

Subjective Perception of Seat Dip Attenuation

W. J. Davies, Trevor J. Cox and Y. W. Lam

Salford University, England

Summary

An investigation has been conducted into the subjective perception of the seat dip effect (a low-frequency attenuation affecting sound travelling at grazing incidence over seating). In a realistic simulation of a concert hall sound field, the threshold of perception was a change of -3.8 ± 0.2 dB in the 200 Hz octave band early energy, from 0 to 80 ms. The threshold was not greatly affected by the presence of reverberation. The size of the threshold means that low-frequency values of monaural early-energy parameters like C_{80} are relatively unimportant. On examining measurements made in a rectangular concert hall, it was shown that the seat dip effect is audible at some seats, and that a combination of design methods would be needed to render it inaudible in most cases.

1. Introduction

The seat dip effect is the name given to the selective low-frequency attenuation experienced by sound travelling at grazing incidence over seating. Its primary cause is interference between the direct sound travelling from the stage of an auditorium and multiple reflections from the seating and floor. The phenomenon was first quantified by Sessler and West [1] and Schultz and Watters [2] in 1964. The attenuation they found was strikingly large, and so conjecture started as to its subjective significance for concert audiences. Since 1964, further objective measurements of the phenomenon have been made in concert halls [3, 4] and on scale model seating [5] and two theoretical models have appeared in the literature [6, 7]. The subjective significance of the phenomenon has yet to be established, however.

The experiments described in this paper were part of a larger study into the mechanism of seat dip attenuation which is described elsewhere [8, 9]. As part of this work, we wished to evaluate the effectiveness of resonant floor absorbers [6] as a means of reducing the attenuation. On searching the literature, it was found that there was a considerable body of work from which some inferences could be drawn for the subjective significance of the attenuation. There was no direct measurement of subjective threshold or difference limen, however. It was felt that the question of whether the seat dip attenuation in a typical concert hall is perceived by listeners was an important one and that it should be answered before much more work is done in this field.

Our measurements were made in a realistic simulation of a concert hall sound field. Considerable care was taken to ensure that objective parameters of the simulated impulse response were within the ranges measured in extant halls and within the ranges known to be subjectively preferred. The subjective threshold of seat dip attenuation was measured under different reverberant conditions, to determine if early attenuation can be compensated by later energy. The results, while directly useful in their own right, also have significance for the usefulness of low frequency values of monaural parameters like clarity and centre time.

The paper is structured as follows: the relevant literature is briefly reviewed, pertinent aspects of the concert hall simulation system are described, then the results of the subjective measurements are considered and finally a sample comparison with real hall measurements is made to show how the subjective results might be used in practice.

2. Previous indications of subjective effects

After making one of the first systematic investigations of seat dip attenuation, Sessler and West [1] concluded that it would produce a poor tone in the early sound and a diminished sense of envelopment at stalls seats. Schultz and Watters [2], on the other hand, thought that the effect might be rendered inaudible by sufficiently high levels of bass reverberant sound. The assumption at the root of this proposal is that the ear is relatively insensitive to delay at low frequencies when processing music. The basis for this idea was probably the pioneering work of Haas [10, 11], whose subjects were less annoyed by echoes in speech when they were low-pass filtered. More recently, however, Olive and Toole [12] found that reducing the cut-off frequency of a low-pass filtered lateral reflection does not greatly raise its subjective threshold. Both results can be accommodated if we infer that the ear is not significantly less sensitive to delay at low frequencies (Olive and Toole), and that high frequencies are more subjectively annoying than low frequencies (Haas).

Several experiments in subjective auditorium acoustics have investigated the importance of low frequencies for auditory spaciousness. Barron and Marshall [13] showed that seat dip filtering a lateral reflection significantly affects its spatial effect in the presence of unfiltered direct sound and reverberation. Blauert and Lindemann [14] confirmed that early lateral reflections are the primary cause of spaciousness, and showed that below 3 kHz depth effects predominate with breadth being caused by higher frequencies. Morimoto et al.

have also conducted experiments into the effects of early reflections and reverberation on spaciousness. The findings of interest here are that the 100-200 Hz components of the early sound have a large subjective effect on spaciousness [15], and that reverberation produces a different spatial effect from early reflections [16, 17].

Taken as a whole, the literature indicates that low-frequency seat dip attenuation may noticeably affect spatial and tonal attributes of the listening experience caused by early reflections. It is likely to influence depth more than width perception. Reverberation can also produce a spatial effect, but since this seems to be different from that caused by early reflections, it may not compensate for the seat dip effect. The questions this paper seeks to answer are: How serious is the subjective impact of seat dip attenuation in a typical hall? Can it be reduced by increasing reverberation?

3. The experimental system

The simulator used nine independent digital delay units to simulate reflections from anechoic music. The reflections could be individually attenuated, and five of them and the direct sound could also be subjected to a seat dip filter with variable attenuation. Each reflection was sent to one of eight loudspeakers spaced in three dimensions in an anechoic chamber. Reverberation was provided by a stereo digital unit, from which the sum and difference of the outputs was formed. These four channels of reverberation (A, B, A+B, A-B) were sent to four near-horizontal loudspeakers. A "pre-reverb" signal, consisting of a 100 ms reflection, was used to smooth the transition from early reflections to reverberation. Except for the addition of the seat dip filter, the system was essentially the same as that described in detail in Ref. [18]. Considerable care was taken to make the simulator realistic in comparisons with data in the literature for objectively measured and subjectively preferred concert hall sound fields. Table I presents mid-frequency values of clarity (C_{80}), centre time (T_s), early decay time (EDT), reverberation time (RT), early lateral energy fraction (L_f) and total level measured at the listening position in the simulator. Only the aspects of the system relevant to seat dip simulation will be further discussed here.

Slight adjustments were made to the simulator until it sounded "natural" to the experimenters and to some of the subjects used later. This was thought to be important, since the tests would require the subjects to listen intently to the

sound field. It was felt that making the simulator sound as realistic as possible to them would reduce the chance of fatigue and perceptual errors. The level, direction and delay of the reflections fixed on is shown in Table II.

3.1. Simulating seat dip attenuation

Comparison of spectra in the literature showed that the shape of the seat dip attenuation spectrum varies considerably from hall to hall. Recent results [9] show that it also varies from seat to seat and over time in one hall. It was decided, therefore, to generalise the problem to that of a low-frequency octave-band attenuation. This might be more meaningful to hall designers than a filter which attempts to represent the received spectrum at a particular seat in a particular hall. 200 Hz was chosen as the centre frequency of the octave; this falls roughly in the middle of the spread of seat dip frequencies in the literature. Two $\frac{1}{2}$ -octave graphic equalisers were therefore cascaded and set so that the 200 Hz octave was maximally attenuated, and the attenuation was evenly applied across the octave. A mixer was constructed so that the signal sent through the equalisers could be combined with an unattenuated signal. The octave band attenuation could then be varied in roughly 1 dB steps, while the pass-band level remained constant. Some typical spectra from the filter are shown in Fig. 1. The maximum attenuation of 18.2 dB across the octave is sufficient to represent the most severe seat dip attenuations in the literature.

The choice of which reflections to apply the filter to was guided by a hybrid ray-tracing/image-source computer simulation of the Royal Festival Hall [19]. In the first ten arrivals, the program gave six lateral reflections and four frontal ones. Of these ten, six were near grazing incidence (two frontal and four lateral). Table II shows that the simulator had six lateral reflections and four frontal ones, including the direct sound. Seven of these ten were near grazing (two frontal and five lateral). Because of the circuitry of the delay lines, it was only possible to apply seat dip attenuation to the direct sound and five delay paths. The one grazing reflection that was picked not to be seat dip filtered was the low-level one at 32 ms.

It should be noted that these six signals are attenuated by the same filter. This is a compromise, since seat dip attenuation varies with angle of incidence [9], but a reasonable one. Certainly the vertical angle of incidence of early lateral reflections in a rectangular hall will be close to that of the direct sound. The horizontal angles would of course be different, but one might expect the seat dip attenuation to be very similar over an octave.

3.2. The effect of the seat dip filter

Clarity, centre time, early decay time, reverberation time and early lateral energy fraction were measured in octave bands either side of 200 Hz, at every attenuation level on the variable seat dip filter. The results appear in Figs. 2-6.

Figure 2 shows that increasing the seat dip attenuation affects C_{80} substantially. This is to be expected: the seat dip filter removes early energy, so decreasing clarity. This graph is in good agreement with recently published C_{80} versus frequency data from real halls [9, 20, 21]. The implications for the subjective perception such a large change in low-frequency clarity will be discussed in the light of the results for the perception of seat dip attenuation later.

The effect of increasing seat dip attenuation on centre time (Fig. 3) is analogous to the effect on C_{80} ; this time, the value rises dramatically with increasing attenuation at 200 Hz, and remains nearly constant elsewhere. This too is similar to real hall data [9].

The graph of EDT versus frequency (Fig. 4) shows a slight increase at 200 Hz as the attenuation is increased. This is because EDT only covers the first 10 dB of decay, and so is sensitive to changes in the early sound field. As expected, removing early energy increases EDT. A small dip can be seen in the EDT for zero attenuation, at 200 Hz. This was not a deliberate artifact of the simulator (a completely flat EDT characteristic was not required) and it is not thought that this has significantly affected the results.

A similar plot for reverberation time, Fig. 5, shows no such effects. RT does not change significantly in any frequency band except 100 Hz over the range of

seat dip attenuations applied. The ripple in RT for large attenuations is due to the decay curve becoming progressively non-exponential as more energy is removed. Low-frequency decays in real halls are often uneven, and hence hard to fit a straight line to in order to estimate RT. Large seat dip attenuations have exacerbated this.

Finally, Fig. 6 shows that early lateral energy fraction also remains unchanged when seat dip attenuation is applied. This is because the frontal and lateral sound are both being attenuated by the same filter. In a real hall, frontal and lateral sound may be attenuated at slightly different frequencies, so the seat dip effect may produce a slightly more uneven L_f spectrum. It is not thought that this discrepancy has substantially affected the results reported here. Of course, seat dip attenuation reduces the overall early sound level at low frequencies, so Fig. 6 does not mean that the seat dip effect will not affect a listener's spatial impression.

3.3. Different reverberant fields

For part of the investigation it was necessary to measure thresholds with much less, and much more, reverberation than that described above. This was done in the first case by switching the digital reverberator off, and in the second by increasing its level and the RT set on the device. The total sound level with music was held at 79 dBA for all sound fields. For both these non-standard fields, the effects of increasing seat dip attenuation were very similar to those portrayed in Figs. 2-6. The effects were slightly less pronounced in the non-reverberant field, and very nearly the same in the highly reverberant one. The mid-frequency parameters measured in the simulator with no seat dip attenuation are given in Table III.

While the non-reverberant field represents an unnatural extreme, the highly reverberant one was thought by subjects to be a realistic representation of a hall with little absorption present. This is to be expected: because the timing of the early reflections was not altered, the hall sounds highly reverberant for its "size". This setting thus represents an extreme among measured real concert halls; it is close to the mid-frequency values in the unoccupied Vienna Grosser Musikvereinssaal [20].

3.4. Test subjects and music

Ten subjects, all experienced listeners, were used: all either worked in acoustics or were musicians; some were both. All subjects had normal hearing.

Two music motifs were used. Both were taken from a recent anechoic orchestral recording available on compact disc (Denon PG-6006) [22]. The first piece lasted for four seconds and consisted of the first two bars of Handel's Water Music Suite. The second motif used was a four-second Mendelssohn excerpt (bars 398-399 of the fourth movement of Symphony no. 3). Though the Mendelssohn is slower than the Handel, it has a similar spectrum when measured at the listening position in the simulator, as shown in Fig. 6 in Ref. [18].

3.5. Test method

The method of minimal changes [23] was used to find a difference limen for the level of attenuation in the 200 Hz octave band. Because this difference is from 0 dB downwards, the difference limen is effectively a threshold for seat dip attenuation. That is, the smallest perceptible change from 0 dB downwards is the absolute threshold of perception for seat dip attenuation. This method was chosen because it seemed to represent a good compromise between accuracy, time expenditure and complexity of equipment. After several training runs, each subject was tested three times in each of two run directions: with attenuation increasing and with attenuation decreasing. The impulse response of the simulator was recorded and checked after each run to ensure that the equipment performed correctly throughout the experiments.

Three experiments are reported. In the first, ten subjects were each tested with the Handel, for the "normal" reverberation and no reverberation settings. In the second experiment, two subjects were tested with the Handel, for the "normal" reverberation and "high" reverberation conditions. Finally, two subjects were tested with the "normal" reverberation, for the Handel and the Mendelssohn. In each case, an analysis of variance and an F-test [24] were used to determine significant variances in the data.

The threshold that was recorded for every subjective test was derived from the impulse response measured at the listening position. The changes made to the impulse response by the seat dip filter were quite complex: the measured attenuation varied in magnitude and (slightly) in frequency over time, as it does in real halls [9]. For a statistical analysis of the subjective tests, it was necessary to reduce the measured impulse response to a single figure representing the attenuation. This was done by finding the change in energy ΔE_T caused by the attenuation at a point T ms after the direct sound arrival:

$$\Delta E_T = 10 \log_{10} \left[\frac{\int_0^T p^2(t) dt}{\int_0^T p_0^2(t) dt} \right] \text{ dB}$$

where $p(t)$ is
(0) the impulse
response
with some
attenuation
setting, and
 $p_0(t)$ is that
with no
attenuation.

Clearly, different values of T would result in different values of ΔE_T . 80 ms is commonly used to calculate musical clarity, though Bradley [4] has used 40 ms to evaluate seat dip attenuation. For the present analysis of variance, $T=80$ ms was used, and the impulse responses subjected to a band-pass filter at the 200 Hz octave band. This parameter will be referred to as $\Delta E_{80,200}$. It represents the change in low-frequency early energy caused by the seat dip attenuation. The average thresholds quoted below are the smallest values of $\Delta E_{80,200}$ that 50% of the test subjects could detect. The uncertainties in the thresholds are ± 2 standard errors, giving a 95% confidence limit.

4. Results

The subjects reported that, though the changes made by the attenuation in the full sound field were slight, they felt able to reliably detect them. The subjects were not instructed to use any particular single subjective attribute to detect the attenuation. Most reported that they perceived the changes as being in bass tone or warmth. A minority said that they perceived an effect on spaciousness.

4.1. The effect of reverberation on seat dip perception

4.1.1. "Normal" reverberation and no reverberation

In the first experiment, using ten subjects, the two different sound fields were described in terms of their reverberation time (0.2 and 2.1 s). An analysis of variance was conducted for the factors "subject" and RT. The factor "subject" was significant at the 2.5% level, and RT was significant at the 1% level.

We are therefore left with a threshold that seems to depend on "subject" and RT. Because "subject" is a random effect, it is not sensible to present separate thresholds for each subject and RT. Hence we proceed to calculate threshold $\Delta E_{80,200}^0$ for each value of RT, averaged across subject. These are

$$\Delta E_{80,200} (RT: 0.2 s) = -3.6 \pm 0.3 \text{ dB} \quad (0)$$

$$\Delta E_{80,200} (RT: 2.1 s) = -4.0 \pm 0.3 \text{ dB} \quad (0)$$

Because these values are so close together it can be said that though the effect of reverberation in this experiment is noticed by subjects, the effect is small. Since the difference between eqs. (2) and (3) is slight, it is sensible to calculate an overall threshold,

$$\Delta E_{80,200} = -3.8 \pm 0.2 \text{ dB} \quad (0)$$

4.1.2. "High" reverberation

To obtain further evidence for the effect of reverberation on the threshold, two subjects were tested with the "high" reverberation field. The two subjects used were chosen because they had the lowest intra-subject variances in the group (i.e., they were the most consistent). This seemed the best way of representing the group, and of obtaining reasonably accurate results, given that there was not enough time to retest more subjects.

Another analysis of variance was then performed on these two subjects and this time, reverberation time took the values 0.2, 2.1 and 3.1 s. RT was not found to be significant for these two subjects. It therefore seems as if broadband reverberant energy in a hall would probably not significantly mask the subjective effects of seat dip attenuation.

4.2. Music motif

The two subjects chosen above were also used in tests to find the effect of the source music used. The tests in part 4.1.1 were repeated, using the standard sound field (RT = 2.1 s only), except that the Mendelssohn motif was used. Another analysis of variance was performed on the results from the two subjects, for the factors "motif" and "subject". The results were dominated by the first-order interaction between "motif" and "subject". This was significant at the 0.1% level, while all the other effects had no significance. Clearly the two subjects each found seat dip attenuation "easier" to hear on a different motif. If a threshold is calculated for each motif, averaged across these two subjects only, we obtain

$$\begin{aligned} \Delta E_{80,200} (\text{Handel}) &= -3.7 \pm 0.7 \text{ dB} & (0) \\ \Delta E_{80,200} (\text{Mendelssohn}) &= -3.8 \pm 0.8 \text{ dB} & (0) \end{aligned}$$

Again, we see
that, though
the motif \times
subject
interaction
is
statistically
y
significant,

the effect it has on the threshold is small.

4.3. Changes in the sound field at threshold

The analysis of variance was carried out using $\Delta E_{80,200}^0$, and it is thought that $\Delta E_{80,200}^0 = -3.8 \pm 0.2$ dB is the clearest way of presenting the threshold. Nevertheless, values of ΔE_T^0 at threshold may be useful for other values of T and in other octave bands. This could be the case when it is necessary to compare these subjective results with data from real concert halls, where T = 80 ms may be thought inappropriate or even impossible. Table IV contains the change in energy in the sound field, at threshold, for three different integration times, in octave bands.

Table IV confirms that, due to the design of the filter, the sound field changes mainly in the 200 Hz octave band and slightly in the bands either side. The total broadband change is zero for any integration time, confirming that subjects were not responding to the total loudness of the sound field. Table IV also shows that the measured spectrum change becomes smaller as longer integration times are used. This is due to the effect of unattenuated reflections (arriving after 40 ms) and reverberation (arriving after 110 ms).

It is also of interest to examine the effect of the changes in reverberation on the spectrum of the complete impulse response, at the threshold attenuation. Table V sets out the change caused by the non-reverberant and highly reverberant settings with respect to the "normal" reverberation. It can be seen that the large changes in reverberation have made a difference to the total level,

particularly in the 200 Hz octave band. Here, moving from no reverberation to "normal" reverberation increased the total level by 3.0 dB; moving from "normal" to high reverberation increased the level by 2.4 dB. Although the reverberation change was not restricted to the attenuation octave, it has had a considerable effect in it. However, from the analysis of variance it is apparent that this change made very little difference to the subjective threshold of the attenuation.

4.4. Discussion

Even over quite extreme variations of reverberation, the threshold of perception for seat dip attenuation changed little. The value of $\Delta E_{80,200} = -3.8 \pm 0.2$ dB should be applicable in halls with widely differing reverberation times. The threshold is probably a severe one: it was obtained, like most subjective test results, from a small group of trained listeners.

Rather than being influenced by the late sound field, it seems more likely that the attenuation can be masked by unattenuated early reflections. During the training of the subjects, it was found that listeners could easily detect small attenuations when listening to the direct sound only. This continued as attenuated reflections were switched in one by one. As soon as an unattenuated reflection was added, however, perception of the attenuation became much more difficult. It seems that a defect in the early sound field may be more easily remedied by adjustments to the early field (e.g., increasing non-grazing early

energy) rather than by changing the late field (increasing total reverberant energy).

4.4.1. Implications for low-frequency monaural early energy parameters

In part 3.2.1 the variations of five room acoustic parameters with seat dip attenuation in the simulator were examined. It was found that the monaural early energy measures C_{80} and T_s were greatly affected at low frequencies by the attenuation, and RT, EDT and L_f hardly at all. This means that the subjective results can be used to estimate a difference limen for low-frequency C_{80} and T_s . Table VI shows the change in C_{80} and T_s going from no attenuation to threshold attenuation. Changes of -3.7 dB in C_{80} and +46 ms in T_s are comparatively large. It has been shown (in the same simulator) that the average mid-frequency difference limen for C_{80} is only 0.67 ± 0.13 dB and that for T_s is only 8.6 ± 1.6 ms [18]. It therefore seems that the ear is considerably less sensitive to monaural early energy indices at low frequencies than it is at mid frequencies. While the mid-frequency values of these parameters are known to be subjectively important, this result means that the collection and prediction of such low-frequency data in halls is less useful, beyond what is needed to identify seat dip attenuation. It should of course be remembered that *binaural* parameters such as L_f are different in this respect: if anything, low frequencies are the most important range for spaciousness.

5. Comparison with concert hall measurements

W. J. Davies, Dept. of Applied Acoustics, Salford University, The Crescent, Salford M5 4WT, England.

As an example, an existing wide rectangular auditorium is considered: the Free Trade Hall in Manchester. This hall has a seating capacity of 2500, of which 1122 are on a stalls floor that is nearly flat. To use the subjective threshold, impulse responses in the real hall had to be reduced to single figures in the same way as those from the simulator. Equation (1) was used again to give ΔE_T , where $p(t)$ was an impulse response recorded in the hall and corrected for distance attenuation, and $p_0(t)$ was an anechoic measurement of the measuring chain at 1 m. An octave band-pass filter was also applied to the data. The centre frequency of this was not fixed at 200 Hz, but taken to be the frequency of worst attenuation in the narrowband spectrum of each hall impulse response. These frequencies varied over the range 118 to 296 Hz. Unfortunately, most of the recorded impulse responses were not long enough to permit an integration time of 80 ms, so 40 ms was used instead. The resulting values of ΔE_{40} were compared with the subjective threshold of -5.7 ± 0.4 dB from Table IV.

Because the 95% confidence limit range for $\Delta E_{40, 200}$ is -5.7 ± 0.4 dB, it seems appropriate to present this as one limit of -5.3 dB, above which any attenuation is probably inaudible, and one of -6.1 dB, below which attenuation probably could be heard. The problem for a hall designer is to maximise the number of seats where ΔE_{40} falls into the inaudible region.

In Fig. 7(a), ΔE_{40} values for some stall seats are plotted as a function of the vertical angle of incidence θ of the direct sound and the number of seat rows

between the source and microphone. (Both these parameters are known to influence direct sound seat dip attenuation [9].) Figure 7(b) presents data for the same measuring positions with resonant absorbers placed on the floor between the seat rows, according to a scheme suggested by Ando et al. [6].

5.1. Improving early bass level

Figure 7(a) shows that there is no simple linear relationship between ΔE_{40}^0 and θ which encompasses all the values of θ investigated. ΔE_{40}^0 does in general worsen with increasing θ , particularly above 83° . A more significant factor, however, is the number of seat rows the sound travels over. This is because the further back the measuring position is, the closer it is to the balcony front, which in this hall provides quite strong non-grazing reflections. This effect takes precedence over the worsening attenuation that is experienced by the direct impulse only, as it travels over each successive seat row (see Fig. 2 in Ref. [9]). This point is reinforced by the fact that all of the three values of ΔE_{40}^0 recorded only three seats back are below the -6.1 dB "audible" line.

Since ΔE_{40}^0 is improved by moving the measuring position closer to a source of non-grazing reflections, then the hall designer might decide to combat seat dip attenuation by adding reflecting surfaces, as proposed by Bradley [4]. This option must be followed carefully, however. The smallest values of ΔE_{40}^0 in Fig. 7(a) are exhibited by a seat 15 rows back. This seat is 2.2 m behind the lip of the balcony overhang and so suffers from the defect usually associated with

under-balcony seats of high-frequency comb filtering due to interference from overhead reflections. This can result in tonal coloration and a listener at this seat is also likely to experience poor spaciousness due to a low value of L_f . Similar detrimental effects can be attributed to large areas of purpose-built overhead reflectors [25], so it seems that progressively introducing reflectors to supply non-grazing sound until ΔE_{400} is above -5.3 dB is not an easy answer for the designer.

Figure 7(b) shows that subjectively significant improvements in ΔE_{400} have been obtained by using floor absorbers at some seats. The improvement is greater for high values of θ further back in the seats. In general, the improvements are not dramatic, so that a seat must already have a value of ΔE_{400} not far into the audible range for it to become inaudible on the installation of floor absorbers.

6. Conclusion

The threshold of perception for seat dip attenuation has been measured using trained subjects in a realistic concert hall simulator. The threshold is -3.8 ± 0.2 dB octave band attenuation in the early energy from 0 to 80 ms. Because the instantaneous attenuation in a hall impulse response changes with the arrival of each reflection, equivalent values for the threshold can be given over different time periods. For example, the threshold can also be stated as -5.7 ± 0.4 dB octave band attenuation in the early energy from 0 to 40 ms.

When measurements of seat dip attenuation at several stalls seats in the Free Trade Hall were evaluated, they were spread in a range about the subjective threshold, and were affected by several factors. The most important factors in reducing the audibility of the attenuation were: a close, elevated, reflecting surface; an angle of incidence far from grazing; and the use of floor absorbers. In general, more than one of these factors was needed to place the attenuation at a seat in the "inaudible" range. Therefore, it is possible to reduce the chance of seat dip attenuation being detected by a listener, but a combination of methods will probably be necessary.

Another ramification of the value of the threshold is that small changes in low-frequency values of monaural early energy measures like C_{80} and T_s are of little subjective significance. In the simulator, it was observed that these parameters changed by 3.7 dB and 46 ms, respectively, over the interval of the attenuation threshold. The size of these changes is five times greater than the difference limen for the same quantities at mid frequencies.

It was shown that the threshold of perception of seat dip attenuation does not change significantly with large changes in broadband reverberation. Certainly, it would not be practical to increase by "passive" means the reverberant level in a real hall by more than 3 dB (this would require that the absorption be halved, for instance). Seat dip attenuation is a defect of the early sound field and it affects perceptual attributes generated by the early field. It may be better

to reduce it by adjusting the early field rather than trying to compensate using a different perceptual attribute caused by reverberation.

To summarise, the threshold of perception of seat dip attenuation is large enough to render low frequency C_{80} values relatively unimportant. However, the threshold is also small enough for the effect to be audible in a typical auditorium. Unfortunately, seat dip attenuation seems not to be compensated by broadband reverberation.

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Table I.
Mid-frequency (500 Hz - 2 kHz) parameters measured in
simulator under "normal" reverberation conditions.

RT	EDT	C_{80}	T_s	L_f	Total level
s	s	dB	ms		dB
2.1	1.8	3.0	80	0.28	79

Table II.
Reflection parameters used in concert hall simulator.

	Delay re: direc t ms	Level re: direc t dB	Angle of incidence (azimuth, elevation) degrees	Seat dip filtered ?
direct sound	0	0	(0, -10)	y
early reflections				
lateral	19	-3	(45, 0)	y
lateral	32	-12	(135, 0)	n
ceiling	41	-6	(-1, 27)	n
corner	46.5	-7.5	(21, 23)	n
lateral	50.5	-10	(-45, 0)	y
lateral rear	61	-12	(-135, 0)	y
stage	81	-12	(-12, -6)	y
ceiling	90	-12	(-1, 27)	n
lateral rear	95	-14	(135, 0)	y
late sound				
burst of reflections	100	-8.4	(0, -10)	n
reverberation	110	-2.2	(±135, 0), (-12, 5), (-1,27), (21, 25)	n

Table III.
Mid-frequency (500 Hz - 2 kHz) parameters measured in
simulator under extreme reverberation conditions.

Sound field	RT	EDT	C_{80}	T_s	Total level
	s	s	dB	ms	dBA
no reverberation	0.2	0.4	11.4	23	79
"high" reverberation	3.1	2.9	0.2	152	79

Table IV.

The change in energy in the sound field ΔE_T^0 , at threshold, for three different integration times T, in octave bands, under "normal" reverberation conditions.

	Frequency						
	100	200	400	800	1600	3200	broadband
ΔE_{40}^0 (dB)	-1.7	-5.7 ± 0.4	-0.8	0.2	0.2	0.3	0.0
ΔE_{80}^0 (dB)	-1.3	-3.8 ± 0.2	-0.6	0.2	0.1	0.2	0.0
$\Delta E_{infinity}^0$ (dB)	-1.0	-2.2 ± 0.1	-0.4	0.1	0.1	0.1	0.0

Table V.

The change in level (dB) of the total sound field caused by the non-reverberant and highly reverberant settings, with respect to the "normal" reverberation, in octave bands, at the threshold attenuation.

	Frequency					
	Hz					
	100	200	400	800	1600	3200
non-reverberant	-1.1	-3.0	-0.7	0.1	-0.2	-0.4
highly reverberant	0.2	2.4	2.1	2.1	1.8	1.5

Table VI.
Changes in C_{80} and T_s recorded in octave bands
for threshold of seat dip attenuation.

	Frequency					
	Hz					
	100	200	400	800	1600	3200
C_{80} (dB)	-1.3	-3.7	-0.5	0.1	0.1	0.2
T_s (ms)	17	46	6	-1	-1	-2

Figure captions

Fig. 1. Frequency response, at three levels of attenuation, of the variable seat dip filter used in the simulator. (—) 6.4 dB; (- - -) 12.5 dB; (.....) 18.2 dB (maximum).

Fig. 2. Clarity (C_{80}) in the simulator as a function of frequency and seat dip attenuation, measured at the listening position.

Fig. 3. Centre time (T_s) in the simulator as a function of frequency and seat dip attenuation, measured at the listening position.

Fig. 4. Early decay time (EDT) in the simulator as a function of frequency and seat dip attenuation, measured at the listening position.

Fig. 5. Reverberation time (RT) in the simulator as a function of frequency and seat dip attenuation, measured at the listening position.

Fig. 6. Early lateral energy fraction (L_f) in the simulator as a function of frequency and seat dip attenuation, measured at the listening position.

Fig. 7. Octave dip level ΔE_{40}^0 for some real stalls seats, plotted as a function of the vertical angle of incidence θ of the direct sound and the number

of seat rows between the source and microphone; (a) without floor absorbers and (b) with floor absorbers. (○) 3 seat rows; (●) 6 rows; (□) 9 rows; (■) 12 rows; (x) 15 rows.

Figure 1

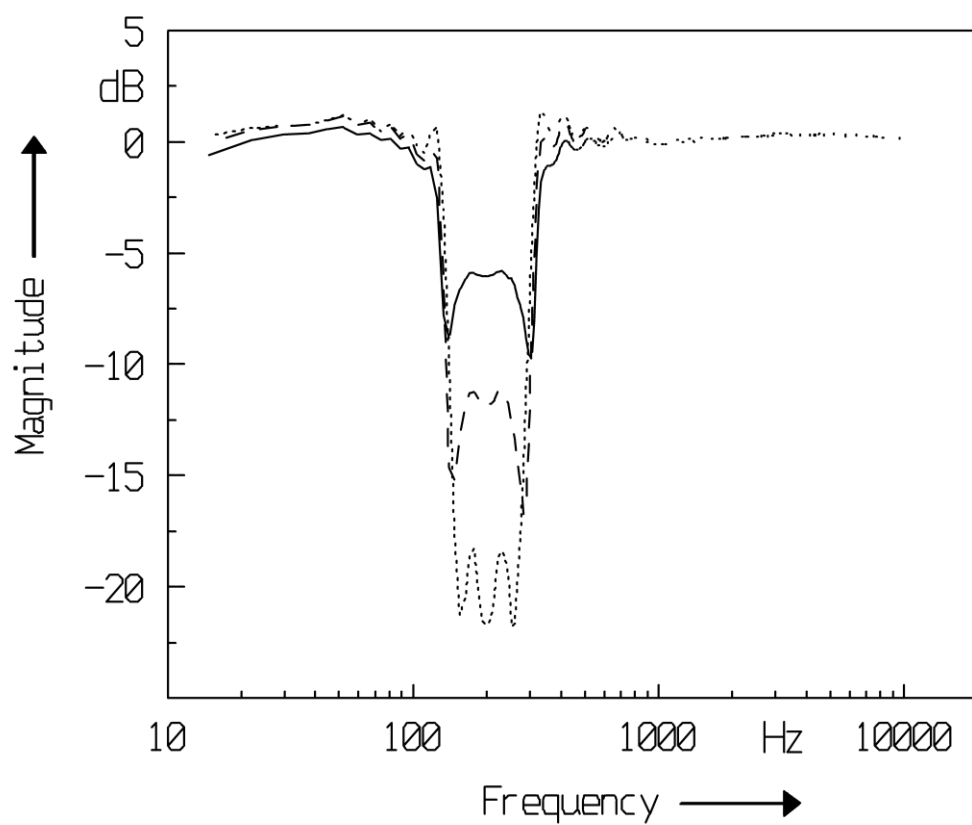


Figure 2

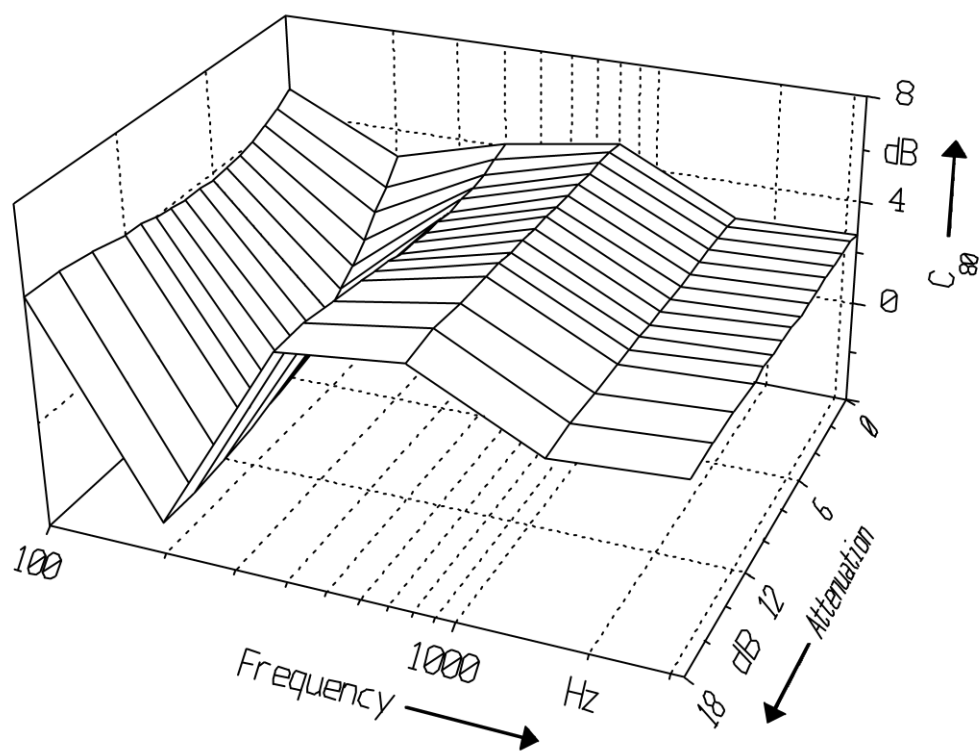
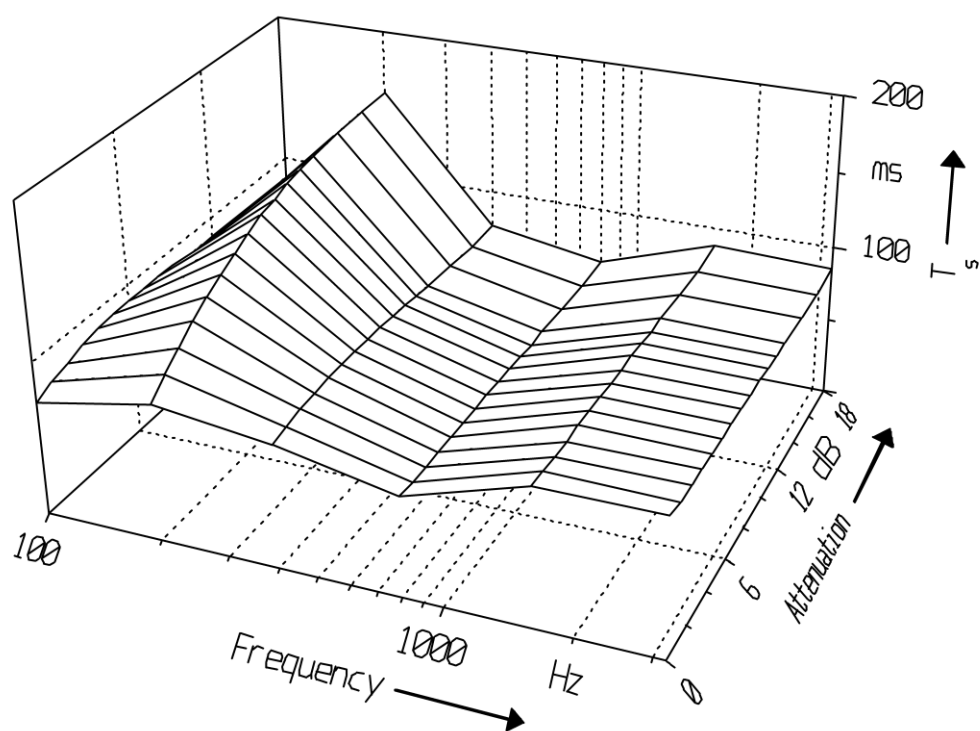


Figure 3



W. J. Davies, Dept. of Applied Acoustics, Salford University, The Crescent, Salford M5 4WT, England.

Figure 4

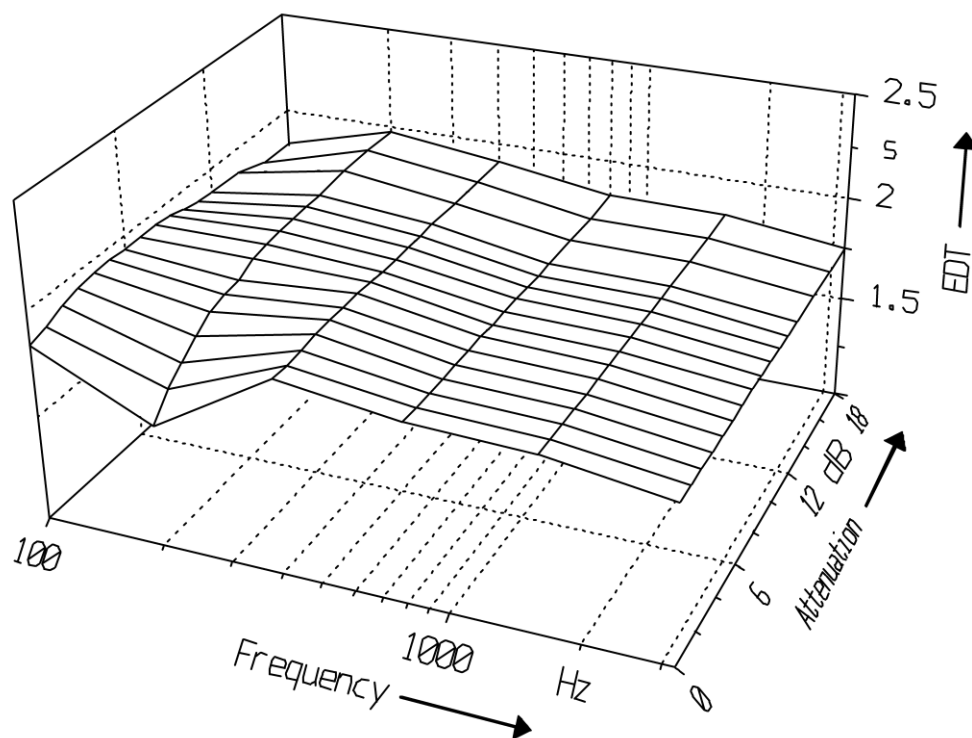


Figure 5

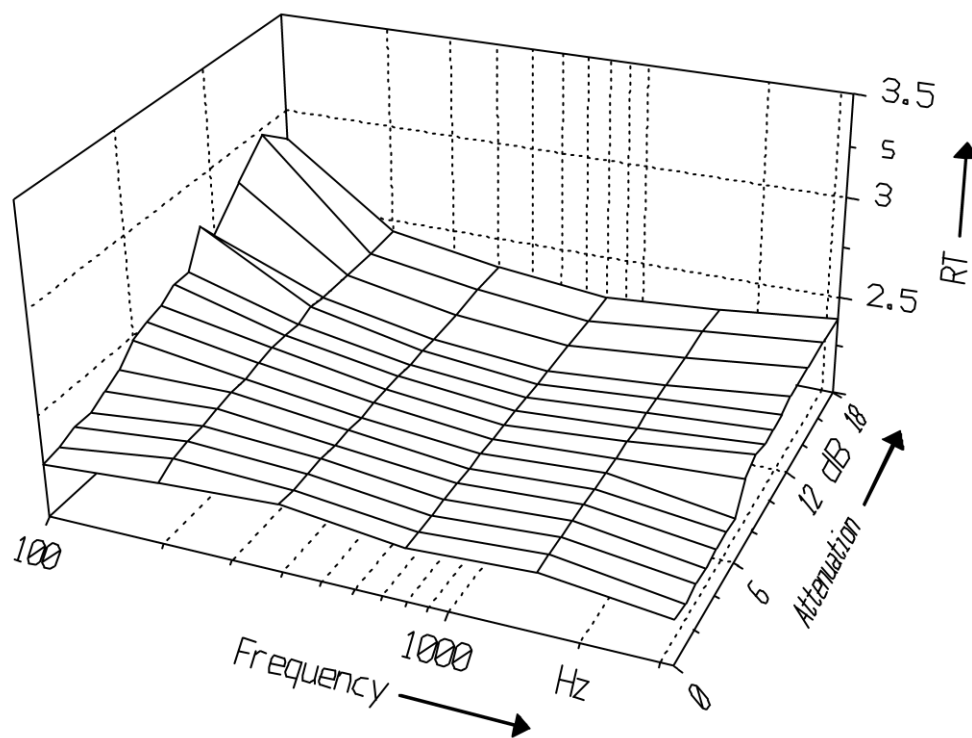
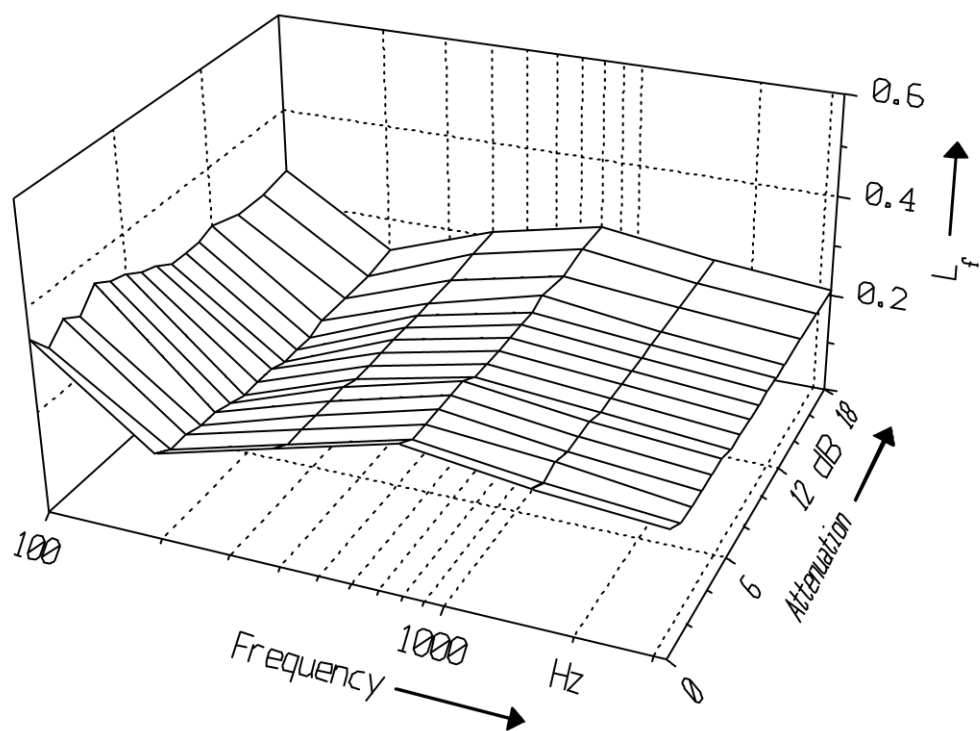


Figure 6



W. J. Davies, Dept. of Applied Acoustics, Salford University, The Crescent,
Salford M5 4WT, England.

Figure 7(a)

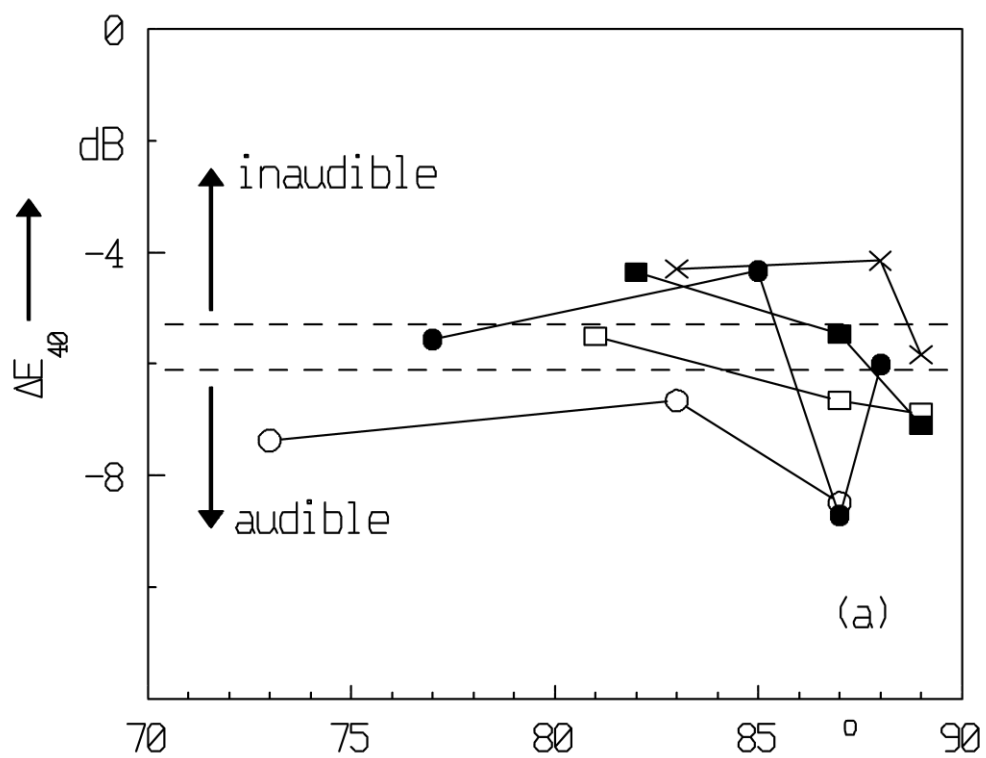


Figure 7(b)

