $G80$ values are largest closer to the source (10- to 15-m distances), but they decrease more rapidly with distance than in the other two halls. The slopes of the regression lines for the Amsterdam and Vienna halls are almost identical but the Amsterdam hall $G80$ values are consistently slightly lower. The fact that $G80$ values are lower in the Amsterdam hall than in the Vienna hall may be related to its greater width. The different behavior of the $G80$ values in the Boston hall is again thought to be due to the shape of the orchestra enclosure that produces a concentration of early reflections to seats near the front of the hall and consequently less early energy at more distant seats.

This explanation is further supported by the results in Fig. 17, which compares regression lines to measurements of

TABLE I. Regression equations for G values as a function of source–receiver distance r in meters.

$G = -0.1035\,r + 7.830$, dB	Amsterdam
$G = -0.0616\,r + 8.037$, dB	Vienna
$G = -0.1634\,r + 8.651$, dB	Boston
$G80 = -0.1323\,r + 3.828$, dB	Amsterdam
$G80 = -0.1264\,r + 4.360$, dB	Vienna
$G80 = -0.2553\,r + 6.718$, dB	Boston
$\text{GEL} = -0.2018\,r - 2.417$, dB	Amsterdam
$\text{GEL} = -0.1357\,r - 3.144$, dB	Vienna
$\text{GEL} = -0.2931\,r + 1.017$, dB	Boston
$G(\text{late}) = -0.0731\,r + 5.227$, dB	Amsterdam
$G(\text{late}) = -0.0237\,r + 5.366$, dB	Vienna
$G(\text{late}) = -0.1008\,r + 4.861$, dB	Boston

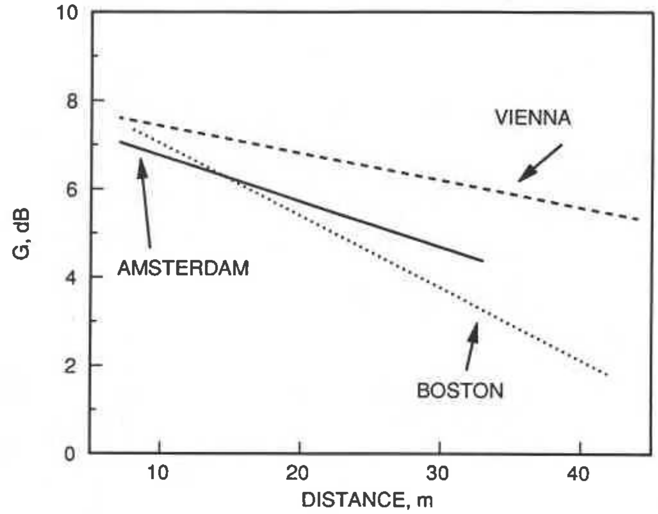

FIG. 15. Comparison of best fit linear regression lines to measured 1-kHz G values in each hall.

GEL values, the G values for the early lateral energy arriving within the first 80 ms after the direct sound. Again, the Boston hall values are larger closer to the source, but they decrease most rapidly with increasing distance. The Amsterdam and Vienna hall results are very similar but, in the wider Amsterdam hall, GEL values decrease slightly more rapidly with distance. The differences between GEL values from the Boston hall and the other halls, at positions closer to the source, are greater than for $G80$ values, indicating that a significant portion of the additional early energy in the Boston hall arrives from the side.

Figure 18 completes the examination of the variation of levels with distance by plotting G(late) values versus the source–receiver distance. These are the G values for the sound energy arriving more than 80 ms after the direct sound. These values are more similar to the total G value data in Fig. 15, indicating that the late arriving energy is the

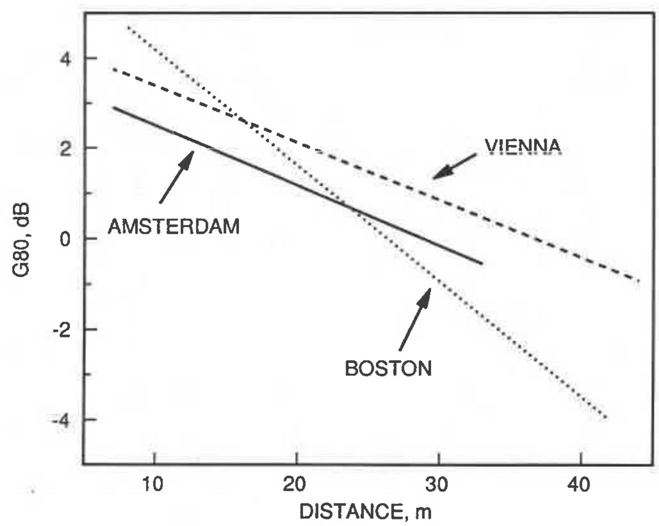

FIG. 16. Comparison of best fit linear regression lines to measured 1-kHz $G80$ values in each hall.

major component of the total sound energy. Again, there are differences in the slopes of these regression lines varying from − 0.2 dB/10 m for the Vienna hall to − 1.0 dB/10 m for the Boston hall. The regression equations are given in Table I. The *G*(late) values closer to the source are very similar in all three halls, but further away there are differences of up to several decibels.

The results of Figs. 16 and 18 and Table I also show that early sound levels (*G*80 values) drop off more rapidly with distance than the late energy levels. Thus the attenuation of the overall *G* values with distance will depend on the portion of the total sound energy that arrives within the first 80 ms after the direct sound.

VIII. MEASUREMENT AND PREDICTION OF LEVELS

The strength or sound level is perhaps the most important basic quantity, other than reverberation time, that one might try to predict in a concert hall. One can estimate expected sound levels from simple diffuse field theory.

$$\mathrm{SPL} = \mathrm{SWL} + 10 \log[Q/(4\pi r^2) + 4/A], \quad \mathrm{dB}, \qquad (8)$$

where SPL is the measured sound-pressure level, SWL is the source sound power level, Q is the directivity factor of the source, and is 1 for an omnidirectional source, r is the source–receiver distance, m, and A is the total sound absorption, m^2. The total sound absorption A can be calculated from the measured RT values using the Sabine reverberation time equation. Thus the total G value calculated from these assumptions would be given by

$$G = 10 \log[Q/(4\pi r^2) + 4\,\mathrm{RT}/(0.161\,V)] + 31, \quad \mathrm{dB}, \qquad (9)$$

where V is the room volume, m^3.

Barron has pointed out[14] that this simple approach does not accurately predict measurements in concert halls. In particular, the simple diffuse field theory predicts that sound levels will be relatively constant throughout most of a large hall. Measured levels in even the present very reverberant

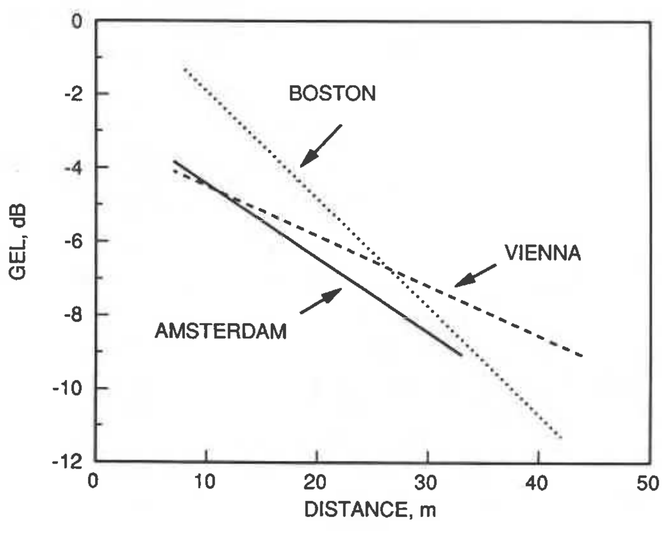

FIG. 17. Comparison of best fit linear regression lines to measured 1-kHz GEL values in each hall.

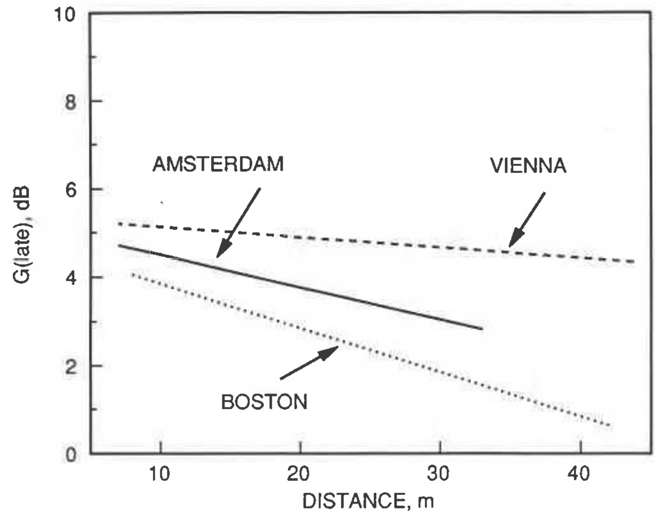

FIG. 18. Comparison of best fit linear regression lines to measured 1-kHz *G*(late) values in each hall.

classical halls decrease with increasing source–receiver distance. Barron accordingly proposed his revised theory to more accurately predict sound levels in concert halls.

The variation of sound levels with distance in each of the present three classical halls is compared with both the simple diffuse field theory and Barron's revised theory in Figs. 19–21. The open circles in these plots represent measurements at main floor seats and the filled circles represent results from balcony seats. In all three halls, the simple diffuse field theory is not a very accurate predictor of measured results and tends to overpredict measured values at all but a few closer seats. Barron's revised theory presents a reasonable approximation to the mean trends of the measured data and would be a useful procedure for predicting sound levels in these three halls.

A more detailed examination revealed differences indicating that, although Barron's revised theory is a consider-

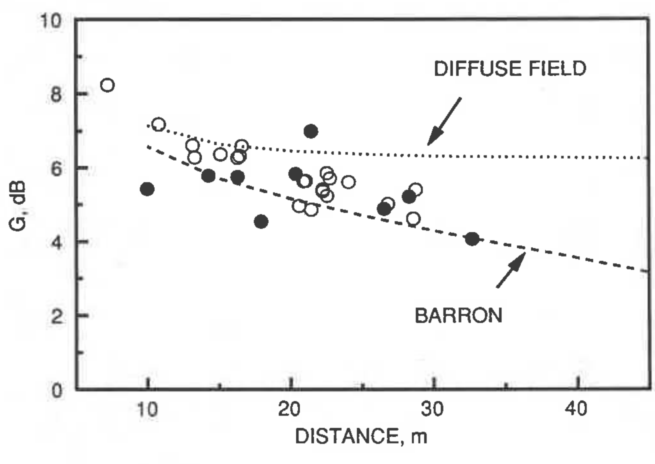

FIG. 19. Comparison of measured 1-kHz *G* values versus source–receiver distance in the Amsterdam hall with predicted values by simple diffuse field theory, and Barron's revised theory.[14]

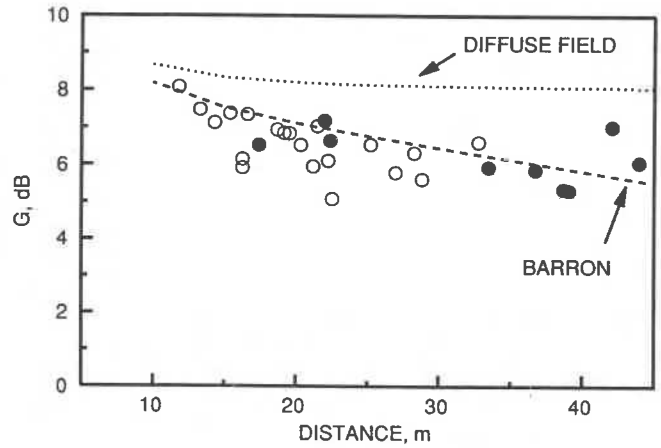

FIG. 20. Comparison of measured 1-kHz G values versus source–receiver distance in the Vienna hall with predicted values by simple diffuse field theory, and Barron's revised theory.[14]

able improvement, there may be factors that it does not include. His revised theory allows one to calculate separately the early and late arriving energies as well as the total sound level or G value. In the case of the Vienna hall results in Fig. 20, the data points suggest, for source–receiver distances greater than approximately 15 m, that G values show no further systematic decrease with distance. Barron's revised theory predicts a continuing small decrease with increasing distance. Both the measured G(late) and $G80$ values seem to exhibit this same trend to vary less with distance than predicted by Barron's theory.

The Amsterdam hall results have several irregularities in the G values of Fig. 19 due to the effects at particular side balcony seats. These were more pronounced for the $G80$ values, and appear to be due to the particular direct sound paths to side balcony seats. For this hall, Barron's theory tended to underpredict the G(late) values by approximately 1 dB.

In the Boston hall results of Fig. 21, Barron's revised theory underpredicts G values at closer seats and overpredicts them at more distant seats. This seems to be largely due to a similar but larger effect with $G80$ values in this hall. Again, this may be due to the shape of the orchestra enclosure in this hall that tends to concentrate early energy at seats closer to the stage.

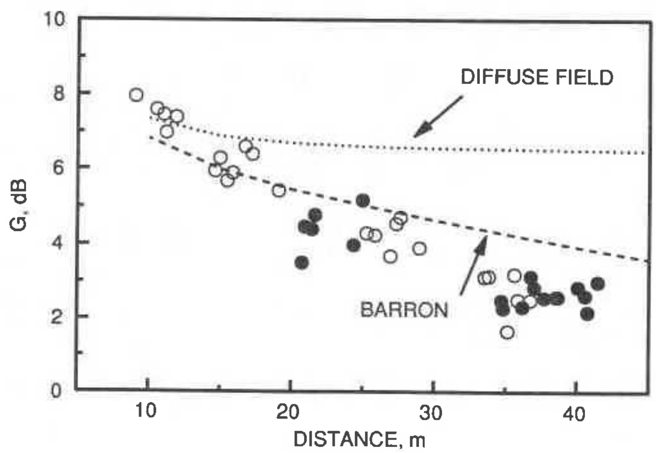

FIG. 21. Comparison of measured 1-kHz G values versus source–receiver distance in the Boston hall with predicted values by simple diffuse field theory, and Barron's revised theory.[14]

Diffuse field theory is thus again confirmed to be inadequate for concert halls and Barron's revised theory is seen to be a considerable improvement. A further improved prediction procedure may require the inclusion of the details of the geometry and materials of each hall such as is possible using computer ray tracing techniques.

IX. FREQUENCY-DEPENDENT EFFECTS AS A FUNCTION OF SEAT POSITION

The results in the previous sections have concentrated on the within-hall variation of midfrequency values. In this section, the variation with frequency of G values in the three halls is discussed. It is desired to examine the average behavior of G values versus frequency in different seating areas without the particular details of individual seats. Thus, in each hall, the main floor measurement positions were grouped as "near," "mid," or "far" seats, depending on their distance from the stage. Average G values were then calculated by averaging over the results for all three source positions and all seats in each group. Similar group averages were calculated for balcony seats.

It is well known that the sound passing at grazing incidence over audience seating is strongly attenuated at particular low frequencies.[24,25] This effect can preferentially attenuate early low-frequency energy as measured by $G80$ values and also influence the ratio of early/late arriving sound energy, $C80$ (see Ref. 6). This effect is smaller in the present three halls than in some other halls,[26] and the effect varies among these halls and between seating areas in the same hall.

Figure 22 compares $G80$ values for main floor seats in the Amsterdam and Vienna halls. In each case the three lines on this graph for each hall correspond, in order of decreasing $G80$ values, to near, mid, and far seats, respectively. Of these two halls, the $G80$ values at the main floor seats of the Amsterdam hall vary less with position. At all three seating areas, there is evidence of a seat dip attenuation, which is greatest at 125 or 250 Hz. (It is assumed that G values would increase below 125 Hz as indicated by previous measurements.[24,25]) These dips in the Amsterdam hall results are quite broad but quite shallow and never exceed 3 dB below the maximum $G80$ values. The greatest difference for the Vienna hall results is the higher $G80$ values at the near seats, where the seat dip attenuation is limited to the 125-Hz octave band. This excess of early energy at these seats was seen to produce smaller EDT values at these same seats in SEC. VI above. For all three seating areas, the seat dip attenuation is again quite shallow.

Figure 23 compares G(late) values versus frequency for the three seating areas in the Amsterdam and Vienna halls. These results exhibit a different characteristic shape than found for the $G80$ values. The G(Late) spectra tend to be relatively flat with an increase sometimes at 125 Hz and a decrease always at 4000 Hz. The high-frequency reduction

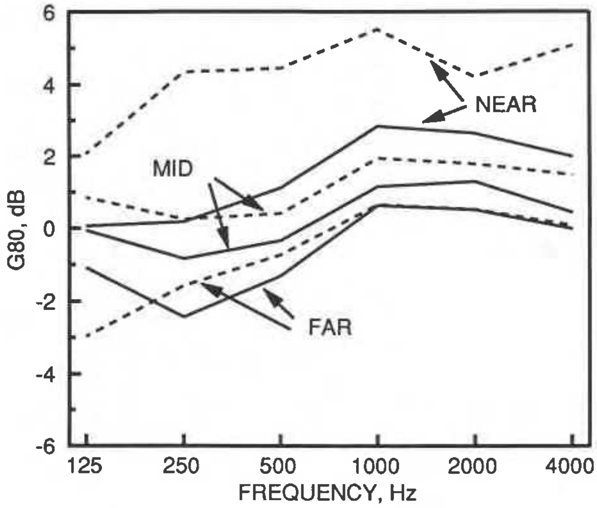

FIG. 22. Comparison of mean octave band $G80$ values by main floor seating area in the Amsterdam hall (solid lines) and the Vienna hall (dashed lines). The curves correspond to near, mid, and far seats.

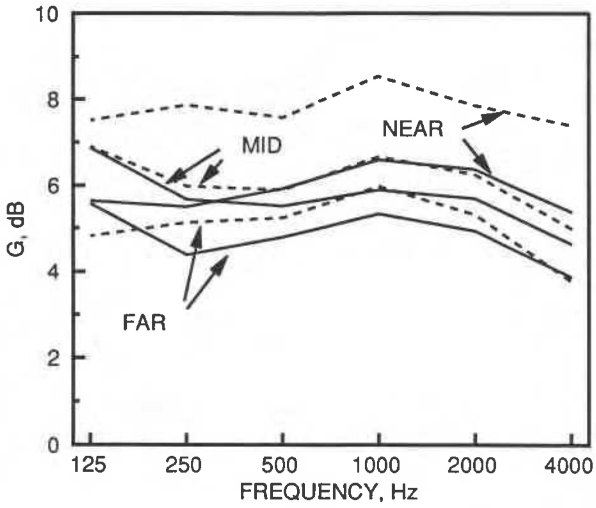

FIG. 24. Comparison of mean octave band G values by main floor seating area in the Amsterdam hall (solid lines) and the Vienna hall (dashed lines). The curves correspond to near, mid, and far seats.

at 4000 Hz is caused by increased air absorption at this frequency. In the Vienna hall, the G(late) values consistently decreased with increasing distance from the stage and so the three dashed curves in Fig. 23 are for near, mid, and far seats in order of decreasing G(late) value. The Amsterdam hall results were more irregular and the mid seats had slightly larger G(late) values than the other seats. However, the near seats did have slightly larger G(late) values than the far seats.

When the early and late arriving sound energy is combined, the total G values are obtained, as illustrated in Fig. 24 for the Amsterdam and Vienna halls. Here, the curves for each hall decrease with increasing distance from the stage, except for a small irregularity in the low-frequency results of the Amsterdam hall. The results are very similar for the two halls except for values that are a little larger at the near seats in the Vienna hall. This increase is due to the higher $G80$ values at these seats. It is quite remarkable how flat these spectra are. Even including the small decrease at 4000 Hz, all of these spectra are flat within approximately ± 1 dB. Thus one would expect that these halls do not greatly change the spectrum of the musical sounds that are radiated from the stage. This characteristic is not found in all halls, and would be modified by the presence of an audience.

The G values from the Boston hall have not been included in these plots because the Boston results are a little different and because it is difficult to compare three sets of curves on a single plot. Figure 25 plots the total G values versus frequency for four main floor seating areas in this hall. These are labeled near, mid, far, and under in order of increasing distance from the stage. The under results are the farthest from the stage and were obtained at seats that were under the

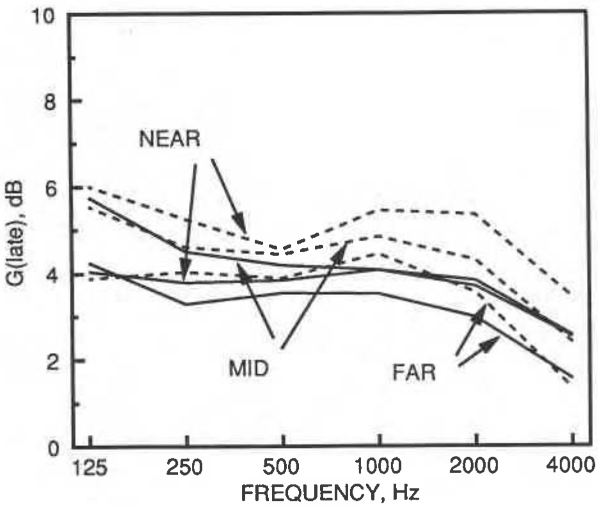

FIG. 23. Comparison of mean octave band G(late) values by main floor seating area in the Amsterdam hall (solid lines) and the Vienna hall (dashed lines). The curves correspond to near, mid, and far seats.

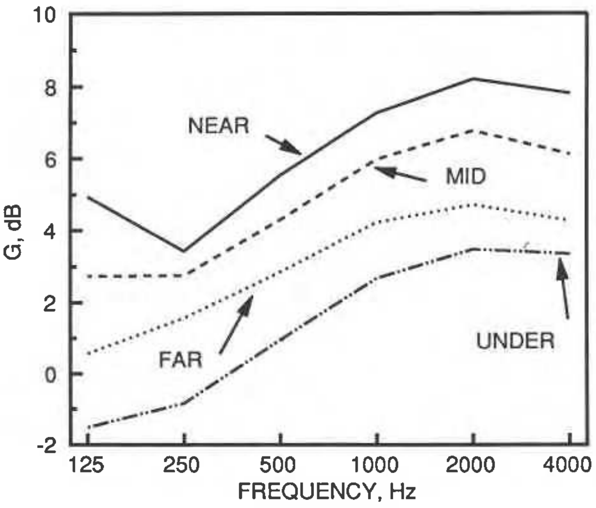

FIG. 25. Comparison of mean octave band G values by main floor seating area in the Boston hall. The curves correspond to near, mid, far, and under seats. Under seats were farthest from the stage and under the balcony.

balcony. The G value spectra in this figure are not as flat as for the other two halls and there is in each spectrum a broad minimum centered at 125 or 250 Hz.

Examination of the $G80$ values at the same main floor seats (not shown) produced a very similar set of spectra with the same broad minima centered at the same frequency bands as in Fig. 25. The G(late) values also presented a very similar pattern with the same low-frequency behavior and some additional small high-frequency attenuation in the 4000-Hz band as found in the other halls. While the low-frequency attenuation of G values in the Boston hall is really not very large, it is different from the measured effects in the other two halls.

Examining the measured G values at balcony seats in the Boston hall gives a more complete understanding of the behavior of sound in this hall. Figure 26 compares the average results at seats in the rear of the first and second balconies. While the two average G(late) spectra are quite similar to those measured at main floor seats, the $G80$ spectra are different. At these balcony seats, the $G80$ spectra are quite flat with only a dip in the 125-Hz octave. These $G80$ spectra are typical of results found at balcony seats in other halls. The early arriving sound traveling to these balcony seats does not pass close to the main floor seats. It only passes close to a few rows of balcony seats before arriving at these receiver positions. Thus the seat dip attenuation is less developed and in this case is only a smaller dip at 125 Hz. The later arriving energy is influenced by the general properties of the hall and is attenuated over a broader low-frequency region as found at other seats in the hall. Very similar effects were found at the balcony seats of the other two halls.

From consideration of the G value measurements in various areas of the Boston hall, it is suggested that the broad low-frequency attenuation that is found in this hall may be caused by the expected low-frequency sound absorbing characteristics of the removable floor. The floor is said to be made of 3/4-in. boards over an air space that varies from very small up to over 1 m in height,[17] and hence could be expected to be a source of low-frequency sound absorption. Such extra low-frequency absorption by the floor would explain why $G80$ values are affected at the main floor seats, but not at seats in the balconies. It is also possible that surfaces such as those of the stage enclosure, that influence early reflections, may exhibit low-frequency panel resonances leading to decreased early low-frequency sound levels. As observed in the present results, any low-frequency absorption would be expected to influence G(late) values throughout the hall. It is interesting to note that the hall average RT values in Fig. 1(a) also show a small decrease at lower frequencies.

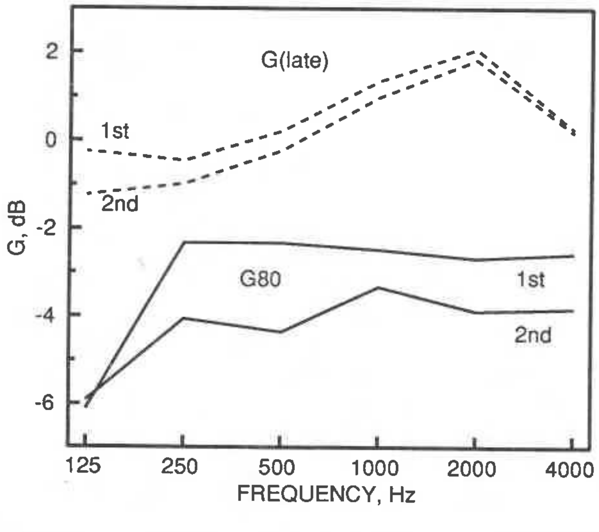

FIG. 26. Comparison of octave band $G80$ values (solid lines) and octave band G(late) values (dashed lines) for rear balcony seats in the Boston hall. Measurements in the first balcony are labeled "1st" and in the second balcony are labeled "2nd."

These results again demonstrate the remarkable homogeneity of acoustical conditions in these three halls. The spectrum of the sound is remarkably unmodified in two of the halls and only small low-frequency effects are observed in the third hall. The results in the Boston hall again demonstrate that these measurements can help to explain in considerable detail the acoustical characteristics of concert halls.

X. TIMBRE-RELATED EFFECTS

The timbre or tone quality imparted to the sound by a hall is one of a small number of parameters that is thought to be an important correlate of subjective impressions.[2,3] Although the effects of the hall on the spectrum of sound levels, as measured by G values, have been suggested to relate to perceived timbre, Barron[3] recently concluded that timbre was more strongly related to the variation of EDT values with frequency, EDT(f). In this paper, we have calculated several quantities that describe how EDT and G values vary with frequency in each of the three halls.

As a simple indicator of variations with frequency, the standard deviation about the mean of the six octave band results was calculated for EDT(f) and $G(f)$ values. These standard deviations indicate only the magnitude of frequency-dependent variations. They do not indicate whether high or low frequencies are stronger or weaker.

More specific timbre-related parameters can be calculated by grouping measurements as low-, medium-, or high-frequency values. For each quantity, the 125- and 250-Hz octave bands are considered to represent low-frequency results, the 500- and 1000-Hz results intermediate frequencies, and the 2000- and 4000-Hz octave bands high-frequency results. By summing values in these two octave groups, the ratio of low- to intermediate-frequency effects and high- to intermediate-frequency effects can be estimated. Thus, for EDT(f) values, a bass and a treble ratio were calculated as follows:

$$\text{bass ratio} = [\text{EDT}(125) + \text{EDT}(250)]/[\text{EDT}(500) + \text{EDT}(1000)],$$

$$\text{treble ratio} = [\text{EDT}(2000) + \text{EDT}(4000)]/[\text{EDT}(500) + \text{EDT}(1000)].$$

Similarly, for $G(f)$ values, bass and treble differences were calculated as follows:

$$\text{bass difference} = [G(125) + G(250)] - [G(500) + G(1000)], \text{dB},$$

$$\text{treble difference} = [G(2000) + G(4000)] - [G(500) + G(1000)], \text{dB},$$

where the summation of octave band G values was a correct energy summation converted back to decibels.

Values of all six parameters were calculated for each source–receiver combination in each hall. The values derived from EDT(f) values tended to be more consistent throughout each hall than the values derived from $G(f)$ values. There were a number of particular combinations of source and receiver that did have spectral differences in EDT(f) values but there were no systematic changes from one area to another. As noted in previous sections, the spectrum of $G(f)$ values did vary from one seating area to another. Thus the timbre measures derived from EDT(f) values are more representative of conditions in the entire hall while those derived from $G(f)$ values are indicative of more localized conditions in these halls.

The hall average values of all six parameters are given in Table II. The standard deviations of EDT(f) values indicate less flat EDT(f) spectra in the Vienna hall. This is paralleled by a smaller treble ratio in the Vienna hall. Thus, in this hall, the high-frequency EDT values are lower relative to the intermediate-frequency values compared to the other two halls. Our measurements of bass ratio values in other halls have varied from about 0.8 to 1.4. Thus the three better halls reported here all have very similar bass ratio values (0.91 to 0.96) that are just less than 1.0 and differ from the extremes found in other halls. In comparison to other halls, these three halls tend to have a quite flat low-frequency spectrum of EDT(f) values. Halls appear to have less variation in the treble ratios and the present results are representative of conditions found in a number of halls. This variation in treble ratios may be largely a question of variations in air absorption.

A different pattern is seen from the $G(f)$ values. The hall average standard deviation of $G(f)$ values is largest in the Boston hall. While the bass differences are very small in the Amsterdam and Vienna halls, there is a larger bass difference in the Boston hall. Our measurements in other halls have given bass difference values from approximately -2 to $+1$ dB. Thus the Boston hall is at the bottom of the range while the other two halls have bass differences indicating relatively flat low-frequency $G(f)$ spectra.

The treble differences again suggest that the Boston hall is different than the other two halls. Our measurements in a number of halls have produced treble difference values from approximately -2 to $+1$ dB. Most halls were in the range -0.5 to -1.0 dB. Thus the values in the Amsterdam and Vienna halls are typical of values in a number of halls. The mean treble difference value in the Boston hall is larger than that found in a number of other halls, but again this may be largely due to differences in air absorption.

While Barron found that EDT ratios were significantly related to subjective judgments of timbre, his bass level difference values were not significantly related to subjective judgments. Thus it is not clear how to interpret the fact that the level differences are different in the Boston hall. While the results seem interesting and reflect physical properties of the hall, they may be of little subjective importance.

TABLE II. Hall average timbre-related quantities.

	Boston	Amsterdam	Vienna
EDT(f) measures			
Standard deviation of EDT(f), s	0.26	0.27	0.41
Bass ratio	0.91	0.96	0.98
Treble ratio	0.95	0.84	0.77
$G(f)$ measures			
Standard deviation of $G(f)$, dB	1.44	0.72	0.87
Bass difference, dB	−1.86	−0.28	−0.17
Treble difference, dB	1.36	−0.80	−0.94

XI. CONCLUSIONS

The results of this paper permit conclusions concerning the general mean characteristics of these halls and the within-hall variation of acoustical characteristics, and give some insight into the individual peculiarities of each hall.

As measured, all three unoccupied halls are quite reverberant, with quite high RT and EDT values. Mean midfrequency RT values varied from 2.4 to 3.1 s for these unoccupied conditions. The mean EDT values are all nearly equal to the corresponding RT values, indicating approximately exponential sound decays. These halls all have high mean G values, indicating that sounds can be quite loud in these halls and that music can be produced with a large dynamic range. Mean measured midfrequency G values vary from 2.9 to 6.6 dB. All three halls have relatively low $C80$ values, suggesting that the high clarity of some more modern halls is not desirable. Mean midfrequency $C80$ values vary from -2.3 to -4.0 dB. Mean LF values are not particularly larger than those found in some other halls,[11] and mean midfrequency values vary between 0.16 and 0.25.

Both the RT and EDT values are reasonably constant with frequency except for the normal high-frequency roll-off due to air absorption. There is no indication of increased values at low frequency. The bass ratios of EDT(f) values for all three halls are all just less than 1.0, indicating a flat low-frequency response. These bass ratio values are intermediate to the extremes found in some other halls. The spectra of mean $G(f)$ values are also quite flat in two of the halls and in the Boston hall decreased a little at low frequencies.

Methods for estimating the effect of the presence of an audience are presented and the estimated occupied mean values of each parameter are compared. These results indicate that the halls would have more similar characteristics when occupied.

In spite of the discussion of the small differences among these halls, there is a general pattern of a quite remarkable homogeneity of characteristics throughout these halls. There is generally little evidence of systematic within-hall variations of parameters. The amount of spatial variation of most parameters is usually smaller than that found in a number of other halls.

Reverberation times usually do not vary greatly from seat to seat in concert halls and this is certainly true for these three halls. The spatial variation of RT values is only a little larger than prediction, indicating that the peculiarities of these halls and the measurement technique do not introduce large spatial variations in RT values. As expected, EDT values vary more than RT values within these halls, but these within-hall variations are small compared to results from some other halls. EDT values vary most in the Boston hall.

The spatial variation of *G* values is particularly small in the Amsterdam and Vienna halls and only a little larger in the Boston hall. The spatial variations of *C*80 values found in these three halls are intermediate to those found elsewhere. The spatial variations of LF values are quite large when considered as a fraction of the mean values. Such large spatial variations of this parameter are the norm.

The spectra of early, late, and total sound levels exhibit similar characteristics in all three halls. Typically early arriving energy is deficient in the low-frequency octaves due to the grazing incidence attenuation of the audience seating. The later arriving energy is characterized by a decrease at higher frequencies due to air absorption. The total sound energy is very constant with frequency in two of the halls and exhibits a small decrease at low frequencies in the Boston hall.

The results also give some insight into the individual peculiarities of each hall. In many ways the Amsterdam hall has characteristics that are intermediate to those of the other two halls. A number of parameters are slightly more homogeneous and some spatial standard deviation values are a little smaller than in the other halls. EDT values vary less with distance, and the decrease of *G* values with distance is quite small. On the other hand, the increased width that is thought to have contributed to this increased homogeneity may also cause the early lateral energy to decrease a little more rapidly with distance.

The Vienna hall has the highest RT, EDT, and *G* values, and the *G* values vary least with distance. The narrow long shape appears to cause EDT values to increase with distance and to be greater than RT values in the rear balcony and gallery.

In the Boston hall, mean EDT values are a little lower than RT values and *C*80 values are a little higher than in the other two halls. Also, *G* values are lower, and decrease at low frequencies compared to the results from the Amsterdam and Vienna halls. The shape of the stage enclosure seems to influence the distribution of early energy in this hall. Thus early energy, and especially early lateral energy, is relatively stronger closer to the stage and relatively weaker at the farthest seats. This also causes the EDT values to vary with distance from the stage. Although Barron's revised theory predicts well the mean behavior of *G* values in the other two halls, there is a tendency for measured *G* values to exceed prediction closer to the stage, and to be below prediction farther from the stage in the Boston hall.

It is hoped that these results will help to define the range of conditions that are to be expected in good concert halls. In general, the three halls that we have studied have quite similar characteristics and it is not difficult to determine intermediate values that would be desirable in other halls. The differences give some insight into the influence of the details of these halls and the range of conditions that can be considered as good. Subjective importance can only be assigned to these differences if the results of controlled experiments indicate that such differences are detectable and subjectively important.

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APPENDIX: SCHULTZ'S PREDICTION OF THE AUDIENCE ABSORPTION EFFECT

Schultz[20] fitted linear regression equations to Beranek's data,[17] relating both occupied and unoccupied RT values. His equations for the 125- to 4000-Hz octave bands presented below estimate the change in RT values that would occur with the addition of an audience.

$$125\text{ Hz: DT} = 0.510\text{ RT} - 0.708\text{, s,}$$
$$250\text{ Hz: DT} = 0.605\text{ RT} - 0.867\text{, s,}$$
$$500\text{ Hz: DT} = 0.668\text{ RT} - 0.929\text{, s,}$$
$$1000\text{ Hz: DT} = 0.696\text{ RT} - 0.935\text{, s,}$$
$$2000\text{ Hz: DT} = 0.694\text{ RT} - 0.889\text{, s,}$$
$$4000\text{ Hz: DT} = 0.652\text{ RT} - 0.752\text{, s,}$$

where RT is the measured unoccupied reverberation time and DT is the change in RT values with the addition of an audience.

[1] J. S. Bradley, "Contemporary Approaches to Evaluating Auditorium Acoustics," *Proceedings of the Audio Engineering Society International Conference on the Sound of Audio*, Washington, DC (April 1989).

[2] L. Cremer and H. A. Müller, *Principles and Applications of Room Acoustics* (Applied Science, London, 1982).

[3] M. Barron, "Subjective Study of British Symphony Concert Halls," Acustica **66**, 1–14 (1988).

[4] V. L. Jordan, "A Group of Objective Acoustical Criteria for Concert Halls," Appl. Acoust. **14**, 253–266 (1981).

[5] J. S. Bradley, "Experience with New Auditorium Acoustics Measurements," J. Acoust. Soc. Am. **73**, 2051–2058 (1983).

[6] J. S. Bradley and R. E. Halliwell, "Making Auditorium Acoustics More

Quantitative," Sound Vib. **23**, 16–23 (1989).
[7]A. C. Gade, "Acoustical Survey of Eleven European Concert Halls," Rep. No. 44, Acoustics Laboratory, Technical University of Denmark (1989).
[8]Y. Ando, *Concert Hall Acoustics* (Springer-Verlag, Berlin, 1985).
[9]J. S. Bradley, "Auditorium Acoustics Measurements from Pistol Shots," J. Acoust. Soc. Am. **80**, 199–205 (1986).
[10]J. S. Bradley and R. E. Halliwell, "New Room Acoustics Measurement Software," J. Acoust. Soc. Am. Suppl. 1 **80**, S39 (1986).
[11]J. S. Bradley, "Hall Average Characteristics of Ten Halls," *Proceedings of the 13th International Congress on Acoustics*, Belgrade (1989).
[12]J. S. Bradley and R. E. Halliwell, "Accuracy and Reproducibility of Auditorium Acoustics Measures," Proc. Br. Inst. Acoust. **10**, 399–406 (1988).
[13]A. C. Gade and J. H. Rindel, "Akustik I Danske Koncertsale," Rep. No. 22, Acoustics Laboratory, Danish Technical University (1984).
[14]M. Barron and L.-J. Lee, "Energy Relations in Concert Auditoria. I," J. Acoust. Soc. Am. **84**, 618–628 (1988).
[15]M. Barron, "Impulse Testing Techniques for Auditoria," Appl. Acoust. **17**, 165–181 (1984).
[16]L. L. Beranek, "Boston Symphony Hall: An Acoustician's Tour," J. Aud. Eng. Soc. **36**, 918–930 (1988).
[17]L. L.Beranek, *Music, Acoustics and Architecture* (Wiley, New York, 1962).
[18]M. J. R. Lamothe and J. S. Bradley, "Acoustical Characteristics of Guns as Impulse Sources," Can. Acoust. **13**, 16–24 (1985).
[19]M. R. Schroeder, "New Method of Measuring Reverberation Time," J. Acoust. Soc. Am. **37**, 409–412 (1965).
[20]T J. Schultz, "Reverberation Time Data for Some North American Concert Halls, Unoccupied," Bolt Beranek and Newman Tech. Inf. Rep. No. 98 (January 1980).
[21]J. L. Davy, I. P. Dunn, and P. Dubout, "The Variance of Decay Rates in Reverberation Rooms," Acustica **43**, 12–25 (1979).
[22]D. Lubman, "Precision of Reverberant Sound Power Measurements," J. Acoust. Soc. Am. **56**, 523–533 (1974).
[23]W. T. Chu, "Precision of Sound Level Measurements in a Reverberation Room," Building Research Note No. 101, National Research Council of Canada (Sept. 1975).
[24]T. J. Schultz and B. G. Watters, "Propagation of Sound Across Audience Seating," J. Acoust. Soc. Am. **36**, 885–896 (1964).
[25]G. M. Sessler and J. E. West, "Sound Transmission Over Theatre Seats," J. Acoust. Soc. Am. **36**, 1725–1732 (1964).
[26]J. S. Bradley, "Some Further Investigations of the Seat Dip Effect," submitted for publication to J. Acoust. Soc. Am. (1991).