SECOND EDITION

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Auditorium Acoustics *and* Architectural Design

MICHAEL BARRON

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Second Edition

Michael Barron

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Preface

With hindsight, the timing of the first edition of this book was fortunate. The understanding of how sound behaves in auditoria and how people react to what they hear had reached a crucial watershed. For the first time, a consistent picture existed of the important factors for listening such as clarity and measurable quantities had been proposed relating to each of these factors. This was especially the case for music performance. Research, which had begun in the 1950s, had finally provided results that made it possible to say that the art and science of auditorium acoustics had reached a certain level of maturity.

A further development had taken place in the 1980s that was to have a major impact on design. Within design teams on auditorium projects, advice from acoustic consultants was being assigned greater importance. What was going to matter more for the client, a visually beautiful hall or a hall with good acoustics? This development however placed greater responsibility on the shoulders of the acoustic consultant, to which the response has often been to play safe and base designs more on successful precedents. New rectangular plan concert halls and horseshoe-plan opera houses have become popular again; both of these precedents come from the nineteenth century.

One can see the last 15 years as a period of consolidation, during which designers have been able to work with much greater confidence in their designs. Disappointing acoustics at the opening of a new auditorium is much less frequent now than was the case about 50 years ago. On the physical acoustic front during this period, the measurable quantities relevant to auditorium listening were included in a standard (ISO3382). Valuable books have also been published by others, in particular Beranek's distinguished surveys of the acoustics of world concert halls and opera houses (most recently in 2004). In addition a compendium of designs between 1982 and 2002 has been produced by Hoffman *et al.* – these references are to be found at the end of Chapter 1 (p.8).

In this second edition, greater reliance can also be placed on the advice offered. The text has been thoroughly reviewed and new developments included where appropriate on such topics as listener envelopment, scattering, auralization and greater use of computer simulation. Five new case studies of recent auditoria have been added: four concert halls and one opera house. The overall aim has remained as before, to illuminate the relationship between auditorium form and acoustic performance, all placed in a historical context and aimed at a wide readership.

For the production of this book, special thanks go to architectural firms that have supplied plans and sections, and auditorium managements who have allowed us to make measurements. I am particularly grateful to Dr. Leo Beranek for permitting me to use so many of the architectural drawings from his books. I am also grateful to the following individuals and organisations who have given permission for reproduction of and in some cases also kindly provided copies of copyright material (figure numbers are in parenthesis):

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In addition to those thanked in the preface to the first edition (reproduced below), warm thanks go to the following who helped with this new edition: Dr. Jin Jeon for assisting with the new auditorium measurements, Sir Harold Marshall for revisions to the foreword, Anders-Christian Gade for revisions to the text on acoustic conditions for performers and Rachel Mundell and Georg Herdt, who produced the new architectural plans and sections. Thank you to my co-workers during this period, Stephen Chiles and Jens Jørgen Dammerud, and especially to my consultancy partner, David Fleming, for being most supportive. Finally I owe many thanks to my university department, my project managers at HWA Text and Data Management, my patient editor, Georgina Johnson-Cook, and Penny for even more patience.

Michael Barron
Bath

Preface to the first edition

What form should one use to enhance to the utmost the brilliance, harmony and depth of sound from a symphony orchestra? Is there perhaps an ideal form on acoustics grounds for a drama theatre for Shakespeare's plays? Such questions must have inspired many of the more original solutions to the auditorium problem. A particularly appealing approach for instance, especially for those sensitive to the charms of classical architecture, is that certain ratios of proportion are propitious. The argument runs that since our ears appreciate harmony and harmony is based on simple proportions, so buildings to support harmony should likewise be built with favourable ratios of proportion. Sadly this charming argument is fallacious since the actual dimensions are also relevant. This means that a concert hall with preferred proportions would only be suitable for one musical key, a concert hall in C perhaps? However there is the further point that the dimensions of auditoria are in any case too large for such considerations to be significant; we can fortunately design halls for all keys.

There are logical sources for a solution, but we have three possible directions in which to look for inspiration. We could start from the characteristics of sources of sound: the properties of violins, wind instruments, the human voice and so on. Or we could respond to the wave nature of sound, by starting from an understanding of the way sound travels away from sound sources and establishing how it is complemented by reflections from wall and ceiling surfaces. And a further possibility is to use the ear as guiding principal: to determine what our ears find particularly desirable when listening to music and what constitutes acceptable conditions for intelligible speech. One can cite examples in built auditoria of each of these guiding principles. Yet each concern on its own is inadequate. We now know that successful design is based on a whole series of independent considerations, that each of the elements between performer and listener has to be considered and understood. This book has its guiding concern to illuminate these questions and to search for the relationship between architectural form and acoustic behaviour. The presentation is directed at both the specialist and non-specialist.

The problem of achieving good concert hall acoustics has stimulated much valuable research since 1950. The results of this work have often been in the form of some preference in reflection characteristics or some new measurable acoustic quantity. In the case of speech, less thorough investigations have been made, but the majority of important issues have been resolved often for goals other than auditoria. However, translating acoustic requirements into three-dimensional built form has received rather less attention. It was this consideration which led to an acoustic survey of existing auditoria of all types: concert halls, recital halls, drama theatres, opera houses and multi-purpose spaces. The survey encompassed two forms of study: measurements of physical acoustic characteristics of auditoria and listening tests conducted at public performances with questionnaires. This book presents an account of the full survey within the framework of a thorough discussion of the concerns and principles of good acoustic design. No discussion of this sort is possible without extensive illustration; the reader will discover that all architectural drawings have been reproduced to the same scale of 1 : 500.

On a personal level, I have many people to thank for help of many kinds towards this book. Much of the original survey work was financed by the Science and Engineering Research Council while the author was at the Martin Centre for Architectural and Urban Studies at Cambridge University. Among many indulgent colleagues there, Lee-Jong Lee was an enthusiatic co-worker for two years and was responsible for the majority of the architectural drawings ot British auditoria. Also at Cambridge, Raf Orlowski and Tim Lewers helped out with field work among much else. Dean Hawkes oversaw operations with admirable detachment.

Particular thanks go to all those who attended concerts or plays armed with a questionnaire, often travelling great distances at their own expense for the privilege. Members of Bickerdike Allen Partners and Sandy Brown Associates were especially conscientious in their attendance, making the whole exercise feasible. The managements of all the auditoria studied in detail generously allowed access for acoustic measurements and gave permission for the author's photographs of their respective halls to be used here. They or the architects concerned must also be thanked for providing the architectural drawings used as the basis for reduced plans and sections.

In the preparation of this book, Professor Philip Doak was most supportive at moments of (minor!) crisis. I owe a special debt to my fellow consultancy partner, David Fleming, who has valiantly provided continual encouragement and much necessary constructive criticism. The quality of the final product also owes much to the support and faith of my editor at E & FN Spon, Martin Hyndman.

I am indebted to Anders-Christian Gade for contributing the section on musicians' acoustic requirements, to John Bradley for allowing me to use the results of his measurements in the Vienna Musikvereinssaal, and to Harold Marshall and Jerry Hyde among much else for permission to reproduce the results of measurements in the New Zealand concert halls in Christchurch and Wellington and the Segerstrom Hall, Orange County, California. My thanks go also to Prof. G.C. Izenour of Yale University for generous permission to reproduce figures from his book *Theater Design*. In a project which has lasted over ten years there are few of one's associates who have not in some way generously participated. For assorted assistance I must include mention of Derek Carruthers, Michael Forsyth, Thomas Fütterer, Dieter Gottlob, Jean-Dominique Polack, Maritz Vandenberg, H.J. Griffiths, Mark and Vicki Wooding and last, but far from least, Penny.

While every effort has been made to ensure the accuracy of the opinions and data presented in this book, the author can accept no responsibility for any inaccuracies it may be found to contain.

This reprint includes corrections to the known inaccuracies in the first edition. One consistent error needs to be brought to the attention of the more technical reader. The early decay time (EDT) is now considered a fundamental measure in spaces for music and in the first edition measured values were included in all figures containing measured results in concert spaces, such as Figures 3.25 and 5.6. However from comparison with EDT measurements by others in some of the same spaces, it became apparent that my measured values were slightly in error. This proved to be due to an error in the analysis program which derived EDT values. The measured data has therefore been reanalysed and the correct EDT's are included in this reprint in Figures 5.6 etc. Further details can be found in *Acustica*, **81,** 320–331 (1995). Fortunately the magnitude of the errors in EDT are generally very minor. The changes are significant at 125Hz in several halls and at mid-frequencies in the two New Zealand halls discussed in section 4.10 and Appendix C. Since all the figures with objective results for concert spaces were being revised, the opportunity has been taken to improve the readability of the figures by indicating on them the preferred ranges for objective clarity and envelopment.

Michael Barron

Foreword

There was a time about 50 years ago when physics reigned unchallenged in the world of science. Its derivative profession, engineering, seemed to offer recipes for everything from earthquake engineering to genetics, and everything that could be thought of would sooner or later be realized. People contemplated with equanimity the possibility of creating harbours by subterranean thermonuclear blasts, moon walks, universal health – concert halls in which by following step-by-step instructions 'perfect acoustics' would be produced for all. Alas for the brave new world. Things have turned out to be much more complicated than they seemed in an age so full of hope and as naïve as the lyrics of the popular music of the day suggested.

One should have been warned by the failure of the acoustical predictions for the Royal Festival Hall that there was much more to understand than was clear from the state of knowledge then. But in the prevailing mood of optimism a miss of 40% in the predicted reverberation time was not sufficient to trigger much research. That had to wait for another monumental miss in the next decade. It was the failure of the design for the now historic New York Philharmonic Hall that sparked a new generation of effort to understand what makes a good concert hall. This book is largely the history of that effort.

Perhaps the most striking change in approach during the last 50 years has been a movement away from the physics of sound in rooms to a concentration on the effects of sound in the virtual space between the ears of the listener. It was extremely difficult to relinquish the linear thinking which had proved so effective in other fields of engineering, and equally difficult to abandon the search for one main ingredient of goodness in concert hall sound which would provide the reductive answer to the designer's task. Even the use of the singular term 'listener' is a relic of this linear paradigm. We now know that audiences are far from homogeneous in their preferences – and the 'space between the ears' is only accessible at one remove.

Rather than a single path with a starting point and a single desired goal, the requirements of successful large performance spaces for music might better be thought of as a four or more dimensional maze with several ways in and at least as many desired outcomes. There are plenty of dead ends as well and it would be a brave person who would assert that they have all been identified at this time.

Michael Barron has been committed to the way through this maze for the past 35 or more years. Indeed, he was largely responsible for the recognition of a number of desired outcomes and for the refinement of the objective measures by which numbers can be set to the subjective impressions to be found there. Patiently, he has compiled both data and wisdom about auditorium design into what must be the most useful review of knowledge since Beranek's *Music Acoustics and Architecture* of 1962.

One discerns a consistent effort in this book to communicate with a broad audience, an effort equally concerned with music and with the rooms in which it takes place. In the late 20th century these rooms have become an essential and positive dimension of the acoustical form of music (as any musician will confirm this robust art also has form which is not acoustical). Of course the book is partisan to the approach which Michael Barron has found most productive of good halls and to those halls with which he is most familiar. But the range is sufficiently large to be considered comprehensive and those that find their theoretical approach omitted and/or their preferred objective measures unused will nevertheless be able to relate their work to Barron's results. Inevitably, there is a huge reduction of data required in a book such as this but information essential for the serious inquirer is not lost.

In the late 1960s, in the linear mode of thought, I believed that I had discovered the one essential source of premium concert hall sound, the lateral reflections. My hypothesis was subjected to critical scrutiny in Michael Barron's doctoral thesis. That work established the beneficial effects of lateral reflections and showed that the audibility of the lateral sound was dependent on the lateral to frontal energy fraction rather than on a lack of masking by frontal sound as I had previously thought. Later, in Goettingen, Gottlob and Siebrasse in their respective theses devised an experiment which further cemented the importance of the lateral reflection concept in place as one of the independent factors in determining concert hall preference. By then the multidimensional nature of preference had been established by Hawkes and Douglas, and the linear approach to subjective room acoustics was history.

Michael Barron went on, at Cambridge, to develop acoustic modelling to a level which it had never reached before. The idea of acoustic modelling using ultrasound was already quite venerable, dating from before the Second World War but was inordinately expensive. The Cambridge work showed that models at scales as small as 1:50 could produce useful data given suitable dry air conditions. The use of these models is now commonplace acoustics design practice and the development of digital data acquisition in conjunction with such models permits numerical compensation for the real air conditions, and so avoids the tedious problem of drying. Modelling is now a truly interactive design aid. It is certainly possible to know what will occur acoustically in the completed performance space but whether it will be liked or not is a question with several answers.

The intriguing uncertainties of audience preference for music do not exist in speech auditoria. There the outcome is uni-dimensional. You have speech clarity or you do not. The design problem is considerably easier than it is for music because speech rooms are usually smaller than music rooms and the signal is more consistent. It is when the speech communication is part of an art-form such as theatre, that the integration of architectural intentions and the acoustics, in a multidimensional way becomes essential. It is no surprise then to discover a substantial section of the book devoted to the history of theatre and the building forms associated with it. Technically, speech rooms are more straightforward but the cultural and symbolic functions of the space in which communication is to occur may well provide as much complexity as one finds in the design of rooms for music.

The maze is still there though not all its dimensions are yet named. The power dimension of the process of making a concert hall is yet to be addressed although buildings stand or are (literally in the case of the NY Philharmonic Hall) demolished because of it, acousticians succeed or fail, and architecture is, or is not created in the context of that power. In the numerous case histories included in this excellent book that is a question the reader is invited to bear in mind.

Emeritus Professor Sir Harold Marshall KNZM, FRSNZ, FASA, FNZIA
Auckland

1 Introduction

Our echoes roll from soul to soul,
And grow for ever and for ever.
Blow, bugle, blow, set the wild echoes flying,
And answer, echoes, answer, dying, dying, dying.
(The Princess, Tennyson)

'Theatre design is based on hard facts and is rarely a matter of inventing new forms of theatre. The architect works within a large number of constraints, some of which are self-imposed, and if inventiveness comes into it at all, it is in the way that theory is put into practice.' These words by the architect Peter Moro (1982) referred to theatre design, but they can equally well be applied to all forms of auditorium design. Many a designer must have greeted the prospect of a new auditorium with ideas of creating a totally new form or of returning to the purity of classical models, only to find his options becoming progressively more limited, with consultants from other disciplines criticizing one feature after another. As with all buildings, structural needs can limit freedom and architectural style is a balance between respect for precedents and current fashion. But for auditoria, there are the additional constraints in planning for good visual conditions and sightlines, of meeting certain social demands in regard to layout of seating and not least providing good acoustic conditions. The designer has to remain continually aware of the relationship he is creating between performer and audience, striving to make it as intimate as possible. Designing auditoria is a complex, elaborate but highly constrained exercise.

All auditoria rely on both visual and acoustic stimulation. Tennyson is referring above to the acoustic response in a mountainous landscape, in which echoes add to the visual imagery and create a sense of space. At the scale of concert halls and theatres, acoustic reflections are no less significant in creating a sense of space, but the ear does not perceive as discrete events or echoes the thousands of reflections it receives. It blends them into a total experience. Only certain aspects of the sound are used to establish the size and character of the enclosed space. The ear also establishes the direction of the sound source and extracts the information content where possible. A world in which the ear was unable to combine sound reflections was described by the Rev. Brewer (1854):

> If the ear ... were capable of appreciating every impulse, the confusion of sounds would be truly terrific. ... Every sound in our houses, every word in our churches, would be repeated ten thousand times. We should hear the direct sound of one syllable mingled with the reflections of another, and both recurring so frequently, that language would be a Babel of 'confusion worse confounded'. The voice of affection and of love, so tranquil, so soothing, and so gentle, would be a clatter more painful than the gibbering of a stammerer.

These are very perceptive comments for the time; the Rev. Brewer would have had to wait a century for a quantitative description of the workings of the ear, which enables us to avoid this 'clatter'. The discussion of auditorium design and development on the basis of precedent were well established in Brewer's day, even if not on a particularly scientific basis. Development from precedent dates of course from the classical Greek era, but sadly no contemporary discussion survives of the development of the earliest theatres. The earliest written record comes from the Roman Vitruvius in the first century BC (Vitruvius, 1960). He appears to base his geometric prescriptions for designing Greek and Roman theatres on an understanding of acoustics. But the validity of his arguments depends on favourable analogies with modern concepts. The most valuable information on ancient classical auditoria is to be gleaned from the surviving examples. The fan-shaped plan and the arena form both became highly developed in classical times and remain a constant point of reference for present design (Figure 1.1). The development of these dominant auditorium plans through the centuries is particularly fascinating (Barron, 1992).

Discussion of auditoria as a building type has a respectable history. The first of its genre, Dumont's *Parallèle de plans des plus belles salles de spectacles* of 1774 contains, as the title indicates, comparisons of plans plus a few sections of then existing theatres and opera houses. Dumont also proposes his own designs with vast concave domed ceilings, which would now give any acoustician nightmares. Louis (1782) included comparative plans in the account of his Bordeaux Grand Théâtre (Figure 1.2) Contant and Filippi's *Parallèle* of 1860 is a thorough review of the major west European theatres. Containing drawings and text, it discusses 33 theatres and became the standard work on proscenium theatre design. In the late nineteenth century, European theatres and opera houses experienced a building boom. By 1896 Sachs could fill his monumental three-volume *Modern opera houses and theatres* with extensive detail about more than 50 theatres completed since Contant's earlier survey. This great work remains a tribute to many of the great houses destroyed in two world wars. Of our own time the closest book in the same vein is Izenour's *Theater design* (1977). This is lavishly illustrated but is more partisan than its predecessors, with discussion

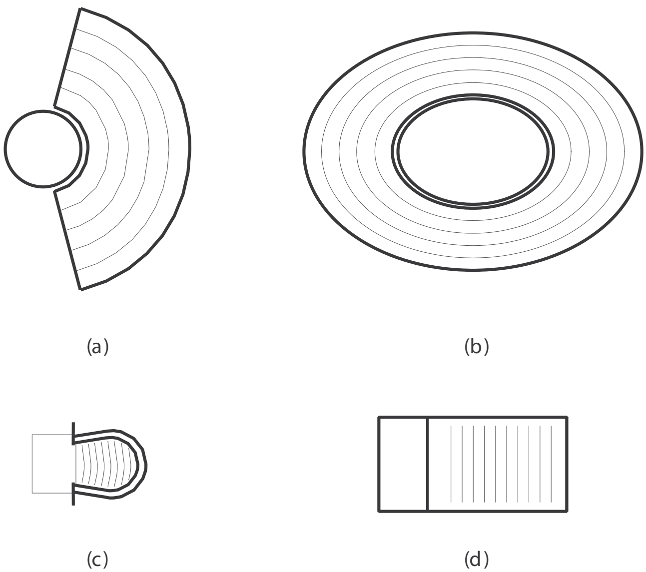

Figure 1.1 Historically dominant auditorium plan forms: (a) classical Greek theatre (fan-shape plan); (b) classical Roman arena; (c) baroque theatre (horseshoe plan); (d) nineteenth-century rectangular concert hall

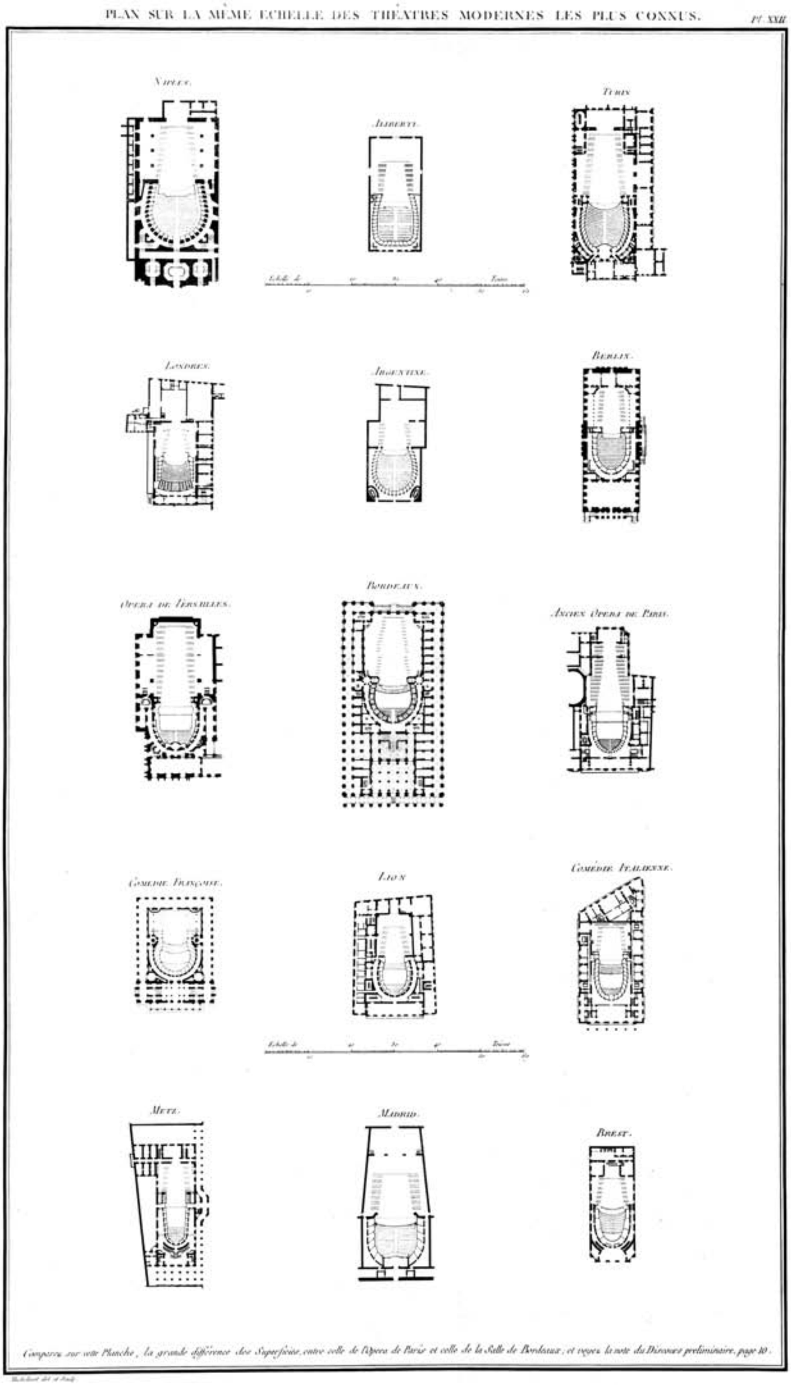

Figure 1.2 Plans of major eighteenth-century theatres to the same scale (V. Louis, 1782)

leading from ancient theatres to modern American multi-purpose performing arts centres. For an architectural analysis, Chapter 6 on 'Theatres' in Pevsner's *A history of building types* (1976) is typically erudite.

The literature for concert hall design is more recent than for theatres. Somehow the history of concert hall development had not been treated until Forsyth's valuable *Buildings for music* appeared in 1985. The first major review of the acoustics of concert hall buildings was Beranek's *Music, acoustics and architecture* (1962), which surveyed 47 world-famous concert halls and seven opera houses. Beranek pioneered analysis of auditorium acoustics on the basis of several independent subjective qualities, such as 'intimacy', 'liveness' and 'warmth'. Beranek has since revised his earlier book twice in 1996 and 2004; the most recent considers 82 concert halls and 18 opera houses. The strengths and weaknesses of his surveys are considered in section 3.2. Other reviews of concert hall designs include Talaske *et al*. (1982), Lord and Templeton (1986), Forsyth (1987) and Hoffman *et al*. (2003).

Beranek's 1962 book was the first to seriously attempt a complete explanation of auditorium acoustics and to answer the many misconceptions on the subject. Acoustics for concert halls, theatres and opera houses is frequently referred to as an inexact science, or worse, an area of myths. While modern technology and computers are considered to be reasonable design aids for a new auditorium, the success of old halls is often considered to be due to secret ingredients. The suggestion, for instance, that concert halls mature with age is still prevalent, as if they behaved like good claret. Wood is often quoted as the optimum material to line concert halls, just because violins are made of the same material. The presumed inaccessibility of acoustic knowledge is long standing. Vitruvius, commenting on the musical basis of acoustics, suggested that: 'Harmonics is an obscure and difficult branch of musical science, especially for those who do not know Greek'. Vitruvius considered that sound propagated curving upwards rather than just horizontally. Interestingly he justified the choice of raked seating not primarily for visual reasons but to optimize the movement of the 'ascending voice'. The ancient Greeks had, of course, studied resonance of stretched strings and found that harmony depended on simple arithmetical ratios. Such mathematical purity led to the concept of 'the music of the spheres', which so appealed to the Renaissance mind. European scientists like Boyle and Newton in the seventeenth century furthered understanding of sound behaviour, and among other things demolished the notion of music in planetary space. In the 'Age of Reason' the first attempts were made at relating auditorium form to acoustic behaviour, with Patte (1782) proposing elliptical plans and Saunders (1790) circular ones. Both plan forms would now be considered dangerous due to focusing by concave surfaces.

Little further progress was made towards understanding the acoustics of rooms in the nineteenth century. A rare voice of inspired understanding is found in the comments of Dr R.B. Reid in 1835, when he said that 'any difficulty in the communication of sound in large rooms arises generally from the interruption of sound produced by a prolonged reverberation'. Reid successfully advised on acoustic treatment of the contemporary House of Commons, Westminster (see Bagenal and Wood, 1931). In Germany, Langhans published a remarkable book in 1810 in which he not only shows that he correctly appreciated how early reflections enhance intelligibility but also came close to understanding the independent role of reverberation (Izenour, 1977; Hartmann, 1990). This work appears not to have reached England or France. Another advance was made by Scott Russell (1838) who calculated the optimum floor profile in long section for good vision and hearing. The ideal profile is curved to provide equal-seeing and 'isoacoustic' conditions. (It is notable that Scott Russell equates vision and sound in this respect, as this is still assumed today.) But concerning useful advice for the architect, the situation remained woeful regarding suggestions for suitable room form and size for good acoustics. Charles Garnier, architect of the Paris Opéra, understandably complained in 1880:

> It is not my fault that acoustics and I can never come to an understanding. I gave myself great pains to master this bizarre science, but after fifteen years' labour, I found myself hardly in advance of where I stood on the first day. ... I had read diligently in my books, and conferred industriously with philosophers – nowhere did I find a positive rule of action to guide me; on the contrary nothing but contradictory statements.

Somewhat ironically, in the face of such scientific ignorance, elaboration on the basis of precedent produced the rectangular 'shoebox' concert hall, some examples of which are still considered by many to have the world's best acoustics. In the case of theatres, many large playhouses built during the theatre-building boom around 1900 are still used and function surprisingly well acoustically. The state of the art in 1861, or rather its lack, was summarized by Roger Smith in his *Acoustics of public buildings*. Smith failed to reconcile the conflicting evidence from the men of science. Even in the major theoretical work of the period, Lord Rayleigh's *Theory of Sound*, which first appeared in 1877/8 but is still extensively referred to, the comments on room acoustics are limited to generalities (Vol.2, §287):

> In connection with the acoustics of public buildings there are many points which remain obscure. ... In order to prevent reverberation it may often be necessary to introduce carpets or hangings to absorb sound. In some cases the presence of an audience is found sufficient to produce the desired effect.

The pleas of Garnier and Smith were answered on the other side of the Atlantic, when in 1895 Sabine began his pioneering work on room acoustics. At a time when physicists were making revolutionary early discoveries in atomic physics, the relative tardiness of concern for the commonplace experience of sound in rooms deserves comment. Two reasons can be advanced for this lack of progress. Firstly the fundamental relationship for sound in rooms requires a statistical rather than simply linear treatment. The linear approach, which can be applied to the single sound wave, has to be applied a thousand times over to provide a complete picture of sound travelling from performer to listener. From this plethora of information, selection of the relevant attributes remains a problem to this day. The second problem until the 1920s was that of measurement. The ear is a highly sophisticated organ but its very adaptation to understanding sounds in enclosed spaces precludes its use as a fully analytic instrument in the scientific sense. The advent of microphones and electronics was obviously a great breakthrough.

In the circumstances, Sabine's achievement was all the more remarkable. W.C. Sabine was an Assistant Professor in the Physics Department of Harvard University. His previous work had been in optics and electricity, when the President of the University

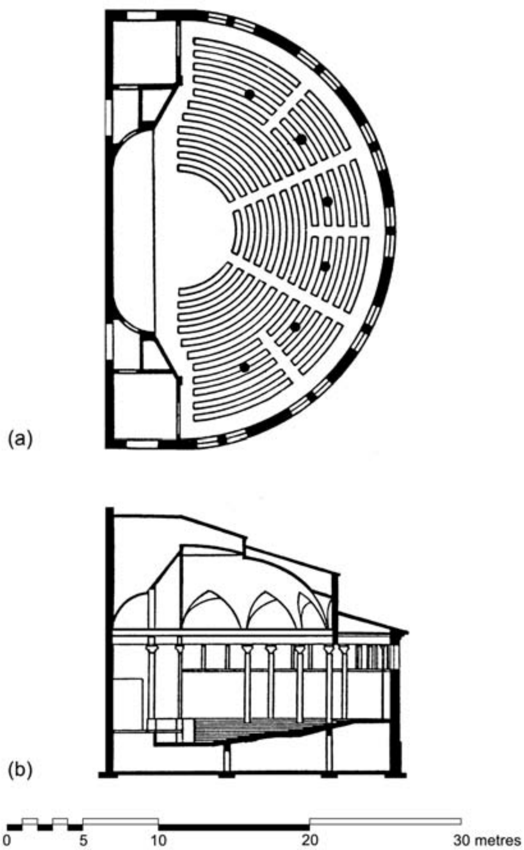

Figure 1.3 Lecture room of the Fogg Art Museum, Cambridge, MA. Plan and long section

asked him to find a solution to the appalling acoustics of the lecture room of the newly completed Fogg Art Museum (Figure 1.3). Sabine quickly realized that there was excessive reverberation in the lecture room (he measured the unoccupied reverberation time as 5.5 seconds; Sabine, 1922). Consultation of the literature would have revealed that this could be reduced by installing sound absorbing material, but Sabine chose to undertake a fundamental investigation into the behaviour of sound in enclosed spaces. He developed a technique for measuring the decay time of residual sound after an organ pipe was switched off, using nothing more than the observer's ears and a stop-watch. Measurements were made of this time, now known as the reverberation time, while different lengths of absorbent cushion were brought into the room from a neighbouring lecture theatre, up to the point where the time had been reduced to 0.75 seconds. Changes to improve the acoustics of the lecture room were made in 1898; the room was finally demolished in 1973 (Cavanaugh and Wilkes, 1999).

In the autumn of 1898, a new Boston Music Hall was being contemplated and Sabine was asked if he would be willing to advise on the acoustics (Beranek, 1979). Sabine hesitated but embarked on a hectic review of the experimental data he had collected in several Harvard rooms. On Saturday evening, 29 October 1898, he suddenly realized the explanation for his results, shouting out to the only other person in the house: 'Mother, it's a hyperbola!' He had discovered that the reverberation time was proportional to the reciprocal of the amount of absorption (Sabine, 1922: introduction in Dover edition). Thus was born the relationship now called the Sabine reverberation equation. He then accepted the commission to advise on what is now known as Boston Symphony Hall, a concert hall which has gained a reputation for having one of the best acoustics worldwide.

What is particularly striking about Sabine was his clarity of vision. In reading his writings, it is difficult to believe 'the meagreness and inconsistency of the current suggestions' (Sabine, 1922) when he began. Much of it reads as relevant to today's problems. For example in his paper of 1898 (Sabine, 1922), the requirements for room acoustics were summarized much as they might be today:

> In order that hearing may be good in any auditorium, it is necessary that the sound should be sufficiently loud; that the simultaneous components of a complex sound should maintain their proper relative intensities; and that the successive sounds in rapidly moving articulation, either of speech or music, should be clear and distinct, free from each other and from extraneous noises. These three are the necessary, as they are the entirely sufficient, conditions for good hearing.

Sabine founded the quantitative approach, not only to internal room acoustics, but also to noise transmission through buildings. His premature death in 1919 meant he was unable to develop what we now appreciate as a necessary multidimensional approach to auditorium acoustics.

In the 1930s two influential books appeared which consolidated the progress of the 'new' science of room acoustics: *Planning for good acoustics* by Bagenal and Wood (1931) and *Architectural acoustics* by Knudsen (1932). Yet auditorium design still remained a somewhat hit-and-miss affair. The Royal Festival Hall, London, of 1951 was typical of several subsequent disappointments. The great successes of the previous century had been due to design by precedent as well as a few grains of fortune. Their excellence had still not been matched in spite of greater understanding. Reverberation time had been proved to be very important but by itself it did not guarantee good acoustics; further aspects required consideration for successful auditorium design. Auditorium form as well as size is now recognized as highly significant. This question of the interplay between architectural form and acoustic behaviour is one of the dominant themes of this book.

The successful search for other significant measurable quantities began around 1950. It had been realized that the unanswered questions concerned the manner in which the ear processes acoustic information. Subjective experiments were initiated with subjects listening and responding to controlled acoustic conditions. Auditorium acoustics had entered the realm of experimental psychology, a story which is elaborated in Chapter 3. Several new measurable quantities have now found wide acceptance as being significant for music listening. Much of this progress has been admirably recorded by Cremer and Müller in *Principles and applications of room acoustics* (1982). More recently, Meyer's *Acoustics and the performance of music* (2009) takes as its basis the characteristics of musical instruments (spectral, directional etc.) and how this is significant for performance.

A leading question however still remains regarding how the form and detailed acoustic characteristics of a design determine acoustic quality. Reverberation time can, with reasonable accuracy, be calculated and thus predicted from architectural drawings. But in the case of the newer measurable quantities such prediction is less straightforward. Acoustic scale models can be useful but a feel for the influence of design features is needed from the very start of development of a design. Computer models are now routinely used but they are not entirely reliable, particularly in inexperienced hands. A knowledge of the way in which form determines the various elements of subjective quality is required. In order to gain this knowledge, the most accessible resource is existing auditoria. In an area as complex as three-dimensional acoustic design, science is forced to rely on precedents.

Thinking along these lines led to an acoustic survey of British auditoria conducted by the author mainly in the years 1982–3. Acoustic measurements were made in over 40 auditoria. In most of these, subjective tests were also conducted with listeners completing questionnaires at public performances. A further five British auditoria completed since 1990 have since been tested and reported on. While many auditoria worldwide are discussed in the following chapters, a detailed understanding of their acoustics is usually only possible where extensive tests have been made. This has been possible in the British halls tested and is recorded here. The book starts with an introduction to acoustics in rooms, before treating acoustic design for symphony concert halls, recital halls, drama theatres, opera houses and finally multi-purpose halls.

The new scientific basis for auditorium acoustics has made acoustic design a more confident exercise, in spaces for both music and speech. But acoustic design is also an art involving choices, as Bagenal (1950) recorded: 'To design a concert hall is to go down into the arena and risk death from the violence of your contending passions'. One hesitates to guarantee excellence, but many of the disasters of the past should be avoidable with present knowledge.

Sophisticated acoustic design however is but one element of an auditorium project. The demands on the architect are considerable. The strongly constrained nature of auditorium design means that the grand gesture is generally out of place. Several auditoria exist around the world where a major world-class architect has wanted to create a great public monument, but the architecture gets in the way of an effective functioning auditorium. Respect by architects for acoustics has fortunately improved over time. One of the grandest music spaces in Britain is St George's Hall, Liverpool of 1854; a colleague of the architect, H.L. Elmes, commented that 'The specific adaptation of this grand interior for the acoustic performance of music was a thing that he (Elmes) held to be beneath his consideration', and this was despite him being a competent violinist!

The ideal requires a good rapport between the architect and his major consultants, a willingness to develop a scheme within the design team, and for the architect to view the needs of other disciplines as a stimulus rather than an irritation. This state of affairs has luckily become more common and depends on suitable stature for all involved. But success reaps many rewards, by providing a venue to sustain the essential live performances in the arts and frequently by rejuvenating the areas in cities around public performance spaces.

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2 Sound and rooms

2.1 The essence of sound waves

Most people remember the school experiment with an electric bell suspended in a vacuum jar. The experiment demonstrates that sound depends on air for its propagation; as the jar is evacuated the bell can no longer be heard. Sound propagation depends on a source of sound and a receiver, but the propagating medium is all around us. This, coupled with the fact that sound bends round corners and that the ear is only barely directional, makes our hearing such an invaluable sense to notify us of danger, to inform us of our surroundings and to communicate. And if there is a mystery associated with this sense then it resides in the complexities of the ear. This remarkable organ is still far from fully understood. At its centre it contains a converter to transform the vibrations conducted from the eardrum into digital nerve pulses. Nerve pulses travel between the ear and brain in both directions, allowing the listener to suppress his/her sensitivity to a continuous noise for instance. The ears' response to music is no less intriguing.

The subject of this chapter is the nature of sound and the manner in which it propagates in rooms. Of necessity the treatment of the subject here is rather selective. Many standard texts cover the standard issues in more detail. For those that like a well-illustrated coverage, the book by Egan (1988) has much to recommend it.

Sound is generated in most cases by a vibrating object. Human vocal chords or the vibrating reed of a clarinet are obvious examples, but any wall which transmits sound from a neighbouring room is also vibrating, even though the amplitude is minuscule. A sound wave consists of a pressure fluctuation alternatively positive and negative relative to atmospheric pressure. As shown in Figure 2.1, passage of a sound wave causes air particles to move backwards and forwards parallel to the direction of motion of the wave. Sound waves are therefore **longitudinal**, rather than transverse like waves travelling along a string, in which string elements move at right angles to the direction of the wave. (Water waves look like transverse waves but are more complicated because the water particles move both vertically and horizontally in roughly circular paths.) For a sound wave, movement of air particles causes localized areas of compression or rarefaction; compression implies a higher pressure, rarefaction a lower one. As long as the amplitudes are not unreasonable, all regions of compression (and rarefaction) travel at a fixed speed, the **speed of sound**, which at 20°C is 343 m/s, or 1125 ft/sec. A

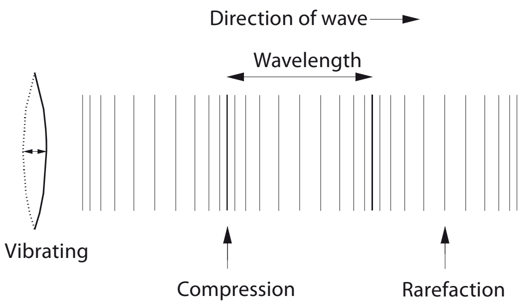

Figure 2.1 Basic sound wave showing alternate areas of compression and rarefaction

sound wave is characterized by amplitude, frequency and direction.

The **amplitude** of a sound wave is determined by the magnitude of the pressure fluctuation. But the range of pressures to which our ears can respond exceeds a ratio of one to a million and the response is not linear. A change from one to two units may be audible; a change from 100 to 101 will not be. Hence the ubiquitous **decibel**, named after Alexander Bell (1847–1922), inventor of the telephone. There are two key aspects of the decibel: it is a ratio measurement of energies or powers and it is logarithmic.

The decibel can be used in two ways: to measure differences or to measure sound (or other) amplitudes. In both cases, the choice of a logarithmic scale overcomes the problem of large numbers. The magnitude of the decibel for differences can be illustrated by some examples. A perceived doubling of loudness corresponds roughly to a change of 10 decibels, or 10 dB. Under controlled conditions, the smallest perceptible change of level is about 1 dB. Improvements in noise situations are generally only considered worthwhile if a 5 db reduction can be achieved.

In physical terms the effect of doubling the size of an orchestra is to produce a 3 db sound level increase. At the other extreme, the sound level difference across a masonry wall, such as a party wall, is typically around 50 dB.

The decibel is based on a ratio. For an absolute measurement of sound level, the ratio is taken between the measured sound pressure or intensity (sound intensity is a measure of energy) and a reference value. For sound pressure level, the reference value is 2.10^{-7} mbar (compared with atmospheric pressure of around 1000 mbar). In fact in acoustics the more usual unit for pressure is newtons per square metre, in which case 2.10^{-5} N/m^2 is the reference pressure. The reference value is chosen to be close to the quietest sound we can hear, so 0 db sound level is roughly the threshold of hearing. Conversational speech has a level of around 50 dB. A very loud sound of 120 db causes pain in the ears and would cause deafness if experienced regularly. An extreme orchestral climax can reach 100 db for a member of the audience in a concert hall. The quietest sound in an auditorium is likely to be no lower than 20 dB, but it can be higher due to ventilation noise. A logarithmic scale for sound level approximately matches the loudness characteristic of the ear.

Frequency intrudes into all aspects of acoustics. A pure tone has a single frequency associated with it. All musical instruments however produce complex sounds made up of several frequencies, though the lowest of these normally determines the **pitch**, the name given to the perceived frequency. If a surface is vibrating, the frequency of vibration is the number of cycles per second, though this is now expressed in **hertz** (**Hz**). (Hertz and cycles per second are identical.) The surface generates a sound wave at the same frequency and in a room this will be judged by the ear as the same pitch as that frequency, in spite of the superposition of many acoustic reflections by the room. The ear can perceive frequencies between 20 Hz and 20 000 Hz, though the upper limit decreases with age. The ear also perceives frequency logarithmically; however in this case no new logarithmic measure is used. The fundamental musical interval is the **octave**, which corresponds to a doubling of frequency. Acoustic measurements are also conventionally made over octave intervals, with centre frequencies of 125, 250, 500, 1000 Hz etc.

The third fundamental quantity is **wavelength**. In Figure 2.1, the wavelength is the distance between adjacent pressure maxima (or minima). There is a simple relationship between frequency, wavelength and the speed of sound, which can be derived from Figure 2.1:

$$\text{speed of sound} = \text{frequency} \times \text{wavelength}$$

The wavelength for a sound in the middle of the frequency range of 1000 Hz is thus 0.343 m (roughly 1 ft). The range of wavelength of audible sounds is between 17 m at 20 Hz and 17 mm at 20 kHz. This implies that these wavelengths are comparable to dimensions of room surfaces and common objects. At low frequencies with large wavelengths sound

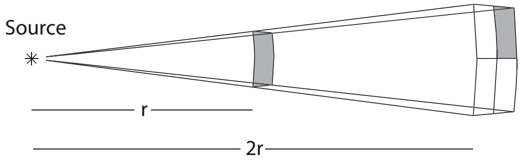

Figure 2.2 Sound spreading from a point occupies four times the area for each doubling of distance, leading to the inverse square law or 6 db decrease in level per doubling of distance

waves commonly bend round objects. But at high frequencies, objects are generally larger in dimension than wavelength and sound behaves much like light, travelling in straight lines and forming shadow zones.

Most sound sources radiate more energy in some directions than others; the human voice is typical in being directional. Violins and other stringed instruments tend to radiate most strongly at right angles to the sounding board. Yet once the sound has left the source, it behaves in the same way as it does from an omni-directional source. For every doubling of distance from the source, the area occupied by the energy increases by a factor of four (Figure 2.2). Intensity thus drops by a quarter and we get the 6 db decrease per doubling of distance characteristic, also known as spherical spreading. In rooms, not only the direct sound but also reflected sound rays behave in this way.

2.2 The nature of music and speech sounds

Both music and speech consist of brief sound events separated by silence. They both cover most of the audible frequency range, though anything above 10 000 Hz need not concern us, and for speech there is very little energy below 100 Hz. The individual sound events with speech are syllables and a typical speaking rate is five syllables per second. Music is obviously much more flexible.

Nearly all musical sounds with pitch depend on **resonance** for their generation. In a resonating musical instrument, a small amount of energy is supplied by the player which maintains oscillations at a particular frequency. The fundamental resonant frequency is determined by the length of string, tube etc.

A room can also be treated as a complex resonant system. To appreciate this, it is perhaps easiest to consider first the one-dimensional situation of a tube. If sound is produced within a tube, certain frequencies are enhanced at resonant frequencies determined by the length of the tube. If sound is produced in a room, certain frequencies are enhanced, which depend on the dimensions of the room. A room can thus be seen as a three-dimensional counterpart of a tube. However for rooms of the size of auditoria, this does not prove to be a particularly productive approach. The number of resonant frequencies in a room is so high (with many per hertz at frequencies above 100 Hz) that the phenomena which we normally associate with resonance are not observed. The word 'resonant' is also often used for rooms which are highly reverberant, in which sound decays only slowly. Though this use of the word is logical, it can be confusing and will therefore be avoided here. Resonance itself does not intrude much in room acoustics, except for certain frequency-specific absorbers (section 2.6.3).

The sound character or timbre of different musical instruments is related to their frequency spectrum. For a continuous sound the spectrum consists of a series of discrete frequencies (Figure 2.3). The lowest frequency, 415 Hz in the figure, is known as the **fundamental** or first **harmonic**. The higher frequencies are simple multiples of the fundamental frequency and are known as the second, third harmonic etc. Our ears interpret the mixture of frequencies in terms of its pitch, given by the fundamental frequency, while the relative strength of the harmonics characterizes the sound quality or timbre of the instrument. In the clarinet spectrum, the odd-numbered harmonics tend to be stronger than the even-numbered ones.

In the case of some instruments, such as the French horn, the relative strength of the harmonics varies in such a way that the frequency region of the **loudest** harmonic is roughly constant. This

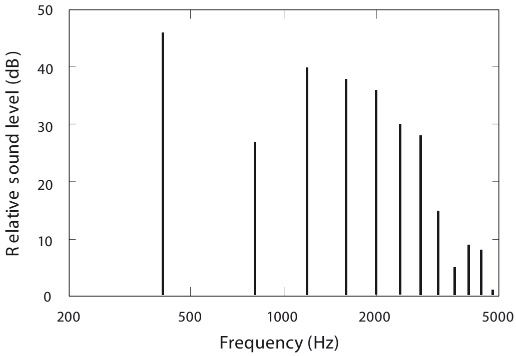

Figure 2.3 Spectrum of the clarinet in its middle range, fundamental frequency 415 Hz (after Meyer, 1978)

implies for instance that, when the horn is played in its lower register, the fundamental is weaker than higher harmonics (Figure 2.4). Maxima in the spectrum which do not change with fundamental frequency are known as **formants**, around 310 Hz in the case of Figure 2.4. The formant nature of an instrument further characterizes its sound. The human voice is unique in its scope for varying the formant frequency and uses this to produce the different vowel sounds.

Much more can be said about musical instrument sound, such as attack characteristics, the change of quality with dynamics etc. The interested reader is referred to Meyer (1978) and Olson (1967).

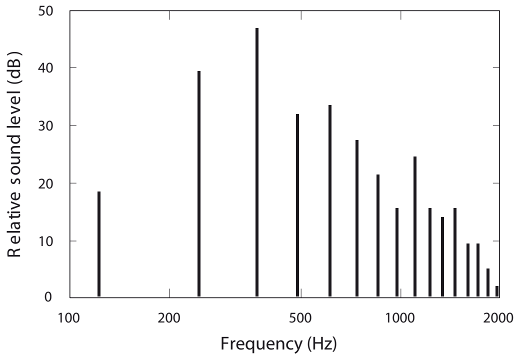

Figure 2.4 French horn spectrum in the lower register, fundamental frequency 123 Hz (after Meyer, 1978)

In fact as long as the appropriate frequency range is preserved in an auditorium, the detail of the sound character in frequency terms generally has little influence on room acoustic design. The harmonic structure of musical notes does explain however why the frequency range of interest extends much higher than the pitch range of musical instruments (Figure 2.5). The highest fundamental of the piccolo is 4186 Hz, yet a sound reproduction system which stopped at 5 kHz would be very low fidelity.

Sound sources are also characterized by their power. Sound generation is usually a very inefficient process; loudspeakers for instance are normally less than 2 per cent efficient. A symphony orchestra when playing *fortissimo* only generates about 2.5 watts of **acoustic power**, while the human voice is typically 25 μW. Both speech and music rely on contrasts of soft and loud, with the **dynamic range** in classical music of over 70 dB. The ability to hear a *pianissimo* can be as vital to the excitement of a live performance as a *fortissimo* climax.

The aspect of speech and music which substantially influences room acoustics is the temporal one. Speech sounds and musical notes can be represented diagrammatically as in Figure 2.6, which uses

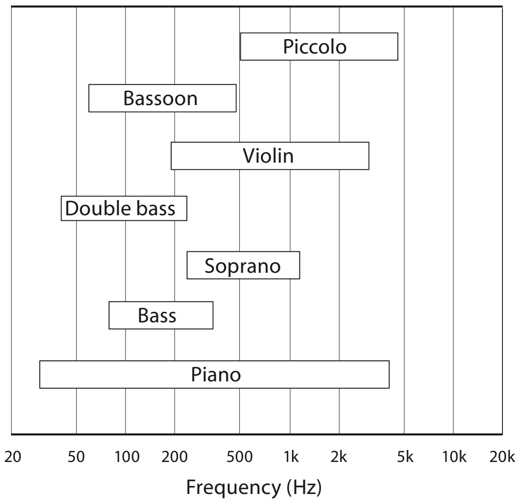

Figure 2.5 Frequency ranges of the fundamentals of musical instruments and voices

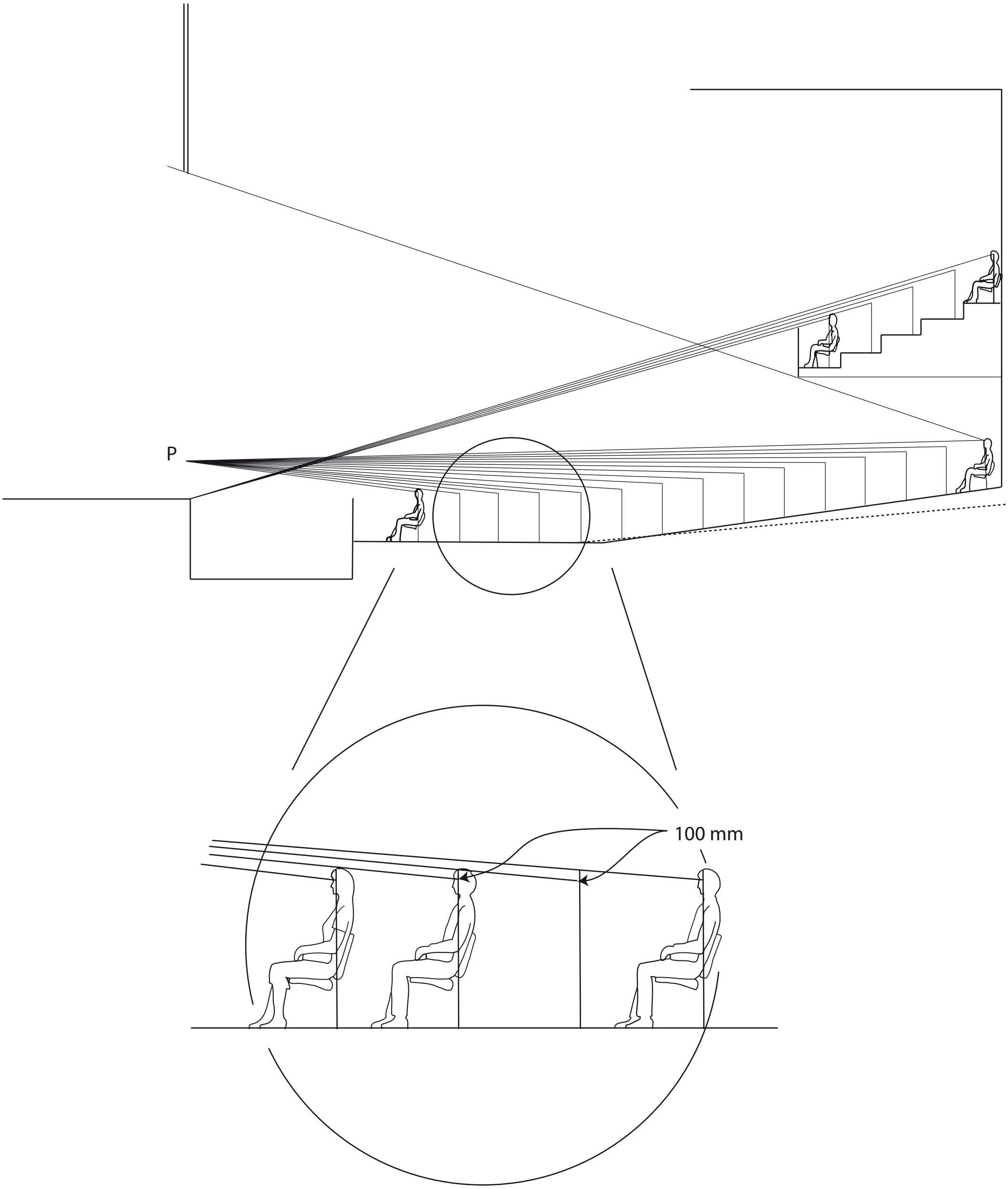

Figure 2.7 Sightline design. P is the setting-out point for the Stalls seating.

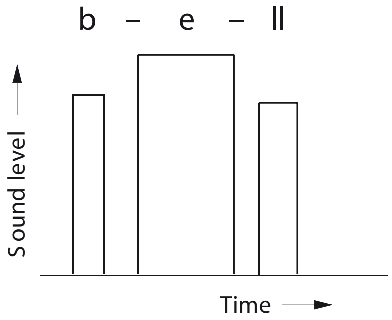

Figure 2.6 The temporal character of speech and music, illustrated with the word 'bell'

the example of a word. Individual speech sounds (or musical notes) have particular amplitudes and durations. Vowels, for instance, tend to be longer and louder than consonants. The relative strengths and durations of concurrent speech sounds or notes are of crucial importance for room acoustics. They determine for instance the degree to which sound reflections can be tolerated without intelligibility or clarity being undermined. Such questions will be further considered below.

2.3 Sound propagation

For a source of sound outside, acoustic energy spreads into free space and since the surface area of a sphere is related to the square of the radius, we get inverse square law propagation. For every doubling of distance the sound level decreases 6 dB. When sound travels long distances outside, it is also influenced by wind and temperature effects. But even at the scale of the Greek classical theatres with typical distances of 50 m, there is no obvious evidence that environmental effects significantly influence the acoustics (except that wind increases the background noise).

In an enclosed space, the **direct sound** of course decreases in level in the same way as outside. The major concern for the direct sound in auditoria is that it is not affected by other audience members. This requirement is generally satisfied if there are adequate sightlines to the stage. The principles of sightline design are simply stated. Since our eyes are below the top of our heads by on average 100 mm, floors should be raked to allow the sightline to pass over the heads of audience in the row in front (Figure 2.7). The setting-out point on the stage, P, influences the result; for stalls seating P is normally taken as 0.6–0.9 m above the stage front and for balconies the stage front itself is often used (Ham, 1987). The sightline criterion generates a curved floor rake, but this is normally approximated by a series of linear rakes. The maximum permissible rake in balconies is normally contained in legislation; 35° is a common limit. Sightline design becomes complicated in three dimensions; indeed optimal results are achieved with non-horizontal seat rows.

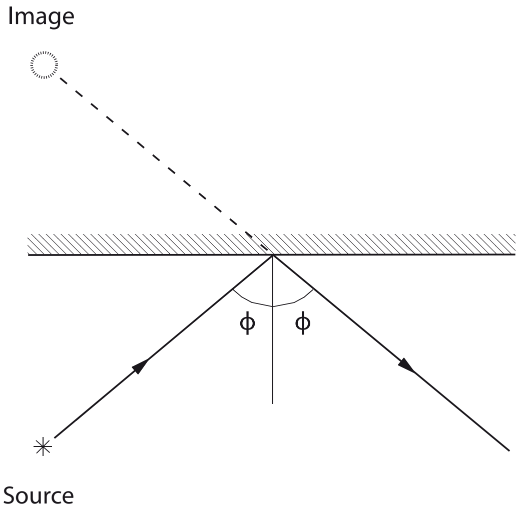

Figure 2.8 The geometry of reflection. The reflected sound behaves as if it had originated at the image point of the source. Angles, ϕ, between the normal to the wall and the incident or reflected sound are the same

Most of the sound energy we receive in enclosed spaces has been reflected off wall and ceiling surfaces. The geometries of **reflection** for light and sound are identical (Figure 2.8). The reflected wave behaves as if it had originated from the image position. But while a small mirror will reflect light, for sound much larger surfaces are required owing to the much longer wavelengths involved. An acoustic mirror is a large, plane, massive surface of, for instance, concrete or plastered masonry. Sound reflected by one surface will continue to be reflected between the room surfaces, until its energy is removed by absorption. Figure 2.9 shows successive image positions for sound reflecting between two surfaces. Moving from the simple to a whole room: if we consider the situation in a large concert hall at the moment one second after a sound source has been switched off, our ears are listening to sound which has been reflected by roughly 20 successive surfaces.

Pure, or specular, reflection is one of four possible consequences when sound hits an obstacle.

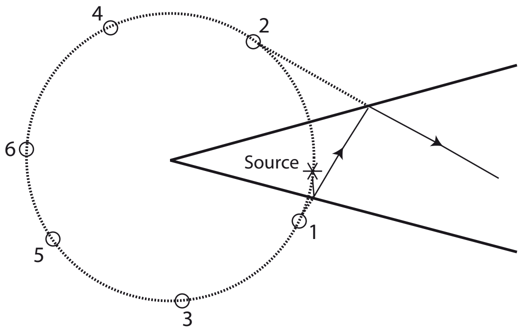

Figure 2.9 Reflection between two planes. Numbered image positions are for reflections that are initially off the lower plane. They all lie on a circle centred on the intersection point of the planes

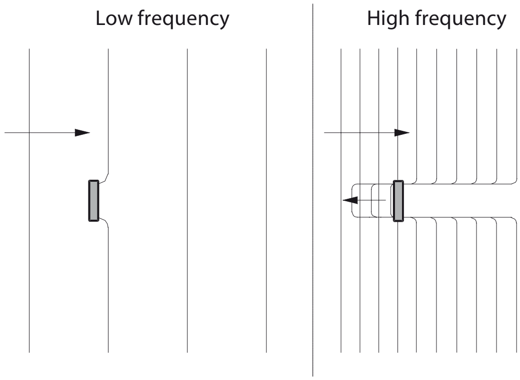

Figure 2.10 Wavefront diagrams of sound waves hitting an obstacle. Diffraction occurs at low frequencies where the obstacle is small relative to the wavelength

For a finite-size reflector, behaviour at low and high frequencies will be different. If the reflector is suspended, high-frequency sound is reflected like light, creating a shadow zone beyond the obstacle (Figure 2.10). But at low frequencies where the wavelength of sound is large compared with the size of the obstacle, bending or **diffraction** will take place and the wavefronts recombine as if the obstacle had not been there. At intermediate frequencies the behaviour becomes mathematically complicated. Bending, or diffraction, of sound waves is thus normally a low-frequency phenomenon.

A white matt surface, like a sheet of paper, is reflective to light but scatters it in all directions. For a surface to be acoustically **scattering** requires an irregularly profiled surface with projections of a depth between 0.3 and 0.6 m. Again the gross nature of projections required is due to the wavelengths of audible sound. A lightly profiled surface will only scatter sound at high frequencies. The word 'diffusing' is often used as an alternative to 'scattering', however a diffusing surface is easily confused with the concept of a diffuse sound field. Scattering surfaces can contribute to a diffuse sound field, but the interplay is complex. Scattering surfaces for sound are an important aspect of auditorium design.

Reflection, diffraction and scattering are all possible without energy loss. In practice, some **absorption** of sound energy occurs for reflection from all surfaces, while some materials are highly absorbent. The most common absorption mechanism is porous absorption; sound energy is dissipated in a porous material owing to the friction involved in movement of air particles in the pores. Typical porous absorbers are fabrics, curtains and carpets; the most efficient materials are mineral wool, fibreglass and acoustic open-cell foam. In auditoria the major absorbing surfaces are the clothed audience and performers, who at mid-frequencies absorb about 90 per cent of incident energy. It is normal practice in large auditoria to keep the amount of additional absorbent material to a minimum. Table 2.1 compares sound and light behaviour at surfaces.

Table 2.1 Surfaces for reflection and absorption with light and sound

	Reflection	*Scattered reflection*	*Absorption*
Light	Mirror	Matt white surface	Matt black surface
Sound	Hard massive smooth surface	Massive surface with projections of 0.3–0.6 m	Thick porous material

2.4 Sound in rooms

Much that is known to be important in auditorium acoustics can be discussed in terms of the acoustic response at a listener's position to a short sound produced on stage. The response to a longer musical note can be calculated from the response to a short impulse. As a listener, the first thing one hears is the **direct sound**, which travels in a straight line from the source (Figure 2.11). This is followed by a series of **early reflections** from the side walls, ceiling etc. Reflected sound has to travel further, so will arrive later; it will not be as loud as the direct component (unless some focusing of the reflection occurs). This response can be represented as a diagram of sound level against time (Figure 2.11). Such a figure is known as an **impulse response** or 'echogram', though this latter name is somewhat anomalous. The word **echo** is used for a reflection which is heard as a discrete event, such as can be heard outside when shouting some way from a large wall. An echo is an intelligible repetition and is not to be confused with reverberation, which is unintelligible. Most reflections in rooms are not heard as echoes.

The listener thus hears the direct sound followed by a series of early reflections whose paths can normally be precisely defined. Sound that is not absorbed continues to be reflected (Figure 2.12), and one sees on the impulse response that after the early reflections the number of reflections arriving

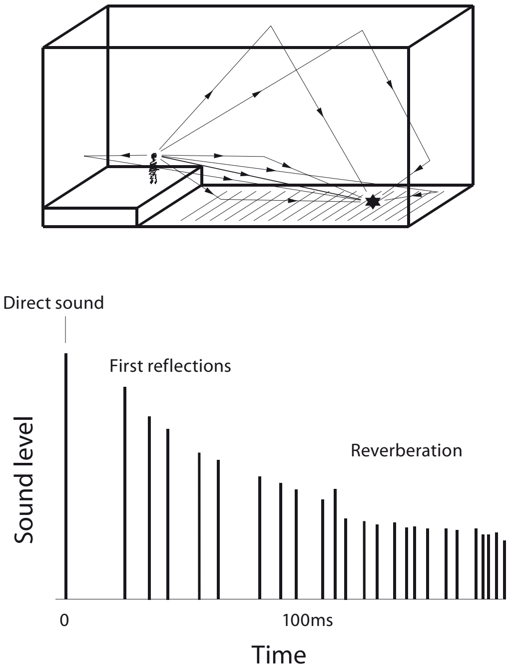

Figure 2.11 Sound rays in rooms. (a) The direct and first reflection paths; (b) sound level against time for a short sound as received by the listener

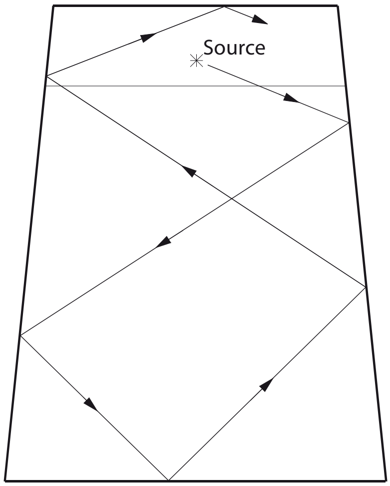

Figure 2.12 Multiple reflection within a room

within say each hundredth of a second (= 10 ms) progressively increases. In large halls, the number of reflections arriving at times later than one-tenth of a second after the direct sound (= 100 ms) is so high that individual reflections are no longer distinguishable. (The 100 ms time limit is shorter in smaller halls.) The late sound after about 100 ms is called the **reverberant sound**. It usually decays in a linear manner when plotted in decibels; its duration is described by the **reverberation time** (section 2.8). Reverberation is particularly obvious in large church or cathedral spaces.

The received sound can thus be divided into three components: the direct sound, early reflections and late reverberant sound. Design features of an auditorium often influence only one rather than all these components. There are several aspects of the impulse response which the ear perceives. The reverberation time is one of them. The reason for its importance is illustrated in Figure 2.13. The temporal nature of speech and music has been described in terms of elements with different amplitudes and durations (Figure 2.6). Figure 2.13 shows the instantaneous sound level in a room for such types of sound. When presented as a sound level in decibels, the build-up time is short, while the decay time is much longer. Reverberation thus provides the background of the decay of previous syllables or notes against which the new speech sounds or musical notes are heard. If the reverberation time is too long (Figure 2.13(b)), then one sound can be rendered inaudible (i.e. masked) by an earlier louder sound. But with too short a reverberation time, the sound quality becomes too stark, like listening in the open air. There is thus an optimum reverberation time mainly determined by programme, such as roughly 2 seconds for symphonic music and 1 second for speech.

But the subjective judgement of acoustics depends on much more than just reverberation time. For speech, the important concern is the proportion of energy in the impulse response which arrives early as a fraction of the whole. For speech to be intelligible requires this proportion to be high; in design terms strong early reflections may be needed. The comparable concern for music is clarity or definition. Also important for music is the sound level for the listener. Clearly this level depends on the orchestra and the music, but the received sound level for the listener is also influenced by the auditorium design and size. These various quantities, relating to intelligibility, clarity and sound level, can all be derived from the impulse response.

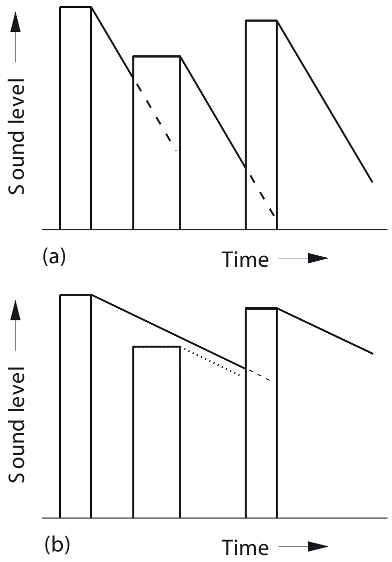

Figure 2.13 Instantaneous sound level with speech or music in a reverberant space. (a) Short reverberation time giving good clarity; (b) long reverberation time producing masking

Unfortunately the impulse response **as such** cannot easily be interpreted as it stands. It can indicate the presence of an audible echo, but a visual inspection is not reliable for assessment of the amount of early reflections, for instance. Figure 2.14 shows two measured impulse responses in a hall at different distances from the source. At a position close to the source the direct sound dominates, the early reflections are well delayed and are weak relative to the direct sound. At remote locations, the first reflections arrive early and are almost as loud as the direct sound. Figure 2.15 shows the reason for this behaviour; it arises because the

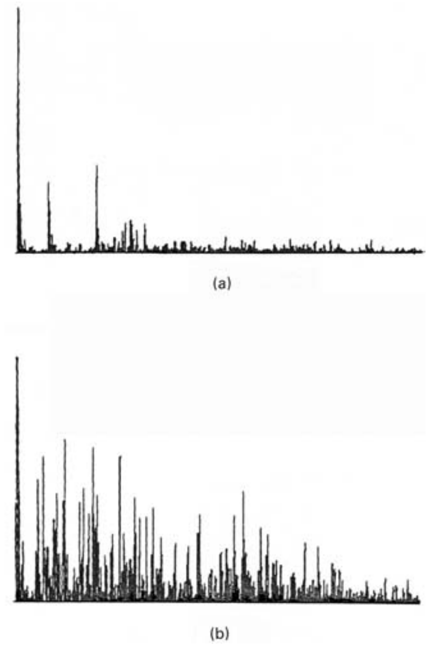

Figure 2.14 Measured (pressure squared) impulse responses in the Royal Festival Hall, London, measured at (a) 18 m and (b) 35 m from the source. Total duration is 200 ms

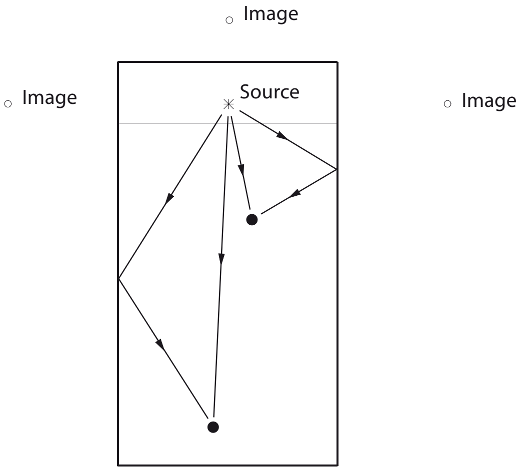

Figure 2.15 Reflections in an auditorium. Images of the source are fixed. The level of reflections relative to the direct sound is lower close to the source because of the large ratio of path distances. Delays, given by path-length differences, are also longer when closer to the source

image positions of reflections are fixed. Since the difference between the reflection path lengths and the direct path length is smaller for a more distant receiver, the delays and level differences of reflections are smaller for a distant receiver than for a receiver close to the source. In general, our ears are not as sensitive to distance as the impulse response plots would suggest.

2.5 Reflections and the ear

In a large concert hall a listener receives about 8000 reflections of a short sound within one second of the direct sound. Each reflection has a delay, a sound level and a direction associated with it. Clearly the ear is highly selective in interpreting this wealth of information. After many years of research and experience, the nature of the selection performed by the ear is becoming clearer.

As a warning sensor the ear needs to establish the direction of the sound source. To do this it is able to isolate the direct sound and localize on the first wavefront received. The localization ability of the ear is such that it can function when the direct sound is substantially weaker than the combined energy of later reflections. Because the wavelengths of sound encompass the dimensions of the head, different localization mechanisms operate at different frequencies. For localization from side to side the lateral position of the ears is used; at low frequencies time differences are predominantly used while at high frequencies sound level differences are exploited. But these mechanisms are useless for vertical localization, since in that case the sound signals at the two ears are virtually identical. For vertical localization, it appears that the ears use the frequency distortion provided by the outer ear, the pinna (Blauert, 1983).

For communication of speech (though the same mechanism also applies to clarity in music), the direct sound on its own has the disadvantage that it decreases substantially in level as one moves away from the source. However for the purposes of intelligibility and clarity, the ear is able to combine the **energy** of the early reflections with that of the direct sound. (Direct sound plus an equally loud early reflection is equivalent to a 3 db increase in the direct sound.) There is a certain time limit involved for a reflection to be 'early' which depends both on the processing performed by the ear and on the programme. A common value used for the limit within which reflections contribute to speech intelligibility is 50 ms, while 80 ms is usually applied for clarity in music. From the point of view of intelligibility alone, later reflections are detrimental but they are valuable and indeed necessary to create for the listener a sense of room sound.

The significance of the ability of the ear to sum energy of early reflections can be illustrated. In a large concert hall the direct sound level decreases by 12 db between 10 and 40 m from the source, while the early energy within 80 ms typically falls only 5 db (Figure 3.29). Hence the importance, particularly in large auditoria, of considering the early reflection distribution at all seating areas. The manifold ways in which the ear processes sound is a fascinating subject (see for instance Tobias, 1972). Much remains to be discovered.

It is worth comparing the aural and visual response to reflections. If we consider a visual reflection such as when a house is seen from across a lake on a still day, the house's reflection is seen as separate from the house itself and in a different vertical direction. The acoustic analogy for this is probably an echo that is heard as a discrete repetition of the original. However an echo is a special case of a sound reflection. The vast majority of sound reflections merge into the total sound experience. The original sound direction remains clear, but as discussed above, early reflections can add to clarity and intelligibility for speech. Later reflections create an audible background. Reflections also contribute towards the spatial character of the sound experience.

2.6 Sound propagation in detail

2.6.1 Direct sound

While sound propagation from the stage to the front row of a balcony is uninterrupted, for the majority of the audience in an auditorium the direct sound has had to travel at **grazing incidence** over a highly absorbent surface: the audience seated in front of the listener. Comments are frequently found in the literature that direct sound is absorbed by this grazing incidence. The situation at mid-frequencies and low frequencies has to be treated separately.

At mid-frequencies, there is no doubt that grazing incidence absorption can occur. But the problem of making elaborate experiments with seated audiences has so far prevented the question from being fully resolved. Measurements in unoccupied seating indicate little attenuation effect at mid-frequencies, Figure 2.16 (Schultz and Watters, 1964). With seated audiences the general rule has already been mentioned: good sightlines should provide good direct sound propagation. It does appear though that steeper seating rakes are acoustically preferable beyond the point of providing adequate vision (Cremer and Müller, 1982, Ch. 1.6). Sceptics on this point may comment that some

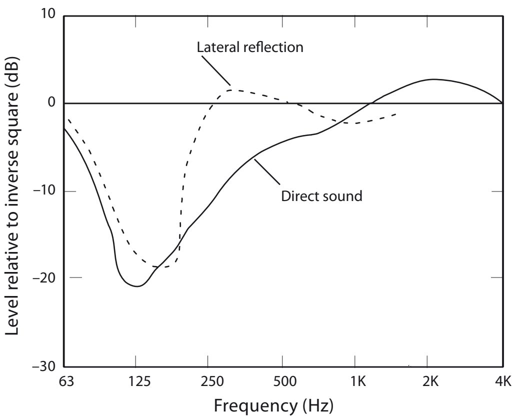

Figure 2.16 Measured propagation over theatre seats in excess of inverse square law behaviour (after Schultz and Watters, 1964)

of the world's most renowned concert halls have flat floors and poor sightlines! Yet within these halls, few would disagree that the best seats do have a good view of the whole orchestra. Unfortunately designing with steep seating rakes tends to restrict the number of seats which can be accommodated.

The situation at low frequencies is better documented. Severe low frequency attenuation was only discovered in 1962, when complaints of poor bass sound were investigated in the New York Philharmonic Hall (section 4.8). The discovery of grazing incidence attenuation, or **seat-dip effect** as is it frequently called, occurred because by chance the reflection from the suspended ceiling in Philharmonic Hall also lacked low frequencies. The grazing incidence effect occurs in all auditoria, but it had gone unnoticed. This is particularly surprising since one would expect the sound quality at a seat in the front row of a balcony (where the attenuation effect does not occur) to be markedly different from that at a seat directly below. That this is not distinctly obvious appears to be due to the fact that many reflections arrive from paths remote from the seating plane, which are thus not affected. Since the ear appears to be relatively insensitive to the arrival times of low frequency sound, later bass sound can compensate for a deficiency in the direct sound.

Figure 2.16 illustrates the extra attenuation due to grazing incidence propagation over audience seats. There is a sharp dip around 150–250 Hz of about 15 dB, as well as a broader-band attenuation up to about 800 Hz. These attenuations are established after sound has passed over only a few rows of seating, but thereafter they are virtually independent of the number of rows covered. The acoustic mechanisms involved seem to be a vertical resonance between the seat rows for the 15 dB dip, and effects due to propagation over an absorbent surface for the broader band effect. Two strategies appear to reduce the attenuation effect: using a steep seating rake such that the angle of arrival of the direct sound is greater than 15° to the seating plane (Bradley, 1991), or by placing the seating over a pit or well of about 1 m depth, with a wire mesh floor covered with light carpet (Davies and Cox, 2000); it appears that this last scheme has yet to be tried in an actual hall.

But the fact that low-frequency grazing attenuation was discovered so late indicates that in most halls it is of little subjective significance. This depends on the presence of enough reflections on paths remote from audience seating, a condition certainly fulfilled in the classical rectangular halls. The relative loudness of the bass can with advantage be enhanced by an extended low-frequency reverberation time (Barron, 1995, and section 2.8.1).

There is a further high-frequency effect on sound intensity which is only significant when sound has travelled many times round an auditorium. Absorption of energy as sound travels through the air is a high-frequency effect which causes the reverberation time at 2 kHz and above to be reduced (section 2.8.5). The major absorption effect is caused by the simultaneous presence of oxygen and water vapour in the air. Air absorption is thus unavoidable. The amount of absorption does in fact increase at low humidity levels, so that in dry, desert-type climates it is appropriate to humidify the air for acoustic, as well as comfort reasons.

2.6.2 Reflection from finite surfaces

Reflection from a finite surface depends on the relationship between the size of the reflector and the wavelength of sound. Perfect reflection occurs at high frequencies, whereas when the frequency is lowered, less and less energy is reflected along the geometrical reflection path. The distance of the reflector from the source and receiver also proves to be significant. The mathematical relationship governing this behaviour is given in Appendix A section A.1.1, and is particularly relevant to the design of suspended reflectors in auditoria. For reflection from elements of the hall envelope the situation is more complicated, particularly at low frequencies. A series of surfaces adjacent but modestly inclined relative to each other will often behave at low frequencies as a single curved surface.

A convex surface will disperse sound (Figure 2.17); it is thus a thoroughly safe feature in an

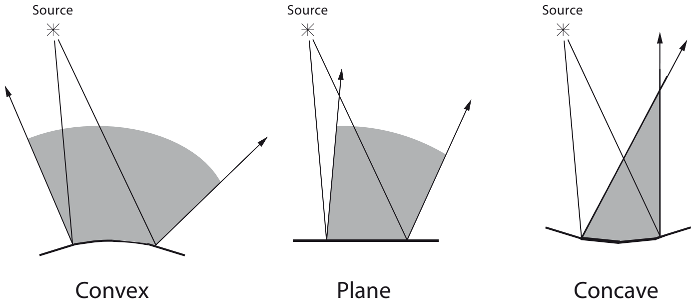

Figure 2.17 Reflection off convex, plane and concave surfaces

auditorium and is valuable in situations where reflection from a plane surface might produce undesirable effects. By contrast, concave surfaces are particularly dangerous because they focus sound. They were a common feature of nineteenth-century concert halls and theatres and indeed the concave domes so common in theatres and opera houses of the period often constitute their major acoustic fault. If the focal point of a concave surface is anywhere near audience or performers, the reflection is likely to be heard as an echo (Cremer and Müller, 1982, Ch. 1.3). Highly curved concave surfaces remote from audience do however act as dispersers of sound (Figure 2.18). The rule for acceptable reflection from a concave surface is simple: if neither the source nor receiver are within the extended circle of the concave surface, then the reflection will be weaker than from a plane surface.

Concave surfaces which focus on or near the audience are now taboo for auditoria. Remedial treatment is difficult. Sound absorbing or scattering treatments are common solutions but the level of sound reflected off a concave surface can still be too high even when absorbent material is applied to the surface. Providing a cure for focusing by a dome is demanding; an interesting solution with suspended panels was used by Reichardt *et al*. (1968) for the 'Haus des Lehrers' in former East Berlin. A quantitative method for calculating reflection levels from curved surfaces is included in Appendix A, section A.1.2.

2.6.3 Acoustic absorption

Acoustic absorption removes acoustic energy. There are three possible mechanisms: porous absorption, panel absorption and Helmholtz resonance. Porous absorption, as already mentioned, occurs with any porous material. In auditoria the major absorbent surface is the audience, whose clothes act as efficient porous absorbers. Absorption is measured by the **absorption coefficient** (α), which is simply the

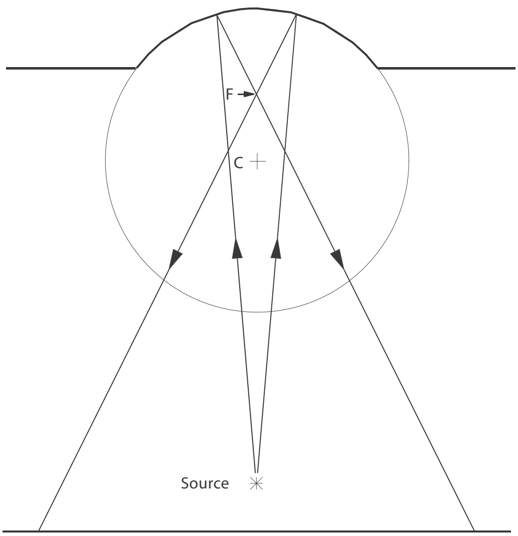

Figure 2.18 Focusing off a remote concave surface. F is the focus point and C is the centre of the circular dome. The situation is safe if the source and receiver are outside the extended circle of the concave surface (after Cremer and Müller, 1982)

fraction of incident energy absorbed. The frequency characteristic for porous absorbers is shown in Figure 2.19. The 'S-shape' characteristic is also found for audience absorption. Porous absorbers are thus efficient at high but not low frequencies. The low-frequency range can be extended by making the material thicker, but this becomes impracticable when absorption over the whole of the important frequency range is required. A much more economical solution is to position the porous material over an air-space; this is almost as effective as continuous porous material of the same total depth. Porous material over an air-space has more application in suspended ceilings for offices than for auditoria.

Any thin panel will absorb some energy in the low frequencies; vibration of the panel converts acoustic energy into heat. A simple tap with the knuckle reveals whether one is dealing with a panel or a solid wall, say, of masonry. Figure 2.20 shows the construction of a purpose-built panel absorber;

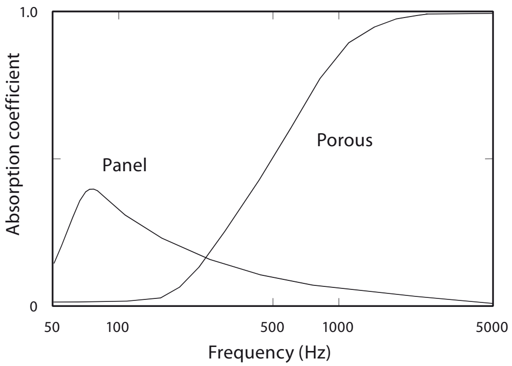

Figure 2.19 Absorption coefficients of porous and panel absorbers as a function of frequency. Making the porous material thicker shifts its characteristic towards low frequencies

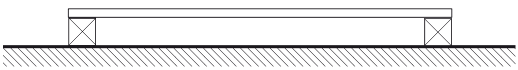

Figure 2.20 Construction of a panel absorber, with a plywood panel mounted on battens. Porous absorbent material is sometimes placed in the cavity

there is a frequency of maximum absorption which can be varied by selection of the panel mass and the depth of the airspace. Traditionally it was thought that 'wood was good' (section 4.3), that a timber finish resonated to enhance musical tone (as it does with a violin); the reality is the opposite, panelling absorbs acoustic energy. The absorption characteristic is included in Figure 2.19. Panel absorbers can complement porous absorbers to give absorption over the whole frequency range, though the maximum absorption coefficient of panel absorbers is not great. Panel absorption strongly influences the low-frequency reverberation time, as discussed further below.

In spite of its grand name, a Helmholtz resonator is familiar to all in the form of an empty wine bottle. When one blows across the top of the bottle, a clear note is produced. If a small amount of porous material is placed in the neck of the bottle, it no longer acts as a resonator aiding sound generation but as a tuned acoustic absorber, highly efficient at absorbing at the resonant frequency but absorbing little at other frequencies. A Helmholtz resonator thus requires a neck region coupled to an enclosed volume. These resonators have been little used in auditoria because of the complications of design, but the Queen Elizabeth Hall, London, is an exception (section 6.5). Further details on acoustic absorption are found in many acoustic texts.

2.6.4 Scattering

A textured surface will provide some scattering of sound, but the degree of texturing must be high for efficient scattering. The general principle is that the deeper the scattering treatment, the lower the frequency down to which the surface will scatter sound. Depths for projections of between 0.3 and 0.6 m are necessary to cover the majority of the audible frequency range. Substantial surface modelling is to be found in concert halls from the nineteenth century in line with the architectural style of the time. Most of the halls from this period are famous for their acoustics. The high degree of profiling of the walls and ceilings render these

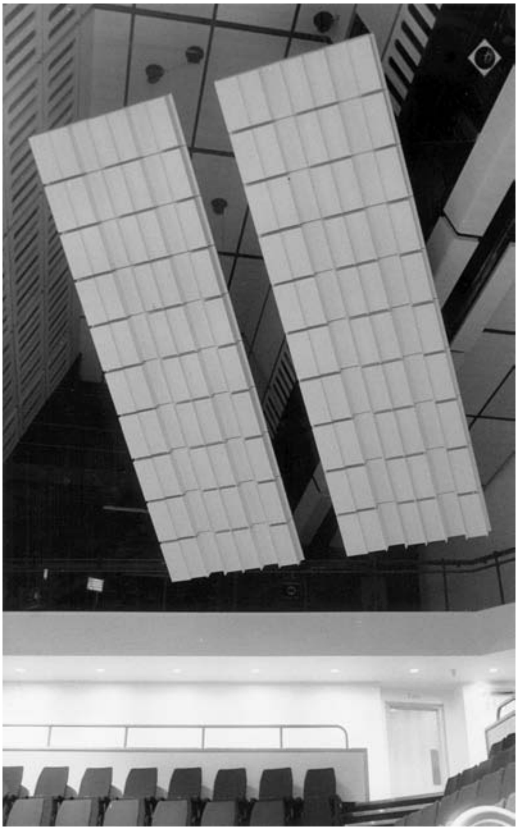

Figure 2.21 A pair of suspended quadratic residue reflectors in the Glasgow Royal Concert Hall, Scotland

surfaces acoustically scattering. The debate about how important this surface treatment is for acoustic quality has been running for at least half a century and still remains far from resolved. It is only recently that progress has been made towards quantifying the scattering offered by particular profiles. Regular profiles must however be avoided as they are frequency selective in their scattering characteristics.

A major development was made by Schroeder (1979) who proposed a group of diffusers whose reflection properties can be calculated in advance. These Schroeder diffusers consist of equal-width slots or wells with depths according to mathematical number theory sequences. The best known is the Quadratic Residue Diffuser (QRD), Figure 2.21, whose profile is based on a prime number. The use of QRD's in concert halls was pioneered by Marshall in Wellington, New Zealand (section 4.10). Both in that hall and in Figure 2.21 the sequence was based on the prime number 7. Quadratic residue diffusers and other types of Schroeder diffusers have also been used in stage enclosures and opera house pits (D'Antonio and Cox, 2000). Some further details about these diffusers are contained in Appendix A.2.

Computer models for prediction of the acoustic behaviour of enclosures require that the reflection behaviour of wall and other surfaces be defined. Early computer models assumed specular (i.e. mirror-like) reflection at all surfaces but this ignored the fact that many room surfaces scatter sound. Most current computer models now include a parameter to account for scattering: the scattering coefficient, *d*. Surfaces which are moderately scattering (Figure 2.22) tend to reflect with a proportion of reflected energy along the direction of the specular reflection with the remaining energy scattered, often fairly randomly. The scattering coefficient is simply the proportion of reflected sound that is scattered as a fraction of the total reflected energy. Wall and other surfaces are specified for the computer model in terms of both their absorption and scattering coefficients.

Progress has been made to enable scattering coefficients to be measured in the laboratory (Vorländer and Mommertz, 2000; Hargreaves *et al.*, 2000). Audience seating is highly scattering, while most finite-size surfaces are only slightly scattering.

Another recent development is the ability to predict reflection behaviour by surfaces (using boundary element methods). Out of this technique have come 'wavy' surfaces optimized for

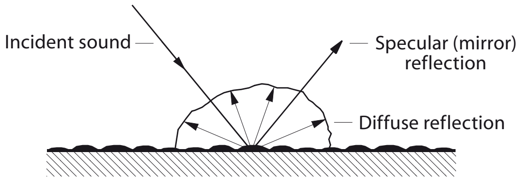

Figure 2.22 Partially scattered reflection from a textured surface showing specular and scattered components

Figure 2.23 A scattering wall in a rehearsal hall with circular geometry in plan. The shape of the wall is based on a wave motif optimized for diffusion using boundary element techniques. (Architects: Patel Taylor; acousticians: Arup Acoustics; diffuser design and installation: RPG.)

their directional reflection characteristics (Cox and D'Antonio, 2004). An impressive use of this technology is for surfaces designed to suppress focusing caused by concave walls, Figure 2.23 (Orlowski, 2000).

2.7 Acoustic defects

2.7.1 Echoes

While many acoustic defects are a matter of degree, such as too much reverberation or inadequate loudness, certain phenomena are always disagreeable. Echoes can certainly be obvious and pernicious. An echo is a reflection which is heard as a discrete event. The most famous example in Great Britain was the echo in the Royal Albert Hall, London. The glass dome was, as the longest free span yet built, the pride of British engineering when it opened in 1871. But acoustically it was a classic case of a surface which acted as a huge concave acoustic mirror. Sound originating from the stage was focused close to audience seating. With a delay of around 1/6 second and with the intensity of the echo in some seating locations actually exceeding that of the direct sound, this constituted an echo on the grand scale, sufficient to make a mockery of all performers' efforts. An account of the efforts to suppress this echo is given in section 5.1.

For a reflection to be heard as an echo it must arrive at least 50 ms later than the direct sound. The reflection also has to be more prominent than its neighbours (Figure 2.24). In all rooms there are numerous reflections arriving at more than 50 ms after the direct sound. To be perceived as an echo requires either reflection from a large surface by

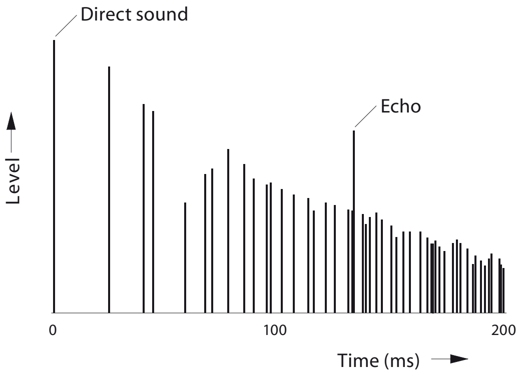

Figure 2.24 Impulse response with an echo

a path simpler than other reflections of the same delay, or reflection involving focusing. In the first category, reflection off the back wall or back wall and adjacent soffit is a frequent cause of echoes on stage, though obviously these are only heard as echoes in large rooms. Focused echoes are a common problem in halls with domes or barrel-vaulted ceilings, or in fan-shaped plans with curved rear walls. Focusing of reflections by curved surfaces is discussed in section 2.6.2 above.

The matter of predicting whether reflections will be audible as echoes is not trivial (Cremer and Müller, 1982, Ch. II.7; Dietsch and Kraak, 1986). The refined localization abilities of the ear can be tuned into detecting echoes. Whereas at first one might not hear an echo, once the echo is detected one may be unable to ignore it. Subjective assessment of impulse responses produced by models can be a useful aid to detect possible echo paths for new auditoria.

Curing echoes in completed buildings can be difficult. Either absorptive or scattering treatment of a reflecting surface can be used or the surface can be remodelled to direct the reflection away from performers and audience. In most auditoria, large areas of acoustic absorbent should be avoided as they lead to a quieter sound and 'holes' in the directional sound distribution. Substantial focusing would require substantial scattering treatment, which may be visually intrusive. To quell an echo from the back wall, inclining the wall upwards or downwards to redirect the reflection is worth considering (Figure 2.25). Scattering treatment may be equally suitable, if sufficiently effective. Nowadays echoes should always be avoided rather than cured at a later date.

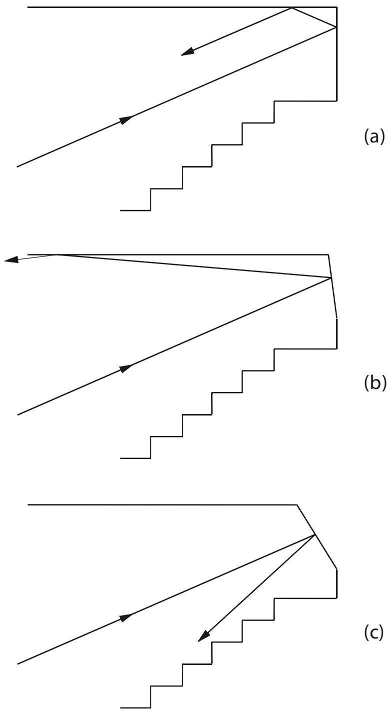

Figure 2.25 Echo off the rear wall and ceiling in an auditorium. (a) A vertical wall and horizontal ceiling return a reflection back towards the source; (b) slight inclination of the rear wall often renders the reflection harmless; (c) major inclination of the wall reflects onto nearby absorbent audience

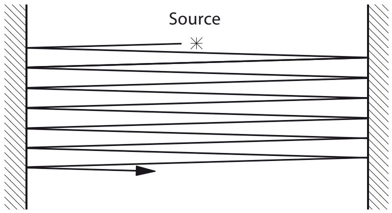

Figure 2.26 Flutter echo between parallel walls

2.7.2 Flutter echoes

While echoes involve large delays and long path lengths, flutter echoes normally involve short path lengths but iterated many times. A common flutter echo situation occurs between two parallel walls (Figure 2.26). The repeated reflections create a characteristic 'twang', which is obvious to anyone who has heard it by clapping their hands in corridors or rooms with flat parallel walls. More complicated repetitive paths are possible but rare.

In auditoria, the obvious concern is that musicians should not be between two parallel surfaces. But even with parallel stage walls, flutter echoes are only likely to be heard when just a few musicians are present. A flutter echo is one of the few acoustic problems which is relatively easy to correct. Reorientation of one of the parallel surfaces by only 5° is adequate to cure it, as is modest application of absorbent or scattering treatment.

2.7.3 Background noise

Auditoria present the engineer with some of the quietest spaces to service. On urban sites, noise intrusion from the exterior also needs to be considered. Traffic noise, railway noise or aircraft noise can necessitate substantial expenditure to achieve inaudibility inside the auditorium. A typical approach is to place the 'box' of the auditorium within the box provided by the shell of the building; the intervening spaces are readily used for foyers (Figure 2.27). Methods for limiting noise ingress are no different in approach than for other building types. There are many books which cover the standard techniques. Vibration from underground trains in particular can also produce problems; the solution in severe cases can be to mount the whole auditorium on resilient pads. This vibration isolation has been used for the recent concert halls in Glasgow, Birmingham and Manchester.

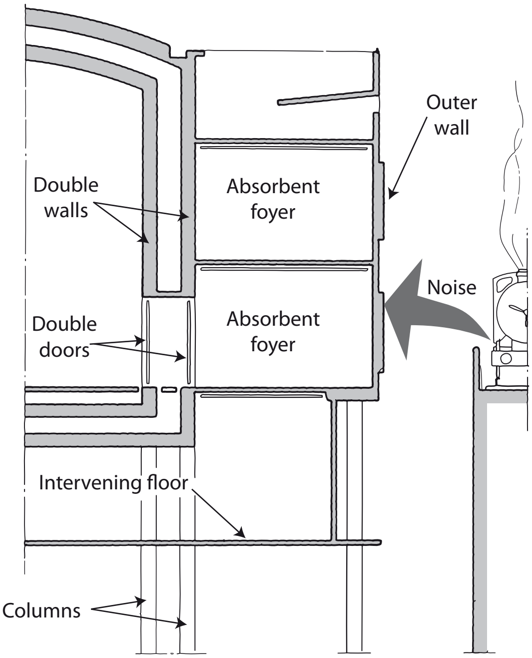

Figure 2.27 Section through the Royal Festival Hall, London, showing sound insulation measures

The main contributor to background noise is usually the ventilation system. Ventilation systems generate noise due to fan noise and noise generated by the air-flow itself. Controlling the noise involves substantial attenuation between air-handling units and the auditorium, as well as low air outlet velocities.

Several criteria are available for background noise, which are based on individual octave band sound levels. The most common European criterion is the NR (Noise Rating) but there is also the American NC (Noise Criterion), a revised version the PNC (Preferred Noise Criterion) and more recently the RC (Room Criterion). A sample of NR curves is given in Figure 2.28; octave band levels are compared with the target curve and should not exceed it at any octave. Criteria for different auditoria are given in Table 2.2.

The audience itself also generates background noise from breathing. Though for one individual this will be insignificant, for a whole audience it can exceed the criteria mentioned. According to measurements by Kleiner (1980), the noise generated by the audience in a typical concert hall could reach NR25, that is 10 db greater than the recommended criterion (Figure 2.28). This is not however cause for complacency regarding ventilation noise. Part of the magic of a live event is the moments when concentrated anticipation by the audience creates a 'dramatic hush'. At these instants one does not wish to be introduced to the deficiencies of the air conditioning system.

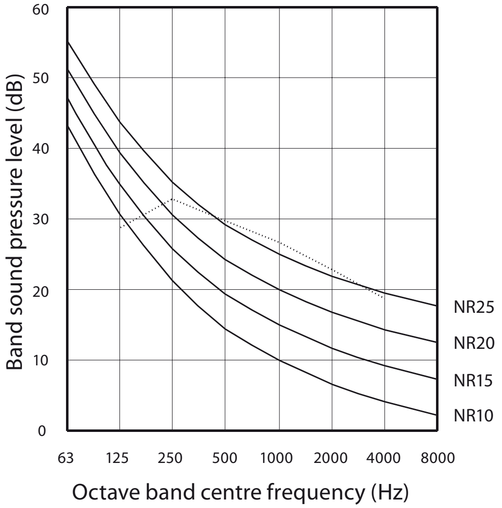

Figure 2.28 Noise rating curves relevant to auditoria and (dotted line) audience noise spectrum (after Kleiner, 1980; auditorium volume = 20 000 m^3 with 1600 seats, reverberation time = 2 seconds)

Partly stimulated by the realization that audience noise is not a fixed quantity, that audiences can be very quiet, the idea has been proposed that ventilation noise should be lowered beyond traditional criteria. With a lower background noise the dynamic range of the performance can perhaps be increased, creating a more exciting sound experience. The first British hall responding to these ideas was Birmingham Symphony Hall of 1991 (section 5.14), where it appears they have achieved a ventilation noise level of NR10 (Newton and James, 1992). Critics of this design approach point out that such low levels just make coughing and other noises that much more irritating. But an intriguing discovery is that audiences in Birmingham have responded by becoming quieter than elsewhere, by perhaps as much as 5 dB.

Table 2.2 Background noise rating criteria for auditoria

Large concert halls	NR15
Opera houses and drama theatres	NR20
Small auditoria (less than 500 seats)	NR25

2.8 Reverberation time design

2.8.1 The criteria

The difference in acoustic character between a cathedral and a domestic living room is immediately obvious. The time for sound to decay to inaudibility in a cathedral can be timed with a stop-watch, much as Sabine did in his pioneering experiments. The audible decay time approximates to the reverberation time – it is 11 seconds in St Paul's Cathedral, London, for instance. Appropriate times in auditoria for orchestral music and speech are much shorter. The reverberation time of a domestic living room is about 0.5 seconds.

The room response, which can be heard after a loud, short-duration sound or after a continuous sound is turned off, is known as **terminal reverberation**. This is used for measurement and the reverberation time is defined as the time for the sound level to decay to one millionth of its energy (Figure 2.29). Yet in music performance or speaking, this terminal response is rarely heard. What is more significant is the level of the reverberant sound which constitutes the background for the **next** musical note or speech syllable (Figure 2.13). The term **running reverberation** has been used for this, for which the early part of the decay is more significant. In many

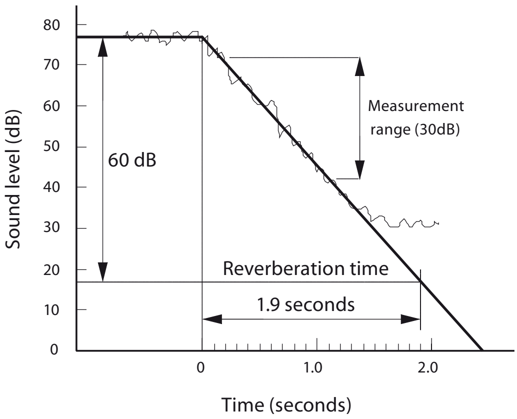

Figure 2.29 Reverberation time definition with a sample decay. The slope of the decay is, in practice, measured between –5 db and –35 db of the initial level

rooms however the reverberation time as traditionally measured is appropriate for both. Despite the many advances of recent years, reverberation time remains the single most valuable measurable quantity for the acoustics of an enclosed space. It has the advantage that it is generally constant throughout the room. An immediate preliminary assessment can be made of the suitability of a space for music or speech from knowledge of the reverberation time.

Though one refers to a 'linear sound decay', as shown in Figure 2.29, the decay of sound **energy** and **pressure** are exponential (Figure 2.30(a)). The pressure reduces by the same **fraction** for equal time intervals; so, if it has reduced to 1/10th after 1/3rd of a second, it will be reduced to 1/100th of its initial value after 2/3rd of a second. When converted into decibels, the decay approaches a straight line (Figure 2.30(b)). In reality the measured decay contains random modulations (Figure 2.31(a)); the reverberation time is measured from the slope of the best-fit straight line.

In some spaces, the decay is non-linear and a reverberation time can no longer be quoted (Figure 2.31(b)). The commonest cause of non-linear decays is coupled spaces with different reverberant conditions. If the decay is measured in the less reverberant space, the decay rate is initially that of the measured space but followed by the decay of the adjacent coupled space. An example of a coupled space is a proscenium theatre auditorium with a reverberant flytower, coupled through the proscenium opening. The orchestra pit and opera house auditorium are another example of coupled spaces.

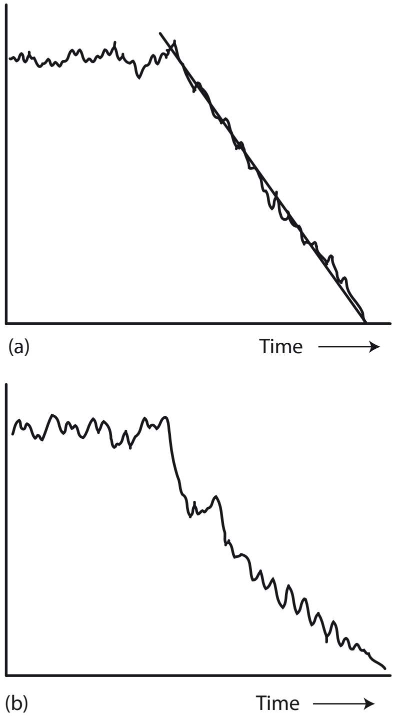

Figure 2.31 Measured reverberant decays. (a) Linear decay; (b) double slope decay

The appropriate reverberation time for an auditorium should be determined principally on the basis of programme (Table 2.3). Many references are found in the literature to optimum reverberation time also being a function of hall volume. In terms of major auditorium spaces, this approach only

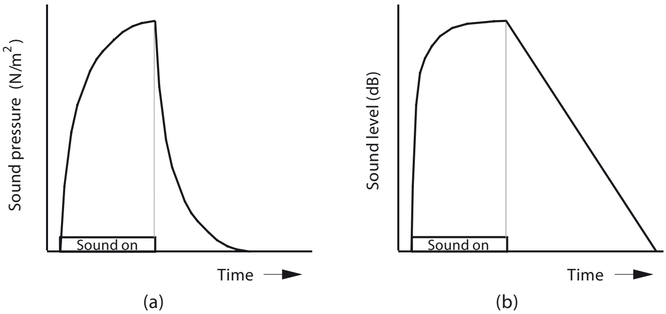

Figure 2.30 Sound build-up and decay displayed by (a) sound pressure and (b) sound level

Table 2.3 Recommended occupied reverberation times (seconds)

Organ music	>2.5
Romantic classical music	1.8–2.2
Early classical music	1.6–1.8
Opera	1.3–1.8
Chamber music	1.4–1.7
Drama theatre	0.7–1.0

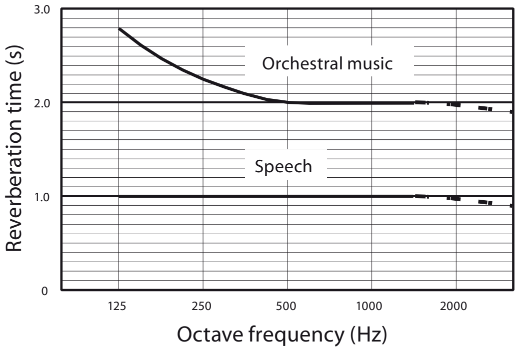

Figure 2.32 General recommended reverberation frequency characteristics for speech and orchestral music use (the latter with a maximum increase of 40% at 125 Hz)

appears relevant in small recital halls (section 6.2). A major dilemma exists for reverberation time design for multi-purpose spaces (Chapter 10). With orchestral music requiring a 2 second reverberation time and speech only 1 second, use of a single space for both speech **and** music is usually not possible without electronic assistance. Selecting a compromise time for such a situation can result in acoustics which are neither able to support intelligible speech nor sufficiently live by musical standards.

If a single figure is quoted for the reverberation time, it generally refers to the mid-frequency value, averaged between 500 and 1000 Hz. Reverberation time will vary with frequency (Figure 2.32). At high frequencies above 1 kHz, the reverberation time inevitably decreases due to air absorption (section 2.6.1). At low frequencies, the situation can be controlled by the designer. For speech there is good reason to keep the reverberation characteristic constant with frequency; a rise in the bass undermines intelligibility. But for music a bass rise in reverberation time is considered by most people as desirable. In this respect there used to be something of an Atlantic divide, with Americans considering that one cannot have too much bass, while some consultants in Europe strove for a flat characteristic with music. For orchestral music, the American argument seems to have won the day. A rational argument for this approach is that a bass reverberation time rise is needed to achieve a constant **perceived** decay time across frequency. This argument is based on the frequency characteristics of the ear: though at high sound levels the ear is roughly equally sensitive to different frequencies, at low sound levels it is much less sensitive to bass frequencies (otherwise we would hear our own heart beats). A longer bass reverberation time can compensate for this. Up to a 40 per cent rise at 125 Hz compared with mid-frequencies is considered appropriate for orchestral music (Figure 2.32).

2.8.2 The Sabine reverberation time equation

While greater theoretical minds in the nineteenth century probably imagined that the problem was not amenable to simple mathematical analysis, Sabine discovered around the year 1900 (Sabine, 1922) that only two quantities determined the reverberation time: the room volume (V) and the **total acoustic absorption** (A). The total absorption is simply the sum of all the sound absorbing areas, determined by adding the product of area (S) and absorption coefficient (α) of **all** surfaces in the room ($A = \Sigma S\alpha = S_1\alpha_1 + S_2\alpha_2 + \ldots$). The Sabine equation, when volume and acoustic absorption are measured in m^3 and m^2, is:

$$\text{Reverberation time (seconds)} = \frac{0.16V}{A}$$

This equation is the basis of virtually all reverberation time prediction in auditoria. The calculation is performed at each octave frequency of interest, at least from 125 to 2000 Hz. Sabine's equation does in fact involve a fallacy in that for a room with fully absorbent walls, floor and ceiling ($\alpha = 1$), a finite time is predicted when it should be zero. Alternative equations are available (particularly that by Eyring) to deal with highly absorbent rooms like recording studios. In auditoria, the coefficients assume use of the Sabine formula.

The major absorbing surface in an auditorium is the audience. Historically due to Sabine, the absorption of audience was calculated on the basis of the number of seats using absorption per person. This, combined with the fact that coefficients were too small, led to reverberation times in many concert halls which were shorter than predicted. One of the last cases of this occurred in the Royal Festival Hall, London, of 1951 (section 5.5).

2.8.3 Volume per seat as a design aid?

If one takes the Sabine equation and ignores the small proportion of incidental absorption by room surfaces other than audience, then, if audience absorption is calculated on the basis of absorption per person ($A = n\alpha_p$, where n is the audience size and α_p is the absorption per person), the consequence is that the reverberation time **should** be proportional to the auditorium volume per seat. For a long reverberation time a large volume per seat is needed. This concept of volume/seat is often used for acoustic design; particularly at the early stages of design, it can provide a valuable rule-of-thumb. For concert halls a value of at least 10 m^3/seat is often recommended. The equivalent values for opera are 7–9 m^3/seat and 4 m^3/seat for drama theatre.

But how reliable is this approach? Figure 2.33(a) shows the relationship between measured occupied reverberation time and volume/seat in British concert halls. Figure 2.33(b) shows a more convincing relationship between measured reverberation time and auditorium volume divided by acoustic seating area. The meaning of this last quantity is explained in the next section.

The alternative view was due to Beranek (1969) who was investigating the reasons for inaccurate reverberation time prediction in concert halls. He found that more accurate predictions were made when audience was treated like other materials, on the basis of absorption per unit area, or absorption coefficient. The absorption coefficient of seating and audience is relatively insensitive to seating density. For precise reverberation time calculations, absorption per person or per seat is little used nowadays and no coefficients for absorption per person will be quoted here.

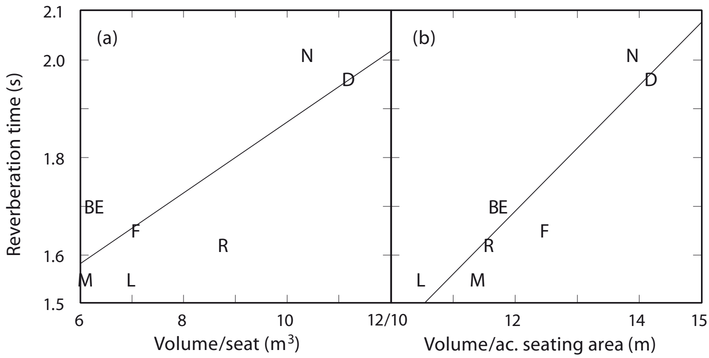

Figure 2.33 Occupied mid-frequency reverberation time vs. (a) volume/seat and (b) volume/acoustic seating area for British concert halls where data is available for halls without added absorption. Hall labels as in Figure 5.1, plus E, Usher Hall, Edinburgh and N, Bridgewater Hall, Manchester

2.8.4 Absorption by seating and audience

A major problem of reverberation time prediction is the choice of appropriate absorption coefficients for unoccupied seating or seated audience. A complication arises in the measurement of actual seats. Acoustic test chambers can only accommodate a maximum of about 24 seats, much smaller than the numbers found in real auditoria. The problem occurs not because of the numbers of seats but because the edge of a seating block absorbs sound in addition to the seating area when viewed from above. The perimeter-to-area ratio of the seating block proves to be important and this ratio is much higher in a test chamber with a small number of seats than it is in a typical auditorium.

One proposal for measuring seating absorption in test chambers is to place barriers around the seating block to screen the edges (also mentioned in the standard ISO354). However Bradley (1992) and Barron and Coleman (2001) have shown that barriers introduce problems of their own, leading to inaccurate measurements. Bradley (1992) proposes a measurement method for test chambers using a sequence of different seating arrangements. The Bradley method appears to be the most reliable one at present, though it has not yet been widely accepted. Many absorption measurements made in test chambers in the past are unlikely to be dependable.

Beranek (1969) derived absorption coefficients for unoccupied seating and seated audience from measured reverberation times in auditoria. A revised set of coefficients were published with Hidaka (1998); these figures appear currently to be the most reliable. Mention was made above that the edges of seating blocks also absorb sound. To deal with this, Beranek proposes that the seating area is enlarged by adding a strip around the seating block perimeter in plan. A perimeter strip 0.5 m wide is added to the true seating area, except where it abuts walls and along balcony fronts (Figure 2.34). The perimeter strip is only added where there is floor area in aisles etc. to which the additional strip can be applied. This enlarged seating area, which is the effective absorbing area of audience, will be called the **acoustic seating area**. The absorption coefficients quoted below are applied to this acoustic seating area.

2.8.5 Prediction of reverberation time

In the recently revised coefficients for seating (Beranek and Hidaka, 1998), the degree of upholstery is included as a parameter. Light upholstery is categorized as 25 mm of seat upholstery, 15 mm of upholstery on the front side of the seat back, a hard rear side of the seat back and solid arm rests. For medium upholstery the thicknesses of upholstery increase to 50 and 25 mm, with again a hard rear side of the seat back and solid arm rests. Heavy upholstery is defined as 100 mm of seat upholstery, 75 mm upholstery on the front side of the seat back, the rear side of the seat back possibly upholstered and 20 mm upholstery on the arm rests.

The recommended coefficients for seating and audience are given in Figure 2.35 and Table 2.4. The heavy upholstery audience coefficients also appear to be suitable for the proscenium opening in a theatre, when the stage area contains many drapes etc. to make it acoustically absorbent. The table also includes coefficients for other materials commonly found in auditoria. There is no entry in Table 2.4 for carpet. This is because carpet under audience

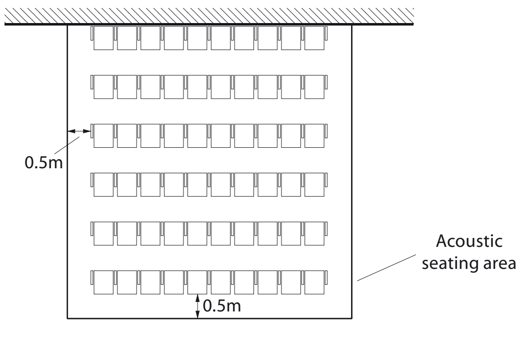

Figure 2.34 'Acoustic seating area' based on adding a 0.5 m perimeter strip round the true seating area

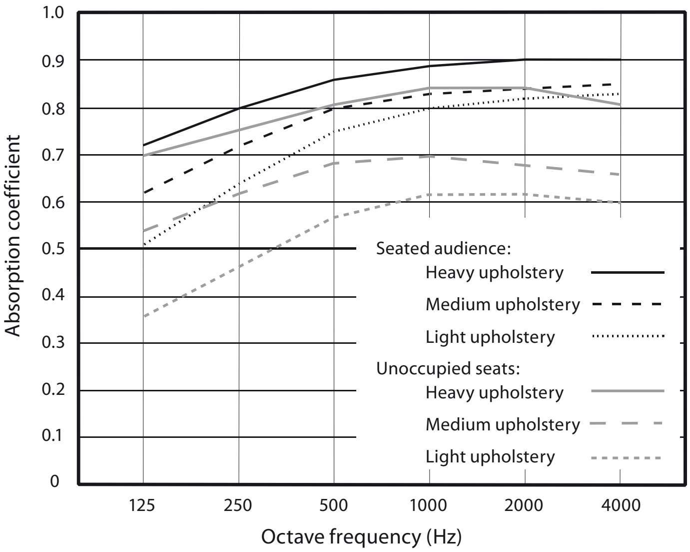

Figure 2.35 Absorption coefficients of seated audience and unoccupied seating after Beranek and Hidaka (1998)

seating is generally considered not to influence the total absorption. However the question of the significance of carpet cannot be considered to be fully resolved.

For accurate calculation of high frequency reverberation time, it is necessary to take account of the small absorption of sound that occurs when it passes through air. The Sabine equation including this component is:

$$\text{Reverberation time (seconds)} = \frac{0.16V}{\sum S\alpha + 4mV}$$

The air absorption coefficient, m, depends on temperature and humidity. Sample values of m are included in Table 2.4, taken from ISO 9613-1 (1993). Air absorption usually only influences reverberation time at 2 kHz and above. At 4 kHz the reverberation time becomes sensitive to temperature and humidity.

A sample reverberation time calculation is given in Appendix A.3. Calculation should be made to the nearest 0.1 seconds, which is probably the smallest detectable difference.

To achieve the criterion, mid-frequency reverberation time requires correct selection of the auditorium volume, which in turn usually influences the ceiling height. The need for a flat reverberation time characteristic for speech or a bass rise for music, Figure 2.32, influences the required area of low-frequency absorbent. By itself, audience acts as a porous absorber, which from Figure 2.19 is efficient at absorbing high frequencies but not low frequencies. Substantial additional low-frequency absorption is required to produce a flat reverberation time with frequency. Panel absorption is the most likely mechanism to be exploited, though resonator absorbers have been used (section 6.5). Although in a space for speech use one might well include purpose-designed panel absorbers (Figure 2.20), incidental light-weight panel materials, such as thin plaster for a suspended ceiling, also exhibit low-frequency absorption. In a concert hall where we want a long bass reverberation time, it is necessary that all walls, ceilings and suspended elements are sufficiently massive to minimize low-frequency absorption. This approach obviously has cost implications.

The accuracy of reverberation time prediction is seldom perfect. The theory assumes a diffuse sound field, in which energy is travelling with equal

Table 2.4 Absorption coefficients of surfaces in auditoria

	Frequency (Hz)					
	125	250	500	1000	2000	4000
Seated audience*:						
Heavy upholstery	0.72	0.80	0.86	0.89	0.90	0.90
Medium upholstery	0.62	0.72	0.80	0.83	0.84	0.85
Light upholstery	0.51	0.64	0.75	0.80	0.82	0.83
Unoccupied seating*:						
Heavy upholstery	0.70	0.76	0.81	0.84	0.84	0.81
Medium upholstery	0.54	0.62	0.68	0.70	0.68	0.66
Light upholstery	0.36	0.47	0.57	0.62	0.62	0.60
Plaster or thick wood*	0.10	0.06	0.05	0.05	0.05	0.04
Plaster on concrete block*	0.06	0.05	0.05	0.04	0.04	0.04
Concrete	0.02	0.02	0.03	0.04	0.05	0.05
Thin wood (approximate)	0.30	0.19	0.09	0.06	0.06	0.06
Curtain (velour, draped)	0.06	0.31	0.44	0.80	0.75	0.65
Absorbing power of orchestra (m^2), 92 players on a 170 m^2 stage with vertical walls*	22	37	44	64	102	132
Air absorption coefficient, 4m (m^{-1})	.000	.001	.003	.004	.009	.027

* After Beranek (1969) and Beranek and Hidaka (1998)

probability in all directions. Where this is not fulfilled, reverberation times different from those predicted may result. Acoustic scale models or good computer models can help monitor the accuracy of prediction. If one is to err on one side as a precautionary measure, it should be towards a longer reverberation time for music use and a shorter one for speech. Extra absorbent can if necessary reduce an excessively live space, while for speech a dead space will have better intelligibility.

2.8.6 Simplified reverberation time prediction

While full calculation is necessary for serious predictions, a simplified method was proposed by Kosten (1966), based on published data in concert halls. It is a tenet of good auditorium design that as little additional mid-frequency absorption should be introduced beyond the unavoidable absorption associated with performers and audience. Kosten found that total acoustic absorption was closely related to audience area. He introduced an **equivalent absorption coefficient** (α_{eq}), which is used to calculate the total absorption by multiplying it by the acoustic seating area, S_T; S_T equals the acoustic seating area (section 2.8.4) plus the orchestral stage area. The equivalent absorption coefficient is thus the absorption coefficient for audience plus an addition to take account of incidental absorption by the remaining hard surfaces in the room. Kosten's simplified equation for the occupied reverberation time (RT) is:

$$\text{Reverberation time (seconds)} = \frac{0.16V}{S_T\alpha_{eq}}$$

The air absorption component has been omitted here. The Kosten approach allows rapid calculation valuable for preliminary design. Kosten's original value for α_{eq} at 500/1000 Hz of 1.07 for occupied seating appears to be too low. For the data used in Figure 2.33(b), the calculated mean value of α_{eq} is slightly higher at 1.14, with a standard deviation of 0.05 (note S_T includes the stage area). This value agrees with the one effectively proposed by Beranek (2004, p. 633).

Simplification of the formula can be taken yet one step further for the case of an auditorium without overhanging balconies. If the floor is fully occupied by audience, access aisles and performers, then S_A equals the floor area. Placing this in the equation above with Kosten's α_{eq} value leads directly to a specification for the mean height (*h*) of the auditorium, namely $h = 7.1 \times \mathrm{RT}$ (m). Thus in a space for speech with a 1 second reverberation time, the average height should be about 7.1 m. Acoustic design does not come much simpler!

2.9 Sound level distribution

Loudness is an obvious acoustic concern, yet for many years it was not felt to be significant in the auditorium context. For speech, the requirement is that it should be loud enough relative to background noise. In the case of symphonic music, many listeners respond enthusiastically to louder sound; it appears to render the experience more intimate (Barron, 1988). The subjective sense of **loudness** is determined by the objective **sound level**, measured in decibels. Traditional theory of reverberation provides a formula for sound level distribution.

Obviously the sound level in a room depends on the sound energy being generated. But the acoustic characteristics of the room also influence the resulting sound level. Both the distance from the source and the total acoustic absorption (*A*) affect the result. The total sound received is divided into two components: the direct sound and the reflected component. (The total level is derived by decibel addition; where the direct and reflected level are the same the total level is 3 db greater, for positions close to the source the direct sound dominates, for distant positions the reflected component dominates.) The direct sound decreases 6 db for every doubling of distance, whereas the reflected component has traditionally been assumed to be constant throughout the space (Figure 2.36). The reflected component is a function of total absorption; an auditorium with a larger audience will have a quieter sound. The distance at which the direct and reflected components are the same is known as the **reverberation radius**. It is around 5 m in a full-size concert hall. Thus nearly all listeners receive more energy which is reflected rather than direct.

This theoretical behaviour for the total sound level makes various assumptions of uniformity of sound travel etc. In reality individual design details cause local variations. Perhaps the most obvious of these is that sound levels decrease under balcony overhangs. Several examples can be found in Chapter 5. A more universal deviation from the traditional theory has been discovered during the process of making measurements in the halls reported in detail here. It became clear that the assumption of constant reflected sound level throughout the space was not valid in auditoria. Typical average measured behaviour is shown in Figure 2.36, with a decrease with distance from the source (Barron and Lee, 1988). The revised theory predicts sound levels at the rear of large concert halls 3 db less than traditional theory. Since halving the size of the orchestra produces only a 3 db reduction, this discrepancy is surely significant.

The theoretical expression for the revised reflected sound level in Figure 2.36 is:

$$\text{Reflected sound pressure level} = \mathrm{SWL} + 10.\log\frac{4}{A} - \frac{0.174r}{T}$$

SWL is the sound power of the source (in watts) expressed in decibels, *A* is again the total acoustic absorption, *r* is the source–receiver distance and *T* is the reverberation time (see Appendix B.3). The traditional expression omits the last term. As already mentioned the dominant quantity determining the sound level is the total acoustic absorption. A situation for which the revised theory might be significant runs as follows: in a drama theatre, which has a lot of extra absorbing material introduced to reduce the reverberation time, the sound levels at the furthest seats might be too low relative to the background noise level.

The revised theory as shown in Figure 2.36 does not by itself help to design better auditoria. Indeed there is some evidence that listeners compensate

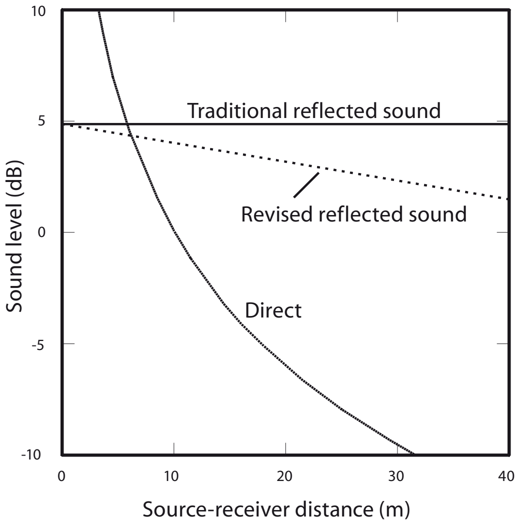

Figure 2.36 Sound level components as a function of source–receiver distance in a hall. Typical measured values of the reflected sound level lie closer to the revised line than the constant value according to traditional theory

for distance when they assess loudness (section 3.2). But the revised values provide a yardstick against which to compare measured results. Some design features cause unusually quiet or loud sound; the theory provides a value for what is usual. For example, insufficient early reflections in large halls lead to a quiet sound, which may be perceived as a lack of intimacy. These aspects are discussed further in section 3.10.5.

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