A Brief History of Design Methods for Building Acoustics

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ABSTRACT: Acoustics has been important to the designers of buildings, especially theatres and concert halls, for at least 2500 years. For most of this time, designers used empirical guidance which, while reliable within its limitations, could not be applied successfully to rooms and auditoria which had no close precedent. The science of acoustics developed in the 18th and 19th centuries, mainly in connection with musical instruments. However, design methods for room acoustics in buildings become scientific and quantitative only in the 20th century. The physicist Wallace Sabine discovered what affects the reverberation time of a room around 1895 and used this, first, to improve the acoustics of a lecture theatre and, later, in the design of new rooms – most famously, the new Boston Music Hall in 1900. The measurement of sound and waveforms became practical with the development of microphones, amplifiers, oscillosopes and early sound recording machines in the 1920s. From the 1930s physical scale models have been used to measure the acoustic response of auditoria. They are still used today, together with increasingly sophisticated analysis of waveforms, to build up more and more reliable predictions of acoustic performance. Architectural acoustic design methods are typical of other engineering design disciplines in how they developed from being purely qualitative, then using empirical data, then making use of physical model testing, and finally using comprehensive mathematical models.

INTRODUCTION

The historical development of architectural acoustics is similar to other fields of building design, in comprising two parallel strands of ideas – the science and mathematics of the subject on the one hand, leading to improved understanding of the phenomena, and the methods used by designers when faced with the challenge of a new building on the other, especially when the task differs markedly from precedent. The two nineteenth-century classic works on the physics of acoustics (Helmholz 1863; Strutt 1877-78) hardly mentioned the acoustics of theatres or other rooms, and the science they contained only began to be used by architectural acousticians in the mid-twentieth century. While these two branches of knowledge are closely related, it was not a case of theory leading to practice, or vice versa: the two were symbiotic.

ACOUSTICS IN THE ANCIENT WORLD

Vitruvius on acoustics and theatre design

The Roman engineer Vitruvius devoted several chapters of his book on building design and construction to the location and design of theatres (Vitruvius, Book V). He advised that they should be located away from winds and from "marshy districts and other unwholesome quarters" and also on their orientation with respect to the sun and the surrounding terrain. He addressed key geometric issues such as the plan and section, sight lines, numbers and locations of entrances and exits, and finally considered the subject of acoustics. This highly theoretical section was not his own; he was repeating what he found in various Greek treatises on acoustics from two or three centuries earlier which, in turn, probably had their origins in Pythagoras who first developed the subject around 530 BC. Vitruvius dealt with acoustics from several points of view. First he introduced harmonics – " an obscure and difficult branch of musical science, especially for those who do not know Greek". This science explained the pitch of notes and the intervals between them in the Greek musical scale, as well as why some combinations of notes are concordant and others discordant. Next Vitruvius discussed sound in the auditorium – in particular the need for sound of all pitches to travel from the stage to the ears of every member of the audience by a direct route, in the manner of waves created by a pebble thrown into water. This led logically to both raked seating and the semi-circular plan. He advised against vertical reflective surfaces that would prevent sound reaching the upper tiers of seats since this particularly impairs the intelligibility of word endings which, in Greek and Latin, are vital to comprehension. Such reflected waves, he wrote, can also interfere with the direct waves and distort sounds for the listener. These explanations differ remarkably little from how we would put it today. Thirdly, Vitruvius explained that the site of a theatre itself must be carefully selected taking account of acoustics: it must not have an echo, nor give reflections that can lead to direct (incident) and reflected sounds interfering.

Vitruvius also discusses the use of sounding vessels – nowadays called Helmholz resonators, after the nineteenth-century German physicist who explained how they function – which, he says, reinforce certain frequencies of the human voice and can increase intelligibility. These open-ended vessels were made of bronze and tuned to six notes of the chromatic scale. Two sets of six were arranged beneath a tier of seats symmetrically either side of the centre line of the theatre. If the theatre were particularly large, two additional sets of vessels should be installed in higher rows, each a few semi tones lower in pitch – a total of thirty six different notes. Vitruvius admits he knows of no theatres that had actually been built in Rome with sounding vessels. The reason, he explains, is that "the many theatres that are constructed in Rome every year contain a good deal of wood which does not lead to the same problems with reflections as stone". Also, he says, the timber panels themselves can resonate in a manner similar to the air in a sounding vessel and so improve intelligibility.

As to the effectiveness of sounding vessels, they are known today not to improve intelligibility and that is probably why they were not used in Rome. Whether the Roman theatres were as good as the Greek ones, we do not know, but there is no doubt that both were designed with great understanding of acoustics and expertise in using this understanding to achieve demonstrably better results.

One final recommendation from Vitruvius on acoustics was for a senate house. The height of a senate house should be half the width of the building, he says, and *coronae*, or cornices, made of woodwork or stucco, should be fixed half way up the inside faces of the walls around the entire room. Without these, he says, the voices of men engaged in discourse are lost in the high roof. With coronae, the sound of the voices is 'detained before rising' and so is more intelligible to the ear.

Acoustics in the mediaeval and renaissance eras

No significant writings on the acoustics of buildings survive from mediaeval or Renaissance times (Hunt 1978). Vitruvius was published in the late 15th century and would have been known by most designers of large buildings. However, it is not possible to identify precise ways in which his guidance was followed, either in cathedrals or, from the late Renaissance, in theatres. The development of music from the 12th century provides evidence of a good understanding of the acoustics of cathedrals, however, their legendary acoustic qualities are more indebted to the skill of composers and musicians than to the buildings themselves or their designers. They have long reverberation times because sound waves are reflected many times with little loss of intensity which means that musical rhythms have to be slow to be intelligible, and percussive instruments must not be used to avoid the inevitable machinegun effect of any echo. The acoustic of the space favours those instruments with a gradual attack to each note, and which sustain their notes – for example the organ, flute, violin and the human voice. For speech, however, the long reverberation time is a disaster. As the distance between speaker and listener increases, so the sound reaching the ear directly is increasingly swamped by the reflected sounds arriving by indirect, longer sound paths. Speech is thus generally unintelligible at any distance greater than a few metres, which phenomenon has an interesting architectural effect. Since it is the longer wavelengths of lower notes that are more effectively reflected, people talking in cathedrals are naturally and unconsciously inclined to whisper, irrespective of any reverence for the religious nature of the buildings they may feel, because whispering removes the lower frequencies of the human voice.

The use of sounding vessels in a theatre with raked seating (as described by Vitruvius) is illustrated in a drawing by Francesco di Giorgio di Martini in around 1485 (Maltese 1967, Vol.1, Plate 13) although he does not say if they were used. However, such vessels made of pottery have been found in some mediaeval monasteries, including Fountains Abbey in England (Arns; Crawford 1995).

EARLY MODERN DESIGN GUIDANCE – EIGHTEENTH CENTURY

As in the ancient world of building described by Vitruvius, it was the intelligibility of speech that drew the attention of 17th and 18th century building designers to the acoustic performance of building interiors, especially in two types of building – theatres and the debating chambers used by politicians. During the eighteenth century the importance of room acoustics was further heightened with the invention of a number of musical instruments such as the harpsichord and fortepiano, and the growing popularity, in elite circles at least, of chamber music. The new instruments used ingenious mechanisms and large sounding boards to produce plucked and percussive notes with unprecedented speed and at much greater volumes than earlier instruments such as the lute, harp and clavichord. When played in a room with a very live acoustic, the individual notes became indistinguishable and the objectives of the instrument makers and musicians were ruined.

It was already well-understood that the size of a room and the reflectivity of the walls, floor and ceiling affected the intelligibility of speech and music, and that two different effects were at work. One was the diminishing loudness or intensity of the sound, both with distance and according to the amount of sound absorbed by the room's surfaces and contents. The second was the increasing confusion of sounds caused by reflections from the room's surfaces.

This understanding of acoustics led building designers to use a number of pragmatic rules that helped them achieve acceptable room acoustics. Three different types of surface could be used – stone or plaster would enhance reflections, woven fabric such as tapestries and curtains would absorb sound, and timber panelling was intermediate between the two. Based on the acoustic performance of existing rooms, a designer could choose what he hoped would be a suitable combination of the three types of surface. The other design factor was the distance between speaker or instrument, and the directness of the sound path. Theatre designers tried to ensure that that the entire audience could see the actors, not only for theatrical effect, but so that at least some of the sound could travel directly from speaker to listener. The other consideration was the distance between the stage and the listener. It was generally agreed that an actor speaking in a normal voice could be understood clearly up to a distance of about 18 metres, and with difficulty up to about 25 metres. The result of these basic rules was the development of the familiar raked seating and tiers of balconies in theatres and dedicated concert halls.

The need for good acoustics was, however, not the only influence on the design of theatres. There was also a tension between the need for actors to be understood, on the one hand, and the patron's desire to increase the size of audience and the income from ticket sales, on the other. Many theatres in the late eighteenth century were built with distances between actor and listener more than thirty metres. This forced actors to change their style of delivery and develop the skill of speaking more loudly, while sounding as if speaking in a normal voice – a good actor could even fill an auditorium with what sounded like a whisper.

Designers of theatres intended for performances of both music and the spoken word faced a further, insuperable challenge since the acoustic characteristics needed for good intelligibility of speech make music sound very dry and unpleasant to listen to. A hall well-suited to music, on the other hand, rendered the spoken word almost unintelligible in all but the seats nearest the stage. The most practical solution to this dilemma was to have different buildings dedicated to each form of entertainment. Theatre, however, often relied on music to enhance the dramatic effect and orchestra pits were incorporated in most large theatres between the front seats and the stage. The acoustics of such theatres was inevitably a matter of compromise, favouring the intelligibility of the spoken word.

Design rules for theatre acoustics were not very reliable in the eighteenth century and there were many acoustic disasters. In his autobiography of 1740, the actor and playwright Colley Cibber wrote of Vanbrugh's Queen's Theatre in London, built in 1704-05, that all its architectural elegance was of no avail:

> . . . when scarce one word in ten could be distinctly heard . . . The extraordinary and superfluous space occasioned such an undulation from the voice of every actor that generally what they said sounded like the gabbling of so many people in the lofty aisles in a cathedral … [and] the articulate[d] sounds of a speaking voice were drowned by the hollow reverberations of one word upon another. (Leacroft 1984, p.103)

Throughout Europe the second half of the eighteenth century saw a boom in theatre building in the major cities, and designers generally learned from the acoustic disasters of the early century. By the late eighteenth century it was common practice to use the ceiling or soffit above the front of the stage as a 'sounding board' (actually a reflector) and the ceiling over the orchestra pit to 'throw the voice forward' from the stage to the back of the stalls and to the galleries. The first design guides for theatres discussed acoustics alongside the equally important issue of line-of-sight (Patte 1782, Saunders 1790, Rhode 1800, Langhans 1810). These and others followed Patte's example in showing ray diagrams to visualise sound paths (Fig. 1).

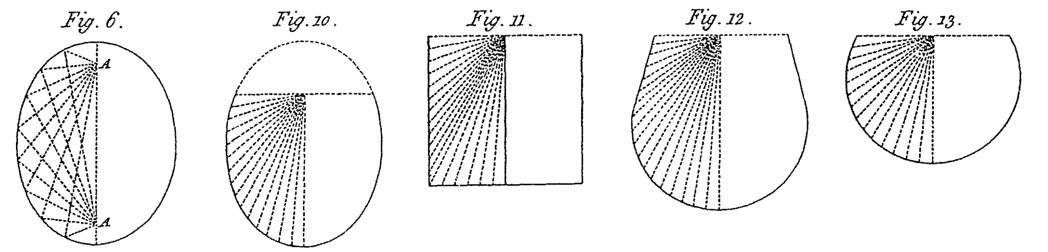

Figure 1: Ray diagrams for different theatre plans; (Patte 1782, Plate 1)

Of these authors it was the architect George Saunders (c.1762-1839) who was the first to publish results of tests he had undertaken on theatre acoustics. He was familiar with Patte's guide and also with the first modern scientific work on acoustics by the French mathematician and music theorist Marin Mersenne (Mersenne 1638) whose scientific approach he adopted:

> Phonics or the doctrine of sounds is particularly distinguished from acoustics or the doctrine of hearing. Instead of dividing into direct, refracted and reflected, I shall, for the sake of brevity and perspicuity, divide phonics into three distinct heads; namely formation of sound, combination of sound, and progression of sound. . . . . But as sound is very much influenced or altered by the bodies it meets with, and the form of its expansion depends much on the manner of its being transmitted, it is necessarily our business to enquire, how it is affected by the different bodies it may meet with in its progress, and more particularly, of the manner in which the voice expands. In examining what has already been written upon these subjects, very little

> could be gained to our purpose; and this occasioned the following experiments, which may help to give this part of science an additional degree of certainty. (Saunders 1790, pp.2-3)

Saunders goes on to describe how he tested seven "propositions" in real auditoria:

1 Of the extension of the voice on a plane;
2 Of the ascension, descension, and cubical form of sound;
3 Does the voice act upon a certain quantity of air of whatever form to which it may be confined?
4 Of screens partially placed before the voice, and opposing angles;
5 How sound operates in different airs, and how much it is affected by currents of air;
6 On the reflection of sound;
7 Of the property of different materials to alter and conduct sound. (Saunders 1790, pp.4-22)

And from the results of these experiments he concludes they lead to several "applications":

> First, that sound expands equally in every direction. Secondly, that to alter the form of its expansion, the intervention of a body is necessary. Thirdly, that all bodies attract sound. Fourthly, that sound is absorbed, and conducted by a body, more or less according to the nature of the material. Fifthly, that in proportion to the conducting power of the material, will be the resonance it occasions. Which being admitted, it follows, that nothing can be depended on, in a theatre, but the direct force of the voice. (Saunders 1790, p.23)

Saunders summarised his experience in a number of clear rules:

- the hearer should never be more than twenty two metres (seventy feet) from the speaker;
- the ceiling should be used to convey sound to the upper seats of the auditorium
- the circular plan is best, and
- the entire audience should have sight of the stage.

Writing about the design of theatres Saunders uses the concept of 'phonics' (i.e. acoustics), for example, criticising theatres that had deep boxes and galleries, as their low height 'obstruct[ed] the sound … [and] the little that enters is presently attracted and absorbed by the persons, clothes, etc. of the spectators in the foremost rows'. Saunders conducted many experiments on the effect of the shape of theatre auditoria on intelligibility, comparing the results to those obtained in the open air, and concluded that the oval or horseshoe form were best, but that these did not allow good views of the stage. He concluded the semi-circular form was best, 'with its centre seventeen feet (five metres) in front of the speaker' and the diameter of the circle should be no greater than sixty feet (eighteen metres). Saunders was also aware that the voice did not carry well above an angle of 45° to the horizontal, and thus the height of the auditorium should be no greater than three quarters of the diameter of the circle. Concerning materials, he wrote that:

> Wood is sonorous, conductive and produces a pleasing tone, and is therefore the very best material for lining a theatre; for not absorbing so much as some, and not conducting so much as others, this medium renders it peculiarly suitable to rooms for musical purposes; the little resonance it occasions being rather agreeable than injurious. (Saunders 1790, p.201-2)

Saunders used his understanding of acoustics to produce designs for both an 'Ideal Theatre' and a similar opera house which also incorporated the latest ideas on protection against fire, including staircases constructed entirely of stone and enclosed by walls.

The first modern comprehensive book on acoustics (Chladni 1802) was written by the German physicist Ernst Chladni (1756 –1827) who studied how musical instruments create their characteristic sounds. His experiments led him to study both the vibration of sheets of wood and metal and also how such vibrations were conveyed through the air to the listener's ear. He published the results of his experimental work on vibrating plates first in "Entdeckungen über die Theorie des Klanges" (Discoveries concerning the theory of sound) in Leipzig in 1787, and then in "Die Akustik" in 1802. Apart from the physics of sound, Chladni included some useful guidance on designing auditoria, though drawn entirely from the practical guidance of both Saunders and Rhode (Saunders 1790; Rhode 1800).

Chladni illustrates one intriguing design for a theatre in which the walls are made of panels that can be rotated about their vertical axis to change their angle and, hence, the direction of reflected sound and also to allow some sound to penetrate into the cavity behind thus reducing the intensity of reflections; he does not say if the theatre was built.

EARLY MODERN DESIGN GUIDANCE – NINETEENTH CENTURY

Saunders' and Chladni's design rules were widely repeated and used for most of the 19th century, for example when designing the growing number of music auditoria, theatres, lecture theatres in the many new polytechnic colleges being built throughout Europe, and also the chambers in which politicians and legislators congregated, both of which also needed good acoustics. The job of ensuring good acoustics naturally fell to the designers of the heating and ventilation systems since they all relied on the common medium of the air. It was also often the case that acoustic performance could be adversely affected by noise born into the room from outside through the ducts providing fresh air.

W.S Inman and David Reid

The destruction by fire, in 1834, of the House of Commons, where English members of Parliament congregated, required the design and construction of a new chamber. As is often the case with new government buildings, this provided an excellent opportunity for a state-of-the-art building. A study was commissioned to establish the best form of room to ensure excellent intelligibility throughout. The resulting reports, papers and books, by W. S. Inman and David Reid, collected not only contemporary experience and published guidance on theatre design such as that written by Saunders and Chladni, but even referred to the acoustic science and building designs from ancient Greece, as described in Vitruvius. In the book based on his studies Inman summarised Chladni's design guidance from a third of a century earlier:

> . . . rooms will be favourable to the transmission of sound:
> 1. When arranged to facilitate its natural progress;
> 2. When its intensity is augmented by resonance or simultaneous reflection, so that the reaction is undistinguishable from the primitive sound;
> 3. When not too lofty or too vaulted;
> 4. When there is not a too extensive surface for the sound to strike against at once
> 5. When the seats are successively elevated.
> He [also] observes that:
> - when the enclosed space does not exceed 65 feet, any form may be adopted for a room;
> - that elliptical, circular, and semi-circular plans produce prolonged reverberations;
> - parabolic plans and ceilings are the best for distinct hearing, and that
> - for concert rooms, square and polygonal plans should have pyramidal ceilings, and circular plans domed ones, and the orchestra be placed on high, in the centre, to produce the best effect and avoid echo. (Inman 1836, p.21)

David Reid described the work he undertook in his studies for the House of Commons in his book on ventilation (Reid 1844; Addis 2007, pp.286-88). He approached his work in a manner little different from that of a modern consulting engineer. Concerning the poor audibility of speakers in the House of Commons, he first established the causes of the problems by interviewing members and by direct observation in the chamber itself. He identified 'six principal causes of the defective communication of sound'. The ceiling was too high which meant the voice had a large volume to fill, a particular problem when a speaker was competing with a general background hum of conversation. The soft fabrics covering the walls of the chamber provided insufficient reflection of incident sounds; the noise entering the chamber through the windows, especially when opened for ventilation, was 'extreme'. Not only was there noise from the adjacent chamber, the House of Peers, but also 'the noise of coaches, cabs and omnibuses, of the letter-carrier's bell and every other noise produced in the Old Palace Yard. He found that the floor covering in the chamber produced a considerable noise when members walked upon it and there was also disturbing noise produced by the opening and closing of the door to the room. Finally, he believed that the rising current of warm (and less-dense) air in the centre of the chamber refracted the sound passing from one side of the room to the other, just as a glass prism refracts light. In fact, while theoretically possible, it unlikely that Reid would have been able to observe such an effect; more likely, the variable intelligibility depending on the listener's position in the room was due to the presence or absence of reflections from walls and ceiling.

Based on his observations and explanations, Reid incorporated various acoustic devices in the new House of Commons chamber built in the late 1830s. The ceiling was lowered and panels of wood and glass were incorporated in the upper parts of the room to reflect sound downwards and towards the centre of the room. Both the floor and ceiling were porous to allow fresh air in and foul air to be extracted, and these surfaces also reduced the reflected sound that had previously led to the 'offensive reverberation' that reduced intelligibility. The new heating system kept the air temperature the same throughout the chamber which prevented the refraction of sound. The floor of the chamber was covered with a 'soft, thick, porous and elastic hair-cloth carpet' which prevented noise caused by people walking, which also absorbed unwanted reflections in the room. Finally, the new and highly effective heating and ventilation system meant it was no longer necessary to open windows and thus disturbance from noises outside the chamber was avoided.

After his work on the new House of Commons, Reid went on to collect information and conduct many experiments on the acoustics of rooms and reported his results and guidance for designers in his book of 1844. He noted particularly the importance of reverberation time and its effect on the intelligibility of speech. He measured an eight second reverberation time inside an iron boiler and mentioned several large rooms he had visited where a sound remained audible for between eight and ten seconds; he had even heard of a room in a palace in St Petersburg where the noise made by stamping a foot was audible for a period of twelve seconds.

Reid realised that the key to intelligibility of speech depended on the ratio of the loudness of direct and reflected sound reaching the hearer. This was well exemplified by the benefit that the presence of an audience would bring to a room by reducing reflected sounds, both by absorption of sound in their cloths and in preventing sound being reflected from a hard floor. He was also aware that speakers could be disturbed by loud reflections of their voice reaching them from the rear wall of a room. He mentioned many examples of how the acoustics of rooms had been improved by applying the rationale he described to reduce disturbing reverberation. In one large lecture room the plaster ceiling was removed, leaving the bare beams and laths. In other cases drapery, curtains, carpets, sofas and soft furniture were used to absorb sound. Reid also carried out numerous experiments on the focusing effect of arched or domed ceilings, especially in Paris at the H*alle au blé* and in the many rooms of the Louvre palace. In one room in Paris he found that the reflection from such a ceiling had been so strong as to prevent it being used; the problem was remedied by suspending a silk balloon in the centre of the ceiling.

Reid's qualitative understanding of acoustics differed little from that of twentieth century acousticians. He was prevented from taking acoustics into the realm of quantitative engineering only by the lack of equipment to measure sound intensities and to analyse sound of different frequencies. This step awaited the invention of the microphone, in the late nineteenth century, which converted sound waves into a varying electric current, and the measuring of both relative and absolute sound intensities in the early twentieth century. Based on the work of Inman and Reid, further useful design guidance began to appear (Lachéz 1848; Upham 1853; Smith 1861).

The late nineteenth century

The late nineteenth century saw the construction of new concert halls to meet the growing popularity of concerts featuring symphony orchestras. These halls differed markedly from the three traditional venues for musical performance – churches, the salons of palaces in which chamber music was played, and theatres and opera houses. The size and construction material of churches were guaranteed to give them long reverberations times (up to six or seven seconds) which constrained the type of music that could be enjoyed. Multiple reflections from the hard surfaces of walls and floor forced composers and musicians to avoid rapid rhythms and staccato or percussive sounds which would degenerate into confusion as new notes interfered with the reflections of earlier ones, both in pitch and rhythm. Chamber music, usually featuring fewer than a score of musicians, developed during the eighteenth and early nineteenth centuries in the houses of the rich and was seldom intended for large audiences. The small sizes of the rooms and the plastered interiors gave a much shorter reverberation time (perhaps three or four seconds) and a lively room acoustic that so well suits the Baroque and early classical music of Handel and Haydn. Such rooms were ideal for the relatively quiet instruments such as the violin family, woodwind and early keyboard instruments such as the harpsichord.

Theatres and opera houses, on the other hand, were dedicated mainly to the human voice. Their design was driven by the need to ensure intelligibility and to avoid the need for actors to have to speak unduly loudly. The maximum distance between the speaker or singer and the listener should be no more than about twenty metres and the interior of the auditorium was covered in fabric and soft furnishings that ensured a low reverberation time (between two and three seconds). The symphony orchestra, by contrast, playing the music of Beethoven or Mahler, could be very loud indeed; and the promoters of public symphony concerts wanted to seat as many listeners as possible. Both features called for much larger halls. In many places the large assembly rooms in town and city halls often served, and still do serve, as acceptable music venues, although their multi-purpose function often meant they were seldom ideally suited to any one purpose. The acoustic design of such halls was entirely empirical and based on the observed characteristics of previous halls that had proved successful, though it would not have been understood precisely what had lead to past successes. A number of halls have attracted widespread acclaim among musicians and concert-going audiences – for example, Vienna's Grosser Musikvereinssaal (1870), the Leipzig Gewandhaus (1885), and the Conzertgebouw in Amsterdam (1895). Yet, until recent times, when a new hall was designed there was little agreement as to precisely which features of an excellent hall should be copied in a new one. Acoustic disasters were not uncommon, and were no better exemplified than at London's Albert Hall, opened in 1871, whose prominent echo gained it the reputation for giving audiences good value for money as they heard every concert twice.

WALLACE CLEMENT SABINE – "FATHER OF ARCHITECTURAL ACOUSTICS"

The man who has no rival in being called "the father of architectural acoustics" was Wallace Clement Sabine (1868-1919) (Sabine 1922; Beyer 1999, pp.186-191; Thompson 1992, 2002). Sabine was a lecturer in physics in the department of natural philosophy at Harvard University and was approached in 1895 to advise on how to improve the poor acoustics of a new lecture theatre in the University's Fogg Art Museum. This lecture theatre had been designed to emulate a classical Greek theatre and followed the same principles of acoustic design that Vitruvius had written down. These addressed the need of intelligibility by focusing mainly on maintaining the volume of the direct sound that reached the listener's ear. The speaker was placed above the level of the front row of the audience; the seating was raked upwards towards back of the auditorium; and a wall was placed behind the speaker to reflect sound into the auditorium. However, such principles were intended for open-air theatres and took no account of sound reflected from walls or the roof. In an enclosed room these reflected sounds also reach the listener's ear and, since there will be many sounds, arriving at different times, the result is confusion with direct sound from a speaker competing with reflections of earlier sounds.

Sabine realised this was how intelligibility was lost, like many before him. Being a physicist, however, his approach was to conduct experiments to measure how the loudness of the reflections was influenced by the reflecting surfaces in the lecture theatre. His aim was to discover the relationship between the dimensions of the room and the rate at which a sound became quieter and eventually became inaudible. He called this rate of decay the *reverberation time* and defined it as the time, in seconds, for a sound to decay to one millionth of its original loudness (a fall of 60dB).

Sabine had to work at night to ensure all extraneous sounds were avoided. He used a single organ pipe with a frequency of 512 Herz (an octave above middle C). In 1895 there were no microphones or audio-electronics and the judgement as to when the sound was inaudible was made by the experimenter himself. An electric chronograph recorded the times to one-hundredth of a second. By covering more and more of the auditorium's wooden seats with soft cushions, he showed that the reverberation time was inversely proportional to the number of seats covered with cushions. He repeated the experiments in eleven other rooms in the university, with volumes ranging from a lecture theatre of 9300 cubic metres down to an office of just 35 cubic metres. From the results he derived the equation for which his name is well-known giving the relationship between the reverberation time (RT), of a room, in seconds, its volume (V), in cubic metres, and the area (A), in square metres, of sound-absorbing surfaces in the room.

$$RT = 0.163\frac{V}{A} \quad (1)$$

Sabine used this equation to give an objective means of comparing different auditoria and, in particular, to compare the proposed design for the new Boston Music Hall with the Leipzig Gewandhaus, on which its overall shape was based, and the old Music Hall in Boston. He was able to specify, for the first time, the precise degree of sound absorption in the interior of the new Boston hall needed to achieve the same reverberation time as the Leipzig Gewandhaus whose seating capacity it exceeded by 70%, and volume by 40%. Sabine's predictions were accurate and the acoustic of the new hall was widely praised. He had fulfilled his goal of overcoming the "unwarranted mysticism" that then surrounded the subject of architectural acoustics and, most importantly, achieved "the calculation of reverberation in advance of construction".

Sabine was soon being approached by the owners of various types of room to advise on how to rectify their acoustic problems. Often this followed the failed attempts by others to deal with the problems. Sabine noted the persistent use of a traditional but wholly ineffective remedy which involved stretching a grid of steel wires in the top of a church, theatre or court room which suffered too much reverberation on the mistaken believe that the wires would resonate and absorb sound. In New York and Boston he had seen theatres and churches with just four or five wires stretched across the room while in other auditoria several miles of wire had been used, all without the slightest effect.

As part of his diagnosis of acoustic problems he would sometimes plot a contour map showing the distribution of the sound intensity. This helped him identify the source of the worst sound reflections from the walls and ceiling and hence reduce them by using sound-absorbing panels or adding decorations that would break up strong reflections from large plane surfaces.

Sabine also turned his attention to the design of new theatres and how best to create a near-uniform acoustic experience for every member of the audience. To help him in these studies he used the newly-perfected *schlieren* method of photography to show sound waves passing through air in two-dimensional models of auditoria (Fig.2). He was thus able to show in plan and section, how sound waves were reflected and broken up as they emanated from the stage into the auditorium. Outside the field of building structures this was probably the first use of a scale model to investigate the engineering behaviour of a building.

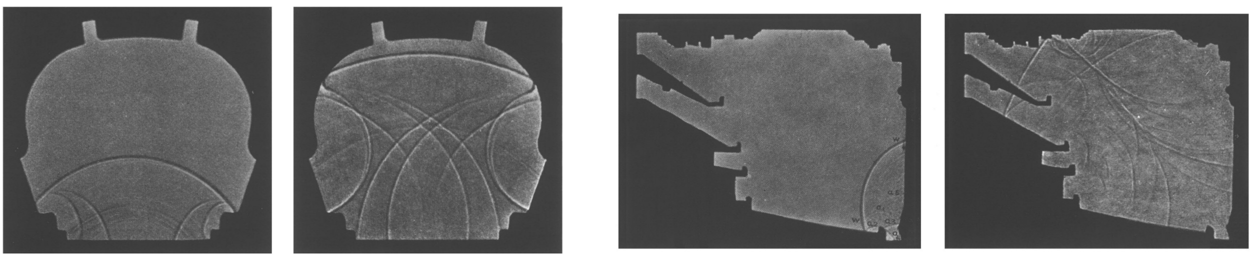

Figure 2: Photographs showing the progress of sound waves through a model of a theatre; (Sabine 1922)

THE PERSISTENCE OF THE TRADITIONAL DESIGN METHODS

Design methods in the 1920s

When designing recording studios, auditoria and concert halls in the 1920s and 1930s, the reverberation time could be predicted using Sabine's method, but otherwise the acoustics was addressed largely as an empirical process based on experience. Good common-sense design guidance available since the 1830s served designers moderately well and was usually adequate as long as concert halls were built in traditional ways. In the 1920s, however, architects began experimenting with new shapes of auditoria to which the familiar acoustic design rules did not apply. It became necessary to think about their acoustics from first principles, considering both the different paths by which sound might reach the listener in the auditorium, and the correct balance between direct sound and sound reflected off the walls or ceiling. The French acoustician Gustave Lyon was one of the pioneers of this approach at the Salle Pleyel in Paris, completed in 1927 who made much use of ray-tracing, the method first illustrated by Patte in 1782 (Fig.1). The architect Victor Horta also used ray-tracing when designing the Salle Henry-le-Boeuf in Brussels in 1928 (Fig.3). Despite his client's wishes, however, Horta refused to consult Lyon, then considered to be the leader of the French school of acoustic design, because he considered Lyon's purely scientific approach paid insufficient attention to how music actually sounded in concert halls. Horta visited a great many halls in Europe and the USA.

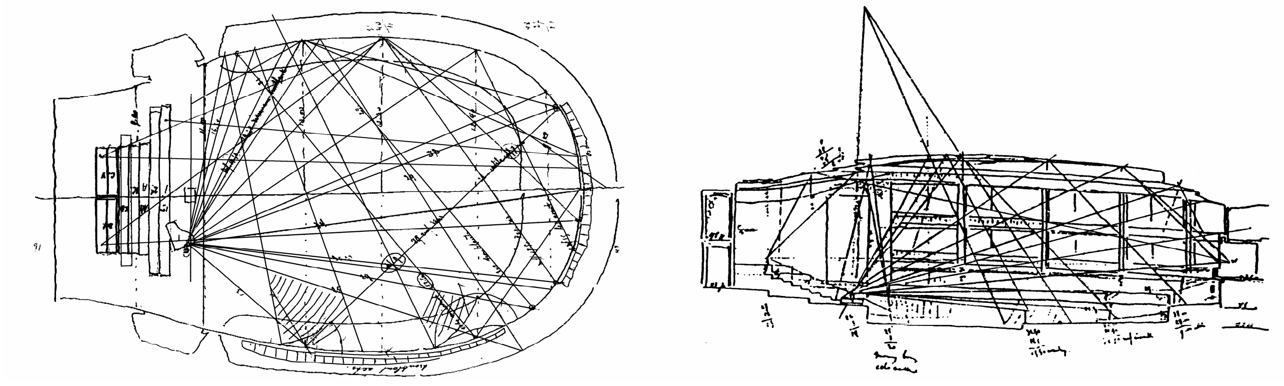

Figure 3: Ray diagrams for Salle Henri-le-Boeuf, Brussels, by Victor Horta, 1928; (Archives of Horta Museum)

In the early 1930s some German acousticians used rays of light in three-dimensional models of theatres to study the path taken by sound waves, but such models gave no help in investigating different frequencies of sound, the reverberation time or the different times that sound would take to reach a listener by different sound paths. Acoustic design was still largely a subjective art at this time.

Design methods in the 1950s

The science of acoustics received an unexpected boost during the Second World War when sound was the primary means for locating the sites of enemy guns and, before the development of radar, in detecting the approach of enemy aircraft. Sound is transmitted even further in water than in air, and underwater microphones were used to detect the engines of ships and submarines. There was also the development of sonar, an underwater version of radar which used the reflections of sound to locate underwater objects such as mines and vessels and also to build up a 3-D map of the sea bed. After the War, many of these acoustics experts became consultants advising building designers on acoustics. Nevertheless, the war-time developments in acoustics did not transform building design overnight. When the Royal Festival Hall in London was designed in 1949-50 the main acoustic consultant was 'one of the old school' who based his advice on his 30 or so years of experience in building design and discussions with musicians, conductors, music critics, music lovers and other acoustics experts, rather than on the latest acoustic science. Some fifty years after Sabine's work, still the only measurable and (relatively) predictable design parameter was the reverberation time. Nevertheless consultants still differed in their recommendations for the most desirable value for the Festival Hall – one said 2.2 seconds, the other 1.7 seconds, a very large difference. 1.7 seconds was chosen but, as it turned out, the reverberation time of the finished hall was found to be just 1.5 seconds, which most people agreed was too short. Acoustics was still far from being a precise science, and assessment was subjective - some musicians and conductors liked the acoustic, while others did not. In its early days a great many studies were undertaken in the Festival Hall to find ways of lengthening the reverberation, but no solution was found. Following further studies in the early 1960s (it was said that the Royal Festival Hall was the most studied hall in the history of acoustics) when the hall was being refurbished, a number of microphones and loudspeakers were installed to provide 'assisted resonance' which increased the reverberation time to the desired value of 1.7 seconds, and the acoustic of the refurbished hall met with widespread acclaim. Taste in the world of music can change, however, and, after many discussions and several trials, it was finally agreed in 1995 to stop using the assisted resonance, since when the acoustics of the hall is still acclaimed.

THE USE OF PHYSICAL MODELS IN ACOUSTIC DESIGN

After Sabine's pioneering work, the most far-reaching progress in acoustic design methods came with the use of scale models. Models have been used to aid the designers of buildings for many millennia, however, their use entered the modern scientific age only in the 1860s. The English engineer William Froude studied the performance of scale models of ships and used non-dimensional constants to adapt the results and predict the performance of full-size ships, even when the parameters varied non-linearly with scale (Addis 2007 p.479-80).
Scale models were first used to measure and analyse the acoustic performance of auditoria by the German physicist Friedrich Spandök in the early 1930s (Spandök 1934) (Baron 1983). Using simple dimensional analysis to find suitable dimensionless constants, he showed that the acoustic behaviour of a room varies inversely with the model scale – for a one-fifth scale model, the sound frequencies used for testing need to be five times higher than normal frequencies. He also recognised the need to ensure that the temperature, pressure and density of the air in the model room were identical to a real room, since these affect the speed of different frequencies of sound differently. Spandök's first concern was to demonstrate that tests on a model were indeed a reliable representation of the acoustic behaviour of a full-size room. He then studied the effect on both the decay of sound and its distribution throughout an auditorium with raked seating (better) and with a

semi-circular wall behind the stage (worse). Using a microphone he displayed the decay of sound in the model auditorium on the screen of an oscilloscope, and recorded the results in a photograph. Although similar studies were undertaken in the late 1930s in a number of other university physics departments, which all demonstrated the possibility of using models during the design of an auditorium, the technique did not gain widespread use by building designers until after the war.
The Danish acoustician Vilhelm Jordan had been one of the pioneers in using scale models in acoustic design In the 1930s using a wire recorder to store the results and allow them to be analysed. He was selected in the mid-1960s to advise the designers of the Sydney Opera House on how to achieve a satisfactory acoustic for the many different uses – including concerts, opera and speech – that were proposed for the auditoria. Since these different uses require different acoustic characteristics, especially reverberation time, one early plan was to provide a large moveable ceiling that could be adjusted to create a reverberation time to suit each need. So different from established practice were the proposals for the auditoria that Jordan advised undertaking acoustic tests using scale models. Over five or six years models of several different proposals for the two auditoria were made at 1-to-10 scale. Made of wood, they included models of the audience with bodies made from neoprene and heads of cardboard. The tests soon established that it would not be possible to create an acoustic that could serve the original idea of multi-purpose auditoria. The curved form of the walls also caused problems in achieving a satisfactory distribution of reflected sound in all parts of the auditoria.

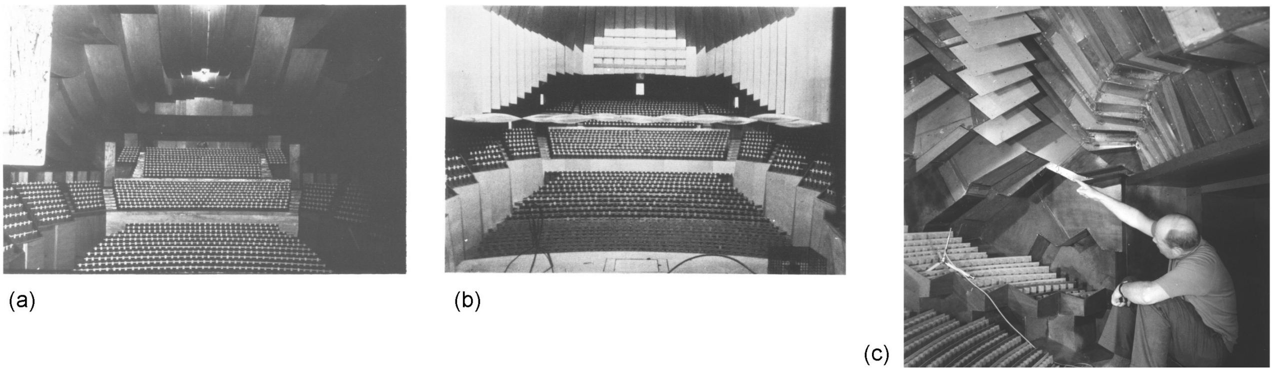
(a) (b) (c)

Figure 4: 1/10 scale wooden models for studying the acoustic performance of (a) early, (b) intermediate, and (c) late interior designs for the Sydney Opera House. The figure in (c) is V.L. Jordan; (V.L. Jordan)

The model tests demonstrated the benefits of introducing flat side walls to the auditoria to provide lateral reflections and reflective interiors to the boxes. They also showed that the original ceiling of the auditorium, consisting of large catenaries hung longitudinally from the external shell, left the orchestra area suffering from a deficiency of early reflected sound. Adding suspended reflectors over the stage did not substantially change this situation and it was decided to reduce the distance between the side walls and raise the auditorium ceiling substantially. Many different shapes and positions of reflectors suspended above the orchestra were studied and the final arrangement used small toroidal discs (slightly convex on the underside) suspended from the ceiling by adjustable cables.
The acoustics of the finished auditoria were finally assessed in a number of test performances with real orchestras and audiences. Magnetic-tape recorders were used to record the decay of sound both after firing a gun on stage (with a blank cartridge), and by getting the conductor to halt the orchestra abruptly while playing Beethoven at full power. The results of these tests were used to recalibrate the model tests and to identify a number of adjustments that could be made to the various moveable reflectors to achieve the best acoustic.
Jordan's work on the Sydney Opera House was a milestone in the development of acoustics (Jordan 1973, 1980). His particular goal was to seek suitable criteria or parameters that could be used to define the acoustic of a room. Since Wallace Sabine's work in the early 1900s, it had become accepted that the key parameter was the reverberation time. However, more and more auditorium designers and musicians were coming to realise that this was not the only factor that made some halls good for concerts, and others bad. The question was, what other parameters should be considered and, if they were to help designers, it had to be possible to measure them. From the 1950s, developments in electronics and tape records gradually opened up the possibility of measuring the acoustic behaviour of auditoria. Gradually qualitative terms often used by musicians, such as 'warmth', 'intimacy', resonance' and 'fullness of tone' came to be replaced by terms with precise scientific definitions. One criterion for speech, proposed by a German acoustician in 1953, was named 'Deutlichkeit' (intelligibility) translated into the English of acoustics as 'definition'. This was the proportion of the total sound energy that had arrived at the listener within the first 50 milliseconds. For music one criterion was the 'rise time' – the time it takes for the sound intensity to reach half its steady-state value. Another was 'steepness' – the rate at which the energy arrived at the listener. For the Sydney Opera House, Jordan was one of the first acousticians to use the 'Early Decay Time' (EDT) – the rate at which the sound intensity decays during the first few milliseconds, rather than later when the sound has reached every part of the auditorium – as a measure that gave a better correspondence between measurable quantities and listeners' subjective judgements of quality. During the final decades of the twentieth century many other acoustic parameters, often with curious names, have been proposed as scientific measure of acoustic quality – terms such as the 'inversion index', the

ratio of the rise time measured in the auditorium to the rise time measured on the stage, which reflects the need for the performers on stage to hear sounds before the audience, and others such as 'hall-mass', 'point of gravity time', 'clarity' and 'index of room impression'. Even today, however, different acousticians prefer their own approach to defining acoustic performance and hence to designing auditoria to achieve the right conditions for different uses (Barron 1997). Perhaps the very fact that acoustic quality is finally judged by people rather than measuring instruments means that some subjectivity is likely to remain.

CONCLUSIONS

The development of design methods for the acoustics of auditoria has followed the same pattern observed in other branches of building engineering design. Initially designers used their own experience to observe and improve their art and collected their experience in the form of simple design rules which could be passed on to other designers. In acoustics this approach was known in ancient times and has continued even into the twentieth century. The technical difficulty of measuring acoustic phenomena delayed a truly scientific approach to understanding acoustics until the late eighteenth century (over a century later than for structural engineering). The first scientific concept in acoustics, defined in quantitative terms by Sabine in the 1890s, was the *reverberation time* whose relationship to the dimensions of a room was expressed as an empirical quantity known as the *absorptivity* of the surfaces of the room. This approach remains the most important in acoustic design today. The testing of scale models together with the use of non-dimensional constants was developed in acoustics simultaneously with their use in the design of building structures, first in the 1930s and more widely in the 1960s. Their use consolidated the understanding of acoustic phenomena and laid the foundation for creating mathematical models using computers.

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