Architectural Acoustics: Some Historical Developments and Ongoing Issues

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Abstract

This paper gives an overview of the history of the development of architectural acoustics and a sampling of the results of several more recent research studies. There are now standardised measures for assessing room acoustics character and there are criteria for room acoustics in terms of these measures. For rooms for speech, such criteria are not so well defined for some special groups of listeners such as the very young or old, hearing impaired listeners, and those listening in a second language. For rooms for musical performance, there is a growing understanding of the more important acoustical characteristics of concert halls, but still a need to improve tools for applying this knowledge to the design of these spaces.

RÉSUMÉ

Cet article donne un aperçu de l'historique du développement de l'acoustique architecturale ainsi qu'un échantillon des résultats des derniers projets de recherche. Il existe actuellement des mesures standardisées pour évaluer l'acoustique d'une pièce et des critères relatifs à ces mesures. Pour les pièces réservées à la communication orale, de tels critères ne sont pas très bien définis pour certains groupes d'auditeurs, tels que les très jeunes ou les gens âgés, les malentendants ou ceux qui écoutent un discours dans une langue qui n'est pas la leur. Dans le domaine musical, les caractéristiques acoustiques les plus importantes des salles de concerts sont de mieux en mieux connues, mais il faut améliorer les outils de façon à appliquer ces connaissances à la conception de ces espaces.

Introduction

Architectural acoustics has a long history that can be traced back to ancient Greece and Rome and the designs of early theatres. More recent quantitative research has progressed over the past 160 years with a number of re-discoveries of the results of earlier research. This paper gives an overview of some key points of this history and illustrates more recent progress with a sampling of various research studies. Although not intended to be comprehensive, a broad range of topics are included and a number of indications of remaining significant problems are mentioned.

Impulse Responses

Most important acoustical characteristics of rooms can be obtained from impulse response measurements in the rooms. Graphs of measured impulse responses are very helpful for explaining the important characteristics of sound in rooms and are introduced here so that they can be used in later explanations of room acoustics effects. Although impulse responses can be obtained by simply recording the response to an impulsive sound in a room (e.g. gun shots or balloon bursts), modern techniques allow us to calculate impulse responses more accurately from the measured response to various broad spectrum test signals such as sine sweeps or maximum length sequences sequences.

Fig. 1 shows an example of the first 300 ms of an impulse response measured in a large auditorium. Although there are a few distinct and higher amplitude features near the start of the impulse response, much of the response seems to consist of somewhat random pressure fluctuations. In practice it is the result of the combination of a large number of reflections of the original sound. Fortunately it is not necessary to understand the effects of each detail in the response and these details would probably change for relatively small movements of the source or the receiver. What is important is the total sound energy associated with each of the 3 main features of the response: (a) the direct sound, (b) the early-arriving reflections, and (c) the later-arriving reflections (or reverberant decay).

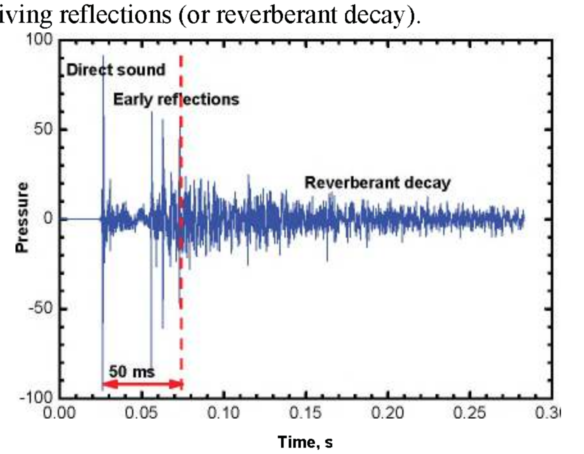


Fig. 1 Impulse response measured in a large auditorium plotted as pressure versus time.

Early-arriving reflections are important physically, because they usually include a large portion of the total sound energy in the impulse response, and subjectively, because they are not heard as separate events but our hearing system integrates them with the direct sound. Thus more early-arriving reflections increase the effective level of the direct sound and increase the perceived clarity of sounds in rooms. Conversely, increased later-arriving sounds would decrease the clarity of sounds. The history of how we have come to understand these features will be discussed in the following section.

Fig. 2 shows a plot of the same impulse response but with the amplitude in decibels. Plotting the response in this way tends to lead to approximately linear sound decays after the initial reflections. We determine the reverberation time, that is the time for sound to decay 60 dB, from the slope of the decay of the later-arriving sound. While reverberation time is widely used as a simple room acoustics design parameter, considering the details of impulse responses, as illustrated in Fig. 1, gives a more complete understanding of room acoustics phenomena.

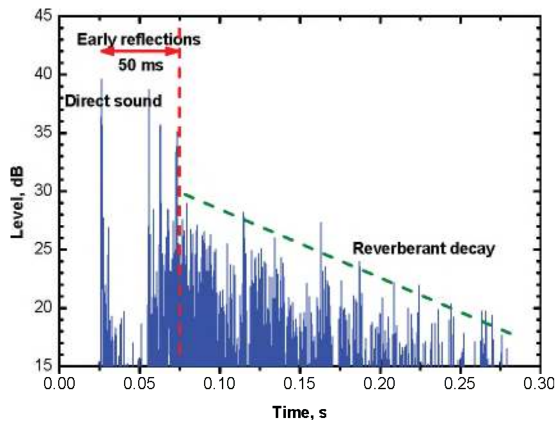


Fig. 2. Impulse response measured in a large auditorium plotted as sound level in dB versus time.

In Fig. 1 and 2 early-arriving is shown as the first 50 ms after the direct sound. This is appropriate for speech sounds but 80 ms is more appropriate for music.

Early History

The history of architectural acoustics is an interesting sequence of discovery and later re-discovery of various key details. Surprisingly, a quite complete understanding of the benefits of early-arriving reflections was reported in the 1850s. Joseph Henry, when head of the Smithsonian in Washington, reported the results of his experiments listening to the reflections of impulsive sounds outdoors [1]. By varying the relative arrival times of the direct sound and the reflection, he discovered that the reflection was not separately heard but enhanced the direct sound when it arrived within up to about 50 ms after the direct sound. He also appreciated that this was important in the design of rooms for speech. He designed a lecture theatre at the Smithsonian shaped to maximize the benefit of early-arriving reflections or as he put it, "to husband every articulation of the voice". This knowledge appears to have been lost for about 100 years before it was re-discovered by Hass [2-4].

Approximately 50 years after Joseph Henry's work, Sabine determined experimentally the relationship between reverberation time and the combination of room volume and the total area of sound absorption in a room. Ever since then his reverberation time equation has been used as a simple method of predicting room acoustics characteristics.

Equation (1) shows the Sabine reverberation time equation, where T_{60} is reverberation time (s), V the room volume (m^3), and A the total sound absorption (m^2).

$$T_{60} = 0.161\ V/A \tag{1}$$

While Sabine's equation was an important step forward, it took acousticians another 50 years to realize that there was more to room acoustics than reverberation time, something that Joseph Henry had understood in the 1850s.

Haas' research [2-4], established in a quantitative manner, the importance of early-arriving reflections. With the aid of electronics he was able to create early-arriving reflections with varied delay and amplitude. Fig. 3 shows the results of several researchers showing how early-arriving reflections can be as much as 10 dB higher in level than the direct sound and still be completely integrated with the direct sound, depending on the actual delay of the reflection relative to the arrival of the direct sound.

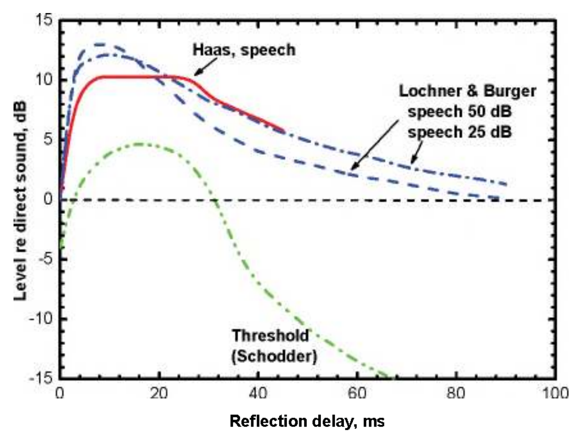


Fig. 3. Upper three curves show the limit of subjective integration of reflections with the direct sound by Haas [2-4] and Lochner and Burger [5].

As shown in Fig. 3 Lochner and Burger's results [5] for speech sounds were very similar to those of Haas. Haas also found that the shape of the curves shown in Fig. 3 vary as the bandwidth of the test signal is varied. The Haas effect also includes the perception that the reflected sound arrives from the same direction as the first arriving sound, which is usually the direct sound. Because of this other aspect of the effect of early-arriving reflections, the *Haas Effect* is also referred to as the *Precedence Effect*. This name was given by Wallach et al. [6] who published their results in the same year as Haas.

Although the papers formally reporting experimental results to demonstrate the Haas or Precedence effect didn't appear until 1949, there is evidence of a much earlier appreciation of these effects. For example, in 1935 Fay and Hall [7] reported using the Haas or Precedence effect to design a sound reinforcement system. By arranging for the sound from the loudspeaker to arrive shortly after the arrival of the direct sound from the talker they could preserve the realism of the sound appearing to come from the location of the actual talker. Gardener has reviewed the history of research related to the Haas effect [8] and cites a number of other earlier studies indicating some understanding of the concepts we now refer to as either the Haas effect or the Precedence effect.

After the publications of Haas and Wallach et al., others considered the effects of more than one reflection. For example, Seraphim [9] explored the subjective integration of a variable second reflection in the presence of a direct sound and a fixed reflection for speech sounds. Lochner and Burger explored the subjective integration of early reflections of speech sounds as a function of the delay and amplitude of the reflections, to develop a model for useful-to-detrimental sound ratios [5].

More recently Bradley et al. [10] published results to confirm the benefits of early reflections for the intelligibility of speech. As illustrated in Fig. 4, they also presented results demonstrating the practical importance of early-arriving reflections by showing that early-arriving reflections can increase the effective direct sound level by as much as 8 or 9 dB in rooms. The early-arriving reflections make it possible to understand speech in

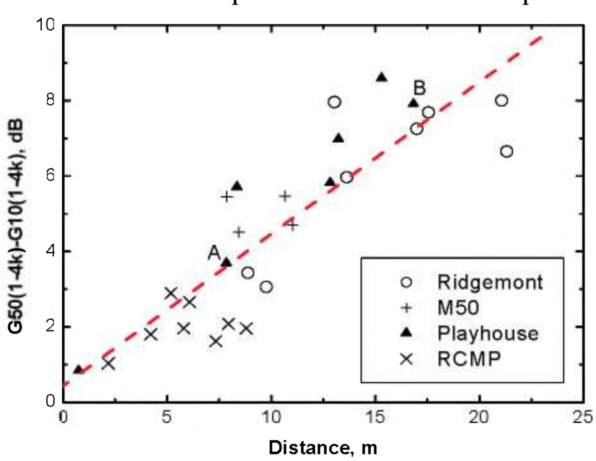


Fig. 4. The increasing contribution of early reflections to early sound strength versus source receiver distance [10].

situations where the direct sound is reduced such as when the talker is turned away from the listener or when the listener is simply farther from the source.

Room Acoustics Measures

The various studies of the subjective integration of early-arriving reflections led to an understanding that the balance between early- and late-arriving sound influenced the perceived clarity of sounds in rooms. Table 1 describes 4 such measures proposed over a 20-year interval. In addition to the mathematical definitions, the calculations are illustrated by pictograms with the shaded areas indicating the integrated parts.

Lochner and Burger took these measures one step further to create the useful-to-detrimental sound ratio (U) concept.

$$U = 10 \log \{(E_d + E_e)/(E_l + E_n)\},\ dB \qquad (2)$$

Here, E_d is the direct sound energy, E_e is the early- arriving sound energy, E_l is the later-arriving sound energy and E_n is the noise energy. This measure includes both the effects of signal-to-noise as well as an accurate rating of the clarity of the room acoustics and is an excellent predictor of the intelligibility of speech in rooms

Although this was published by Lochner and Burger as a

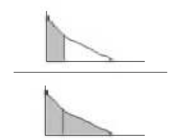
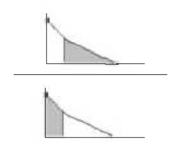
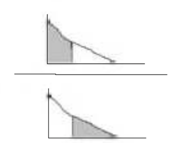
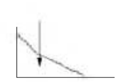
Measure	Definition	Pictogram
Deutlichkeit (Thiele, 1953)	$D = \dfrac{\int_0^{50} p^2(t)\cdot dt}{\int_0^{\infty} p^2(t)\cdot dt}$	
Running Liveness (Schultz, 1965)	$R = 10 \log\left(\dfrac{\int_{50}^{\infty} p^2(t)\cdot dt}{\int_0^{50} p^2(t)\cdot dt}\right)$	
Clarity (Reichardt, 1975)	$C80 = 10 \log\left(\dfrac{\int_0^{80} p^2(t)\cdot dt}{\int_{80}^{\infty} p^2(t)\cdot dt}\right)$	
Centre Time (Kürer, 1973)	$TS = \dfrac{\int_0^{\infty} t\cdot p^2(t)\cdot dt}{\int_0^{\infty} p^2(t)\cdot dt}$	

Table 1. Measures of clarity and the balance between reverberance and clarity [12-15].

new concept [5], it was very similar to the remarkable earlier work of Aigner and Strutt [11]. In addition to mentioning an integration limit of about 60 ms for early reflections, they proposed a measure of syllable articulation (intelligibility) Q, which was the same as equation (2) except it was a linear ratio without the '10log' part.

Although U ratios have been shown to be good predictors of the intelligibility of speech in rooms [16, 17], a standard format has never been proposed and it is not established how one should best combine information over the range of speech frequencies.

In the 1970s Houtgast and Steeneken [18] proposed the Speech Transmission Index (STI) as a measure of the combined effects of room acoustics and signal-to-noise on the intelligibility of speech in rooms. The measure is based on the assumption that intelligibility is related to the degradations of the amplitude modulation of speech by noise and reverberant sound. It uses modulation transfer functions to determine the expected speech intelligibility between points. The procedure calculates modulation reductions for the 98 combinations of 7 acoustical octave bands (125 to 8k Hz) and 14 1/3-octave bands for modulation frequencies from 0.63 to 12.5 Hz. Houtgast and Steeneken have made great efforts to fully develop STI and it is described in an IEC standard [19].

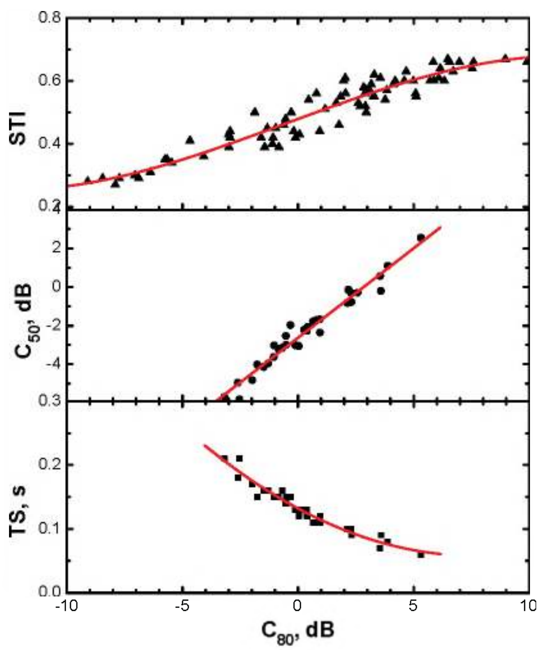


Fig. 5. Plot of measured STI, C_{50} and TS values versus C_{80} values. The STI values were calculated without the influence of signal-to-noise ratios so that room acoustics only measures can be compared [20].

Although STI seems completely different than U ratios, values of the two types of measures are highly correlated and are seem to provide the same information about conditions for speech in rooms. Fig. 5 includes a plot of STI values (with the signal-to-noise component ignored) versus C_{80} values (an early-to-late arriving sound ratio with an 80 ms early time limit). The STI values as well as the C_{50} and TS values are all quite well related with the C_{80} values. That is, the room acoustic component of STI is equivalent to an early-to-late arriving sound ratio. The results in Fig. 6 similarly show that STI values (including the signal-to-noise component) are strongly correlated with U_{50}(A) values (an A-weighted useful-to-ratio that included a 50 ms early time interval). Although the Useful-to-Detrimental Ratio and the Speech Transmission Index measures are based on quite different concepts. they seem to be similarly accurate predictors of the intelligibility of speech in rooms.

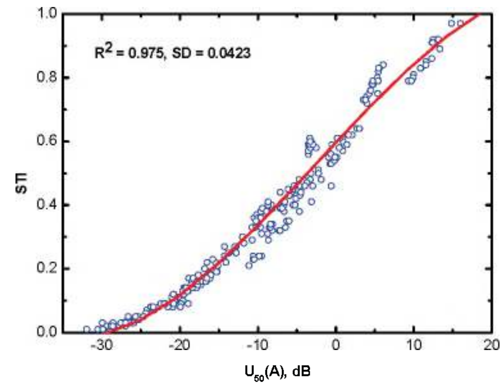


Fig. 6. Plot of STI values versus $U_{50}(A)$ values [20].

There are also measures of reverberance. The reverberation time, T_{60}, (s), is the time for sound to decay by 60 decibels after the source has stopped. It is usually measured from the slope of the sound decay between points -5 dB and –35 dB below the initial maximum. T_{60} is an important physical parameter, but Early Decay Times, EDT (s), are better related to the perceived degree of reverberance. EDT is calculated from the slope of the sound decay between points 0 dB and –10 dB below the initial maximum.

One of the most subjectively important characteristics of sound in rooms is the level of the sounds and in particular the contribution of the room to the level of the sound. This is measured by the sound strength, G dB, which is the level of the sound relative to the level of the same source at a distance of 10 m in a free field. It is an indicator of how the room affects the level of sounds. G values can also be calculated separately for the early-arriving or late-arriving sounds [22].

All of the room acoustics parameters are measured in octave bands and are described in ISO3382 measurement standard [21].

Classrooms and Younger Listeners

Although criteria exist to indicate ideal conditions for speech communication in rooms, there still are questions as to appropriate criteria for some groups of listeners with special needs. These would include: younger children, second language listeners, older listeners and, of course, the hearing impaired. The case of conditions for younger children will be used to illustrate how criteria for this one special group have been studied and how their needs differ from the average non-impaired adult listener.

Many studies have shown that younger children are less able to understand simple speech in noise than adults. Although previous results all showed that younger children have greater difficulties, the relationships between intelligibility scores and signal-to-noise ratios were quite different among the studies and did not agree well with previous results in actual classrooms. The differences were thought to be due to the often unrealistic conditions of the tests that frequently used monaural headphone listening and usually made no attempt to duplicate binaural listening conditions in typical classrooms.

Fig. 7 shows the results of speech tests on grade 1, 3 and 6 students carried out while they were seated at their normal seats in their own classrooms [23]. The scores for the three age groups increase with increasing age as expected and agree with the limited previously available classroom data [17]. The results show that for very high signal-to-noise ratios all children could get scores of 98% or better. As signal-to-noise ratios decrease, scores decrease, and the differences among the 3 age groups grow. The scatter of the results about the mean trends also increases with decreasing signal-to-noise ratio.

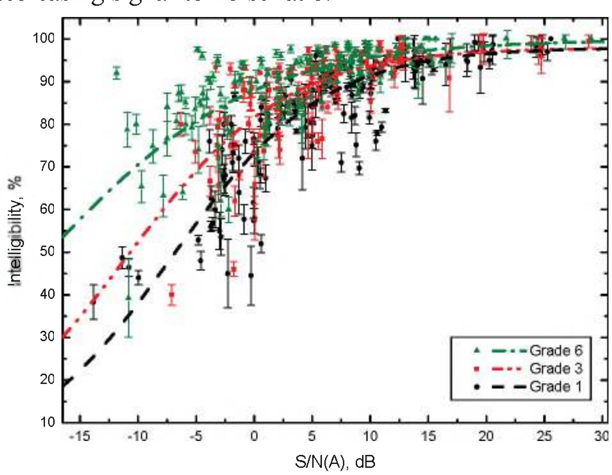


Fig. 7. Mean speech intelligibility scores versus A-weighted signal-to-noise ratio (S/N(A)) for grade 1, 3 and 6 students [23].

Although ideal conditions for speech communication are usually said to require a S/N(A) of at least 15 dB, an analysis of these data concluded that grade 1 children needed an S/N (A) of at least 20 dB, the grade 3 students at least 18 dB and the grade 6 students at least 15 dB. Using the measured speech levels of the teachers, it was possible to determine that the preferred maximum ambient noise level of 35 dBA, recommended in ANSI S12.60, was easily justified.

Some question why 35 dBA is needed when children themselves often create higher levels of disturbing sounds than this. However, the children's sounds are influenced by the existing ambient noise of heating and ventilating systems. Due to an effect similar to the Lombard effect [24] they will tend to talk to their neighbours and make other sounds at a level that can be heard above the sounds of the existing ambient noises. It can be argued that we do not completely understand how room acoustics conditions and existing ambient noise interact with the behaviours of the teachers and students to create the combined interfering sound levels that exist in classrooms.

Classroom acoustics criteria usually also specify acceptable reverberation times. Frequently reverberation is assumed to be a negative factor for speech communication and therefore it should be as short as possible. Of course, this ignores room acoustics and the fact that reflected sounds enhance speech levels and can provide better conditions for speech communication. Joseph Henry understood this 160 years ago but many are not familiar with the importance of early-arriving reflections and why they are so important in rooms.

To explore optimum reverberation times for elementary school classrooms, children were tested using the same speech tests as in the previous study and by recording the tests in simulated conditions with a range of reverberation times [25]. Great care was taken to create conditions representative of classrooms. Binaural recordings of the speech test material were played back to individual students using headphones. Fig. 8 plots one of the results showing mean intelligibility scores versus reverberation time. In this example, sound fields were created in which the added reflections with increasing reverberation time were allowed to increase the overall speech levels as can occur in rooms.

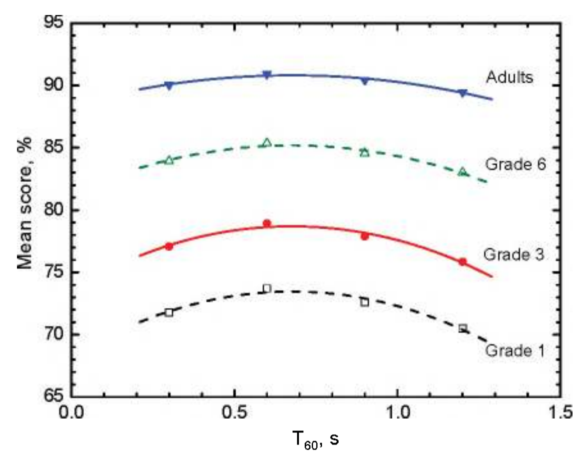


Fig. 8. Mean intelligibility scores versus reverberation time for 4 age groups [25].

The results in Fig. 8 show large difference between the age groups because of the different effects of signal-to-noise ratio with age. However, the variations with reverberation time are quite similar for all age groups. These results indicate that a range of reverberation times would lead to approximately the same near maximum intelligibility scores. The differences between the curves in Fig. 8 indicate that excessive noise is a more important problem than non-optimum room acoustics. Of course, other particular groups of listeners may be differently affected by reverberation time.

Rooms for Music: Bass Sounds

Most of the issues for rooms for speech are also important for rooms for musical performances. However, in rooms for music the acoustical issues are more complex and there are some additional concerns to consider. One of these is the strength of low frequency or bass sounds in rooms for music. Although not necessary for speech, the room should strongly reproduce bass sounds for most types of musical performances.

The classical approach for providing adequate strength of the bass sounds assumes that the strength of bass is related to low frequency reverberation times and that rooms for musical performances should have increased low frequency reverberation times. Typically the 125 Hz reverberation time is required to be 1.5 times the mid-frequency value. This sometimes leads to quite extreme efforts to reduce low frequency absorption in halls.

Listening tests were carried out in simulated conditions in an anechoic room to determine whether the level or the reverberation time of the low frequency sound determines perceived bass strength [26]. Subjects heard the same piece of music played for 8 different conditions consisting of the combinations of 4 levels of the early-arriving bass sounds and two low frequency reverberation times. Subjects rated the perceived bass strength on a 5-point scale. As shown in

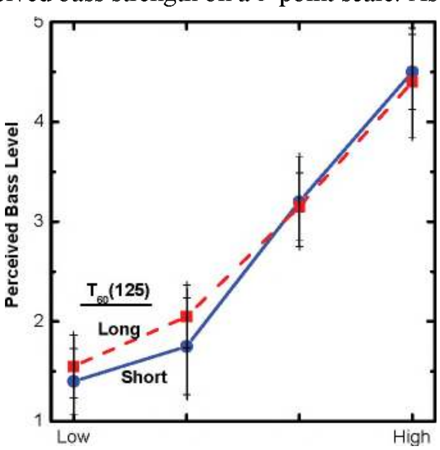


Fig. 9. Mean ratings of perceived bass level versus the strength of the early arriving bass sounds for two 125 Hz reverberation times (1.4 and 3.2 s) [26].

Fig. 9, the perceived strength of the bass sound was strongly and significantly affected by the level of the early arriving low frequency sound. However, the varied low frequency reverberation time (1.4 to 3.2 s) did not significantly influence the results. The perceived bass strength was determined by the level of the bass sounds and not by the reverberation time.

It is also important to understand the propagation of early-arriving low frequency sounds in concert halls. There is a phenomenon known as the seat dip effect [27, 28] that can strongly attenuate low frequency sound travelling at near grazing incidence to the audience surface. This attenuation is essentially due to an interference of the direct sound and reflections from the audience or the seating that cause large cancellations over a band of frequencies that is typically around 125 Hz. Fig. 10 plots measurements of this attenuation for varied angle of incidence. The frequency of the interference minimum shifts systematically higher in frequency as the angel of incidence increases. As indicated in Fig. 10, the maximum attenuation can be 10 dB or more. This is a much larger effect than can be obtained by decreasing the low frequency absorption in a hall. The usual design goal to increase 125 Hz reverberation times by 50% would only increase bass levels by about 2 dB.

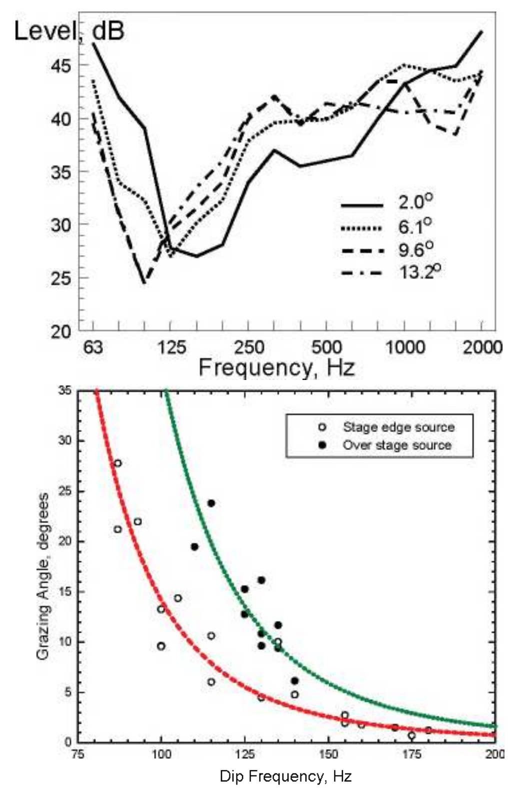


Fig. 10. (Upper) Spectrum of early arriving sound at positions above the audience seating for 4 different angles of incidence. (Lower) Frequency of the attenuation maximum for two different on-stage source positions and varied source height [29].

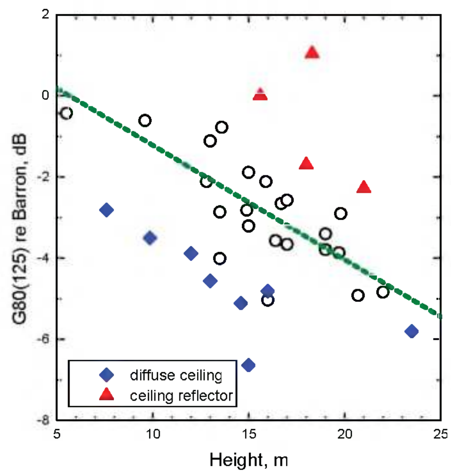


Fig. 11. Hall average 125 Hz octave band early-arriving sound strength ($G_{80}(125)$) versus ceiling height. $G_{80}(125)$ values were normalized relative to the predicted levels using Barron's theory to remove the effects of room volume and reverberation [30].

Although the problem is now better understood, a clear design approach to achieving strong bass sound is not available. One factor that does influence this bass attenuation is the reflecting properties of the ceiling. Fig. 11 plots the average strength of the early arriving 125 octave band sound levels versus ceiling height and identifies the ceilings as one of 3 types. Lower ceilings lead to increased low frequency sound levels. Diffusely reflecting ceilings reduce the strength of low frequency sound relative to other ceilings and halls with special ceiling reflectors can have increased levels of low frequency sound. Presumably stronger ceiling reflections can minimize the interference effects that lead to the seat dip attenuation. However, more research is needed to more fully understand the merits of various ceiling types in concert halls.

Rooms for Music: Spatial Impression

Another topic that must be considered in rooms for musical performance is spatial impression. Spatial impression was initially loosely deescribed as the difference between more or less 'looking at the sound' as in outdoor situations and being immersed in the sound as in a good concert hall. Spatial impression was said to include apparent broadening of the sound source and a sense of being enveloped in the sound. Barron's pioneering work [31,32] showed that early-arriving lateral reflections led to perceived spatial impression. Fig. 12 shows Barron's graph indicating the combinations of the relative level of early arriving lateral reflections and the time delay after the arrival of the direct sound that led to the perception of spatial impression.

Barron's work also led to the definition of the lateral energy fraction (LF) as a measure of spatial impression. LF is simply the linear ratio of the early-arriving lateral energy to the total early-arriving energy. The early time period is taken as the first 80 ms and the first 5 ms of the early lateral energy is ignored to avoid any influence of the direct sound.

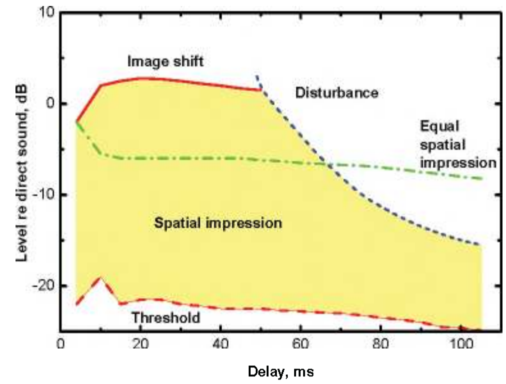


Fig. 12. The shaded area indicates combinations of the relative level of early-arriving lateral reflections and time delay after the arrival of the direct sound that led to perceived spatial impression [31].

Somewhat later Bradley and Soulodre tried to repeat Barron's experiments and found that they could not create a sense of envelopment with early-arriving lateral reflections. The early-arriving lateral reflections led to an impression of increasing apparent source width (ASW). After several experiments they demonstrated that a sense of listener envelopment (LEV) was created when later-arriving lateral reflections were present [33,34]. Fig. 13 includes the results of one experiment showing that increased reverberation time and increased late-arriving sound levels led to an increased sense of envelopment. Further experiments showed that the direction of arrival was important too.

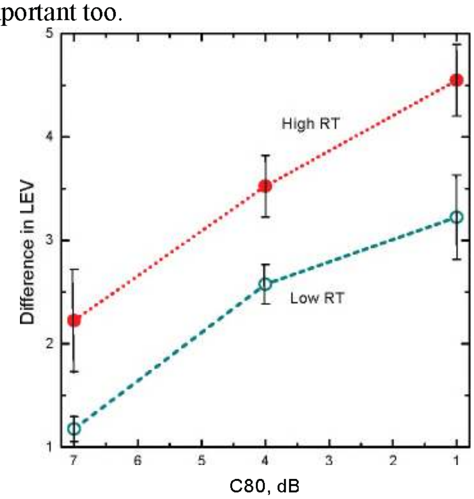


Fig. 13. LEV increases with reverberation time and the level of the late-arriving sound [33].

The strength of the later-arriving lateral energy was shown to be a good measure for predicting the amount of LEV

[34]. Fig 14. shows a plot of increasing LEV versus the strength of late-arriving lateral sound over the octave bands from 125 to 1000 Hz.

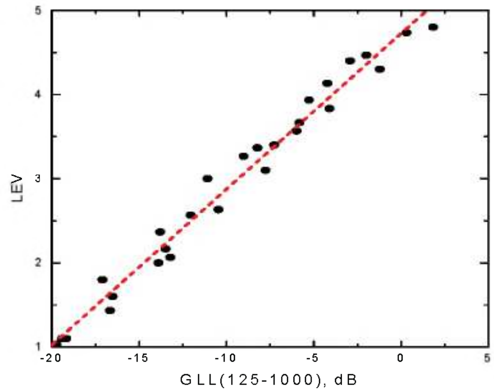


Fig. 14. LEV plotted versus the strength of the late-arriving sound energy calculated over the octave bands from 125 to 1000 Hz [34].

We now have a clearer understanding of spatial impression and how it has two components: ASW related to the strength of early-arriving lateral reflections and LEV related to the strength of later arriving lateral reflections.

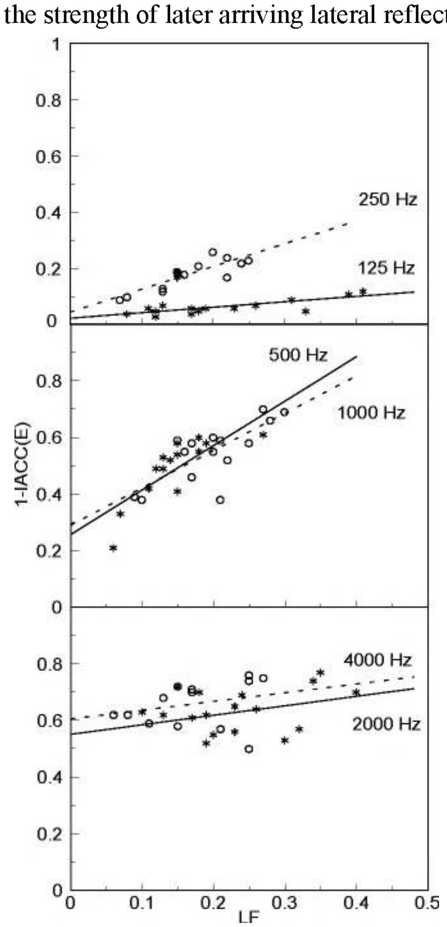


Fig. 15. Octave-band hall-average values of 1-IACC values plotted versus octave-band LF values [35].

While the LF measure proposed by Barron has been well accepted and used to evaluated concert halls, others have proposed using inter-aural cross correlations (IACC) to evaluate spatial impression. IACC values are usually calculated from impulse responses recorded at the two ears of an acoustical mannequin. When this is done for the early sound, that is the first 80 ms of the impulse response, the IACC values would be expected to relate to LF values and to be an indicator of the perceived ASW. Comparisons of hall-average values of these quantities in terms of octave band values are compared in Fig. 15. The 1-IACC values are quite significantly related to the LF values in all 6 octave bands. This strong correlation between the two measures suggests that they provide similar information about the average acoustical conditions of the halls. However in the lowest octave band (125 Hz), the variation in 1-IACC values is relatively small compared to the range of LF values. The same effect is seen in the 2k and 4k Hz octave bands.

When the individual seat measurements are compared in Fig. 16, the results are quite different. For the mid-frequency octave bands (500 and 1000 Hz) there is a reasonably good correlation between the two quantities.

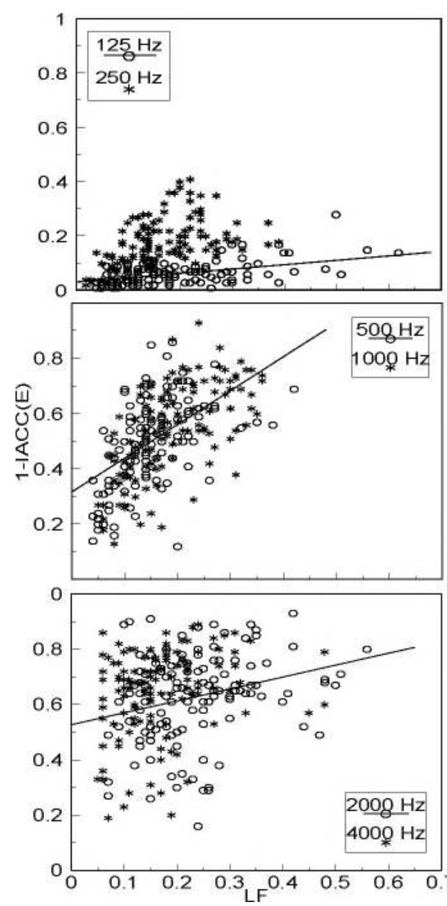


Fig. 16. Octave-band values of individual measurements of 1-IACC values plotted versus octave-band LF values [35].

However, for the lowest and highest two octave bands, the scatter is greater than the variation of the mean trend as indicated by the regression lines. There are other factors that cause greater variations in the 1-IACC values that do not have the same effects on LF values. At lower frequencies the differences might be due to interference effects that influence 1-IACC values but not the LF values which are a result of energy additions. The differences at higher frequencies might be due to scattered sound. However, neither explanation has been confirmed and it is not clear which measure best relates to the perceived changes in spatial impression.

Design and Evaluation of Rooms for Music

Room acoustics computer models have taken the acoustical design of new auditoria and modifications to existing halls a large step forward. The models usually are based on geometrical acoustics principles and trace rays (or some similar process) and add up calculated reflections on an energy basis. They often include ‘fudge’ factors to account for the effects of non-specular reflections and the scattering of sound. These have significant effects on the final results but the choice of appropriate values is greatly influenced by the experience of the user. Being based on geometrical acoustics they also do not include interference effects such as are important for understanding the low frequency seat dip attenuation. Many of the models can be used to create auralizations of sound in a planned hall, but of course although these can sound very impressive they are limited by the basic limitations of the models. These models are particularly useful for determining the basic geometry of a new hall and are, in most cases, a much more convenient replacement for scale models.

Although there are many issues that are not fully understood, there has been progress and there are better techniques for assessing conditions in existing rooms intended for musical performances. The ISO 3382 standard [21] describes a number of room acoustics quantities and measurement procedures that can be used to assess conditions in auditoria and concert halls. These are increasingly being used to document the acoustical conditions in halls and to help understand and resolve problems that are reported. All new halls and major renovations should be objectively evaluated using these measurements to ensure all parties know exactly what has been achieved. There is a long history of small but often expensive modifications to halls being recognized as ineffective after initial opinions to the contrary.

Figures 17 and 18 help to illustrate the use of measurements to understand conditions by comparing results from two very different halls. Both figures include plots of early-arriving and late-arriving strength values in the 1000 Hz octave versus source-to-receiver distance. Fig. 17 shows measurements from Boston Symphony Hall, a hall that is famous for it’s acoustical quality. Fig. 18 shows

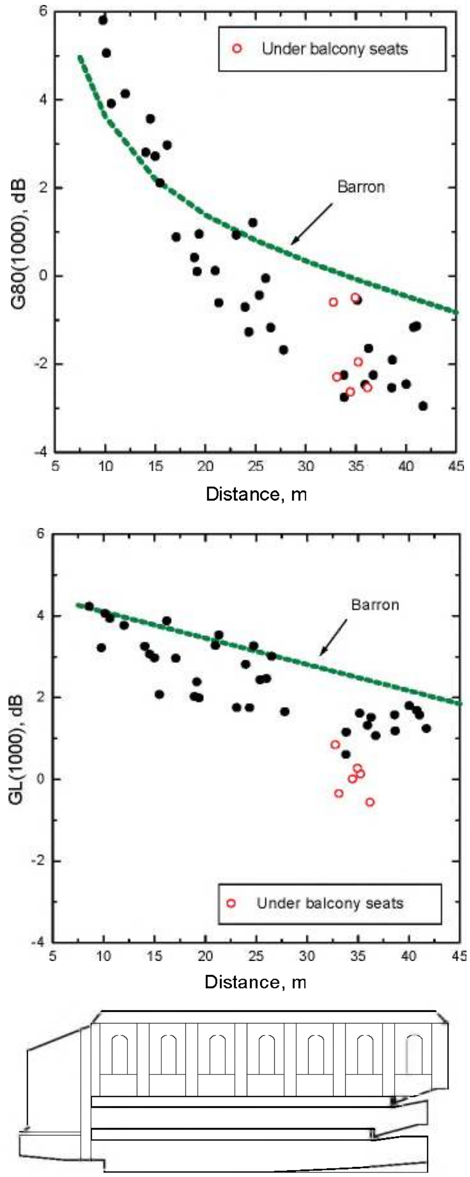


Fig. 17. Early-arriving 1000 Hz strength (upper) and later-arriving 1000 Hz strength (middle) versus source receive distance in Boston Symphony Hall. Dashed line shows values predicted using Barron’s theory [37].

results measured in the Orpheum in Vancouver before it was renovated a few years ago [36].

The upper part of Fig. 17. shows that early-arriving sound levels decrease in a regular manner with increasing distance and that seats located under the relatively small balconies have early-arriving sound levels similar to seats at the same distance in the balconies. The middle part of Fig. 17 shows a similar decrease in late-arriving sound levels with distance but the seats under the balcony do tend to have lower values than those in the balcony at the same distance. This would suggest that in the under-balcony seats, it might sound a little less reverberant and a little less enveloping. For both early-arriving and later-arriving sounds the decrease in level with distance is a little more rapid than predicted by Barron's theory.

The results in Fig. 18 are quite different. The variation of early-arriving sound levels with distance show a large amount of scatter and especially for the seats in the balcony. This was determined to be due to various concave surfaces in the ceiling focusing early reflection energy to particular areas. However, there is again no evidence that under-balcony seats have systematically different early-arriving levels than seats in the balcony at the same distance. The later-arriving sound levels show reasonably good agreement with Barron's theory for seats in the balcony but much lower levels at seats under the large balcony. The measurement results clearly identify the problems and helped the acoustical consultant (John O'Keefe, Aercoustics) to successfully renovate the hall [36].

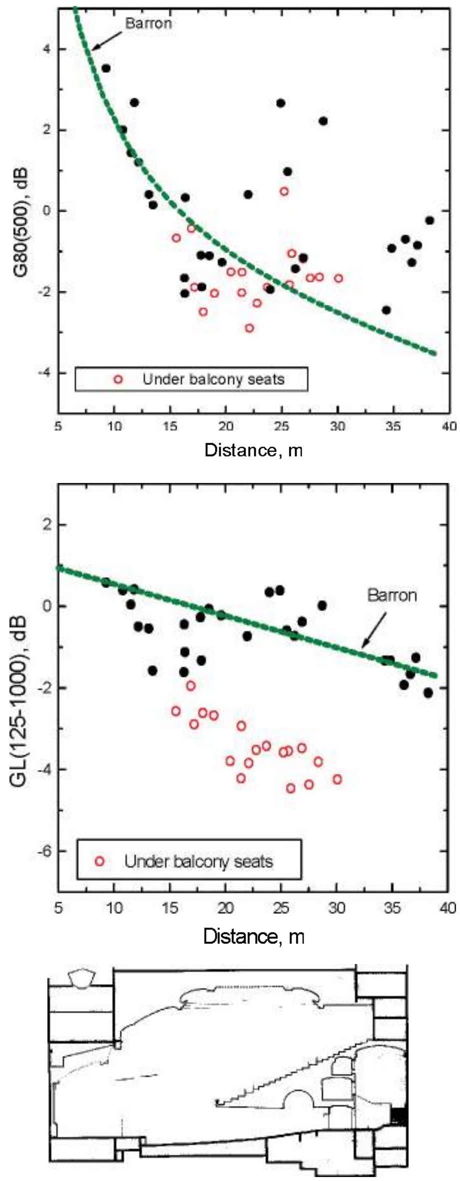


Fig. 18. *Early-arriving 1000 Hz strength (upper) and later-arriving 1000 Hz strength (middle) versus source receive distance in the Orpheum in Vancouver. Dashed line shows values predicted using Barron's theory[37].*

Conclusions

The development of architectural acoustics has many occasions of discovery and later-rediscovery, but progress is being made. There are many unresolved problems and with adequate resources substantial progress could be readily achieved.

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