Chapter 6
Acoustical Properties of Old and New Performance Spaces

6.1 Concert Halls

6.1.1 Tonal Requirements

Among the spaces used for musical performances, large halls for symphonic concerts play a particular role when considering acoustical properties, because in these, the musical experience of the listener is least influenced by visual impressions. While in the opera, the action on the stage, for chamber music performances, the close visual contact with the performers, and for church concerts the atmosphere of the room can make an essential contribution to the overall impression, for symphonic performances the sound – esthetic evaluation assumes predominant importance. Nevertheless, one should not underestimate the visual relationship between listener and podium, as well as the architectural impression of the room, as they influence the tonal sensation (Winkler, 1992; Opitz, 1993).

An important criterion for the acoustical quality of a concert hall is its reverberation time. As mentioned earlier, reverberation enhances the melting of the individual voices of the orchestra into a closed overall sound and lends a uniform flow to melodic phrases in their time progression. Furthermore, the reverberation time plays a role in the loudness impression, since the resulting energy density and thus, the sound pressure is directly proportional to the reverberation time for tones which are not excessively short. Extremely long reverberation, naturally can also lead to negative effects, when short pauses are no longer clear or when a piano passage after a forte ending gets lost in the reverberation.

Next to the homogeneity of the overall sound, the clarity of passages with strong rhythmic structure or of polyphonic vocal arrangements is essential for favorable sound impressions by the audience. Since this condition must be met by the intensity relationship between the direct sound (including the first, only slightly delayed reflections) and the later reverberant sound, the various seating groups in a hall naturally don't exhibit the same acoustic quality in this respect.

J. Meyer, *Acoustic and the Performance of Music.*
DOI: 10.1007/978-0-387-09517-2_6;

A balanced relationship between the early sound and the reverberant sound is a necessary requirement for a concert hall, to give the audience a satisfying tonal impression. However, there are additional considerations which also play an important role, thus, the listener does not want to be confronted by the orchestra from a tonal standpoint, but rather be included in the musical experience. In addition to adequate loudness, this effect is brought about by the direction of incidence of the first reflections combined with the diffuse reverberations for which sound arrives uniformly from all sides (Meyer, 1965). The opposite of spatial impression is observed when music with reverberation is heard from a loudspeaker: the reverberation can bring about a good overall sound, but it cannot provide spatial inclusion of the listener.

Finally, at different locations in the audience, the intensity relationships between the individual instrument groups, dispersed laterally and in depth over the podium, must be as uniform as possible and should not deviate too much from the sound picture at the position of the conductor. This addresses a particular problem of acoustical relationships during musical performances: the listener should obtain a possibly complete tonal impression, however, the conductor can only shape the sound of the orchestra on the basis of the aural impression from his position. Only during the rehearsal can he gain an impression of the tonal effect in the hall. He must, therefore, be able to obtain an optimal acoustic tonal impression from the podium in order to achieve the best possible artistic result.

The individual players must also be able to hear each other well, otherwise the ensemble performance suffers. With regards to the demands placed by the musician on the acoustical and also the nonacoustical requirements for the platform, three stages can be identified which lead to a difference in quality of performance and thus, to the orchestral sound. At the lowest level we have the minimal demand of a technical ensemble performance, free of errors in relation to intonation, rhythmical precision and adherence to dynamical categories. Already at this stage, difficulties can arise. When the self perception of the musician is too loud and other performers are heard too little, harmonic relations are still perceived and intonation can still be correct, but the precision of rhythmic adaptation and consequently, the certainty of entries and articulations will suffer. In contrast, if the self perception of the performer is inadequate in its rise above the sound of the orchestra, the intonation is compromised, while the insufficient aural impression from the instrument of the performer will still permit a temporal precision in the performance by virtue of the performance mechanics controlled by the feeling of the musician.

On the second level, the individual performer senses optimal conditions for the shaping of the tone of his own voice, including a sure and easy attack of the instrument: the performer has a “feeling of well-being.” Within this framework, dynamic and tone color variation possibilities can be exhausted to the technical limits. Included in this limit is also the circumstance that performers of low instruments, especially the bass, should not feel disturbed by sympathetic vibration of their own instruments or the floor, which are excited by other voices, as for example, low percussion instruments. This could make their own intonation more difficult.

The highest level results in a common artistic achievement of all participants. This especially includes an integrated overall sound of the individual string groups based on a high measure of uniformity with respect to the temporal fine structure of the tone formation. To accomplish this, the individual performer must sense a tonal inclusion in the group. This involves the knowledge of reactions of other performers and also, the trained experience based on the traditions of the orchestra. Visual contact and joint breathing play an equal valued role next to acoustical communication (Meyer, 1994a).

Similarly, these conditions of mutual listening can be transferred to the situation of a soloist. On the one hand, the necessary "resonance" in the form of early reflections and appropriate reverberation is expected (which at the same time is sensed as an easier approach to the instrument), on the other hand, the feeling is desirable to be carried by the instrument (in relation to intensity). For singers it has even been noticed that the acoustical feedback of the room is capable of a physiological enhancement of the vocal functions (Husson, 1952). In this context it should be mentioned that instrumental soloists, especially string players, feel very uncomfortable in rooms in which the sound is reflected too strongly by the walls and the ceiling from the area of the podium into the auditorium, because the missing or overly weak first reflections to the podium cause the impression that the tone can no longer be influenced by the instrument, as soon as it is placed in the room. On the other hand, the soloist should be easily heard by the audience, therefore, the position on the podium in relationship to the orchestra should not be acoustically disadvantaged, but rather occupy a preferred position.

Inasmuch as mutual listening by musicians in the concert hall is determined by the spatial arrangement of the region around the podium, while the resonances noticed by the soloist are determined by the acoustical relationships in the entire hall, it is not surprising that hall quality judgments of musicians are very different, depending on their function, and that they in turn can be very different from the judgment of the audience. This discrepancy in evaluation of halls is all the more evident because many musicians rarely take the opportunity to hear concerts in a fully occupied hall from the location of a normal listener.

6.1.2 Reverberation Time and Hall Size

With the multitude of factors which influence the acoustical quality of a concert hall, naturally the question of optimal relationships for symphonic performances arises. In order to be able to draw conclusions about the necessary requirements for excellent acoustics from technical data, it is important to determine which halls are judged to be especially good, both by musicians and audiences.

In the years from 1950 to 1955, F. Winckel conducted a survey of approximately 25 internationally recognized conductors concerning the acoustically best concert halls. The result was the rank-ordered listing of the five best halls given in Table 6.1, for which also the year of dedication, the volume, number of seats, reverberation

Table 6.1 Concert halls before 1940

Concert hall	Constr. year	Volume (m^3)	Seats	Reverberation time (s)	
				Mid	Low-frequency
1. Large Musikvereinssaal Vienna	1870	14,600	1,680	2.05	2.4
2. Theatro Colon Buenos Aires	1908	20,550	2,487	1.8	–
3. Concertgebouw Amsterdam	1887	18,700	2,206	2.0	2.2
4. Symphony Hall Boston	1900	18,740	2,631	1.8	2.2
5. Konzerthus Göteborg	1935	11,900	1,371	1.7	1.9

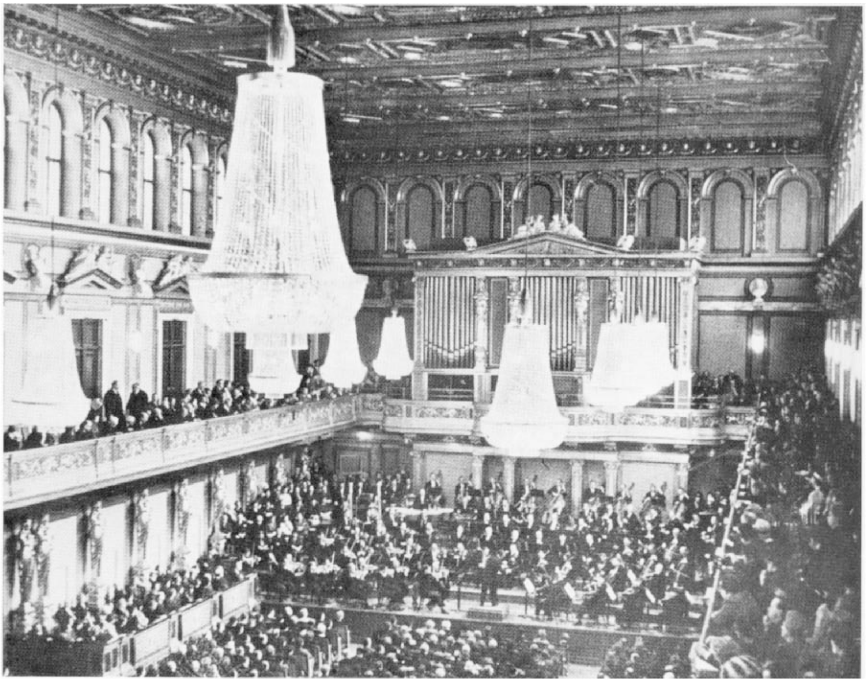

Fig. 6.1 Grosser Musikvereinssaal in Vienna (Bärenreiter – Verlag Kassel (MGG))

times in the middle and low frequency region (500–1,000 Hz and 125 Hz, respectively) are given under occupied conditions.

This table shows that the optimum of the average reverberation time for halls of that size is evidently in the region between 1.7 and slightly above 2 s. The Musikvereinssaal (Fig. 6.1) has the longest reverberation time, even though it is next to the smallest of the five halls. This hall is famous for its ability to enhance the performance of romantic works, yet the acoustics are also praised for an ability to present classical compositions. In contrast, the hall in Amsterdam is judged by sensitive musicians not to be as reverberant, even though the difference of the reverberation times is only approximately 0.05 s. Finally, the Konzerthus in Göteborg is the driest of the halls considered, it also is nearly the smallest.

The connection of J. Brahms and A. Bruckner to the Vienna Musikvereinssaal is often pointed out. Both performed their own works here, therefore it is considered especially authentic for their music. Nevertheless, one should not overlook the fact that this hall has undergone changes during reconstruction in 1911 which also affect the room acoustics. Among other things, the wood construction of the upper galleries was replaced by steel beams and the load bearing statues, which earlier were located at the front edge of the galleries, were moved to a location in front of the side walls. The entire weight of the ceiling construction was increased by a layer of sand and bricks. The stage surface was widened, and the number of seats was increased. From an acoustical standpoint, this meant an increase in the effective hall volume, a decrease in the absorption of the low frequencies, and a change in the time sequence determined by the widening of the hall. Even though the hall was praised for its good acoustics before the renovation, one can assume that the renovation resulted in a further improvement of the hall acoustics (Clements, 1999).

For newly constructed concert halls, those that were built within the first 20 years after the second world war, experiences with older halls were utilized. However, in the meantime, the body of knowledge related to room acoustics has increased so much, that from today's standpoint, those newer halls, which by now are almost designated as historic halls, are no longer evaluated as equally good. Table 6.2 gives five examples of well known concert halls from the 1950s and 1960s. Their listing order is given according to the building year and in no way reflects a value judgment.

From this listing it is clearly noted that at the time an effort was made to obtain shorter reverberation times. In the case of the Royal Festival Hall, this may be related to the extraordinarily large number of seats. It can also be concluded that the tastes of musicians and listeners has changed with time, as has the interpretation style for classical and romantic music. For example, the Liederhalle in Stuttgart was initially judged as acoustically excellent upon completion (Beranek, 1962), while today it is considered relatively dry. The tendency for this development of room acoustical perceptions in these, now considered historic concert halls shifts from a greater transparency of the tonal picture in the years around the middle of the

Table 6.2 Concert halls after 1950

Concert hall	Constr. year	Volume (m^3)	Seats	Reverberation time (s)	
				Mid	Low-frequency
1. Royal festival Hall London	1951	22,000	3,000	1.45	1.35
2. Liederhalle Stuttgart	1956	16,000	2,000	1.65	1.8
3. Beethovenhalle Bonn	1959	15,700	1,407	1.7	2.0
4. Philharmonie Berlin	1963	26,000	2,218	2.0	2.4
5. Meistersingerhalle Nürnberg	1963	23,000	2,002	2.05	2.2

Source: 1. Parkin et al. (1952); 2. Cremer et al. (1956); Gade (1989b); 3. Meyer and Kuttruff, (1959); 4. Cremer and Müller (1964) century to a more homogenous richness of sound in the subsequent decades. Among other things, this may be based on the sound expectation of the 1950s related to the larger transparency of radio and record reproductions, while later the sound aesthetic expectation for real concert experiences became clearly separated from that for sound recordings. A concert hall cannot reach the transparency of a recording, nor a recording the spaciousness of a concert hall. Judgments about the acoustic qualities of concert halls can therefore only be interpreted in the context of the times, detailed questions are not necessarily universally applicable.

Thus it becomes understandable that the long-time chief conductor of the Berlin Philharmonic, A. Nikisch, in the years around 1920, considered the Hall of pillars in the "House of Unions" in Moscow as the acoustically best concert hall in Europe: this hall has room for 1,600 people, a volume of 12,500 m^3, and an average reverberation time of 1.75 s when occupied (Lifschitz, 1925). It is particularly suitable for transparent presentations of polyphonic structures, as found in the neo-baroque composition style of that era. For that matter, the "Neue Gewandhaus" (1886) in Leipzig, famous for its room acoustics, had an average reverberation time of only 1.55 s (Kuhl, 1959).

The fact that the actual reverberation time of 2 s of the Berlin Philharmonie (Fig. 6.2) and the Nürnberg Meistersingerhalle for a long time was considered as optimal, suggest a comparison not only with the Vienna Musikvereinssaal but also with the majority of concert halls built in recent years throughout the world. Extensive comparisons are found in Barron (1993) and Beranek (1996). Table 6.3 assembles (again five) examples of concert hall development in Germany in the 1980s and 1990s. While the Schaupielhaus in Berlin and the Bamberg Hall (Fig. 6.3) – with a volume similar to the Musikvereinssaal- today are counted among the smaller new constructions, the Munich Philharmonie, with its size, approaches the limit of the framework acceptable for symphony concerts. Characteristic for the Leipzig Gewandhaus (Fig. 6.4) is a reverberation time which remains uniform for low frequencies while in the old opera house in Frankfurt the reverberation time clearly diminishes.

Table 6.3 Concert halls after 1980

Concert hall	Year of construction	Vol. (m^3)	No of seats	Rev. time (s)	
				Mid	Low fr.
1. Gewandhaus Leipzig	1981	21,560	1,905	2.0	2.0
2. Old Opera Frankfurt	1981	22,500	2,353	1.95	1.55
3. Schauspielhaus Berlin	1984	15,000	1,674	2.0	2.2[a]
4. Philharmonie Munich	1985	30,000	2,400	2.1	2.2
5. Sinfonie a.d. Regnitz Bamberg	1993	14,300	1,420	1.9	2.2

Source: 1. Fasold et al. (1981, 1982); 2. Brückmann (1984); 3. Fasold et al. (1986, 1991); 4. Müller and Opitz (1986); 5. Opitz (1993)
[a] Now 2.6

Fig. 6.2 New Philharmonie in Berlin. In the background left, one of the three small tower stages for spatial sound effects can be recognized (Foto Friedrich, Berlin)

As is the case for the remaining three examples of this table, the majority of other halls of all periods, recognized as having good acoustical properties, show a frequency dependence of the reverberation time in the lower registers with a more or less clear rise, which supports the aural reverberation sensation. As the two curves for occupied halls in Fig. 6.5 make clear, this lengthening of the reverberation time becomes noticeable below a frequency of approximately 200 Hz. For a frequency of 125 Hz, the curves of these two halls even reach a value of 2.4 s. Such an increase in reverberation time is very advantageous for orchestra concerts for energetic reasons, since most low instruments have their strongest sound contributions above 200 Hz and radiate only relatively weakly at lower frequencies. It is therefore advantageous when the fundamental registers of bass voices are strengthened by the hall.

At high frequencies the reverberation curve in all halls drops. This is associated with dissipation losses and surface roughness of walls and ceilings. In general, the reverberation time at 2,000 Hz is by 5–10%, and at 4,000 Hz around 15% less than at 1,000 Hz. There are, however, current tendencies to use technical means, such as covering wood surfaces without pores, in order to maintain the 2,000 Hz reverberation time constant at the same value as for the midfrequencies (Munich Philharmonie and Bamberg). The value at 4,000 Hz lies by 10–15% lower (Müller and Opitz, 1986; Opitz, 1993). This rise of the region around 2,000 Hz gives a particular brilliance to the tonal picture and also supports the singers formant.

Fig. 6.3 Joeph-Keilberth-Hall of the "Sinfonie an der Regnitz" in Bamberg (Stadthallen GmbH, Bamberg) (See Color Plate 6 following p. 178)

The two reverberation curves for halls in Vienna and Berlin show a difference in detail which can be considered typical for these two kinds of concert halls. While the reverberation time in Vienna decreases relatively steadily for higher frequencies, the curve for the Philharmonie is nearly horizontal in the midregion. In fact, the open tonal effect is enhanced by a slight rise in the region around 1,000 Hz, i.e., in the frequency region of the a(ah)-formant, a circumstance which can be considered advantageous, particularly in view of the reflection conditions caused by the shape of the hall, since it enhances the clarity of the tone picture. In contrast, the reverberation behavior of the Musikvereinssaal leads to a more soft and rounded sound.

Figure 6.5 at the same time visualizes the difference which can arise between acoustical conditions in an occupied and an empty hall. If the seating from its inception is not arranged in such a way that it causes similar sound absorption properties as the audience, the absorption in the hall is increased significantly by the audience. Thus, in the Musikvereinssaal, as a result of the un-upholstered wooden chairs, the empty hall has a reverberation time of more than 3.5 s at frequencies near 500 Hz, so that for rehearsals or recordings a far greater reverberation is present than in a concert, therefore, during recording sessions, additional absorption surfaces are brought into the hall (e.g., wool blankets hung over the chairs). In contrast, in the Berlin Philharmonie, the seats are strongly absorbing. The audience and

Fig. 6.4 Large hall of the Gewandhaus in Leipzig (Gert Mothes, Leipzig) (See Color Plate 7 following p. 178)

orchestra reduce the reverberation only by about 0.4 s. In a studio setting, i.e., with orchestra but without audience, the reverberation curve follows a path approximately midway between the two drawn curves (Cremer, 1964). Inasmuch as the audience is responsible for the largest portion of the absorption in an occupied hall, the upholstery in an occupied hall should, if possible, not serve as an additional absorption surface, since otherwise the desired reverberation time of 2 s can hardly be realized. This is accomplished by having the cloth cover of the back only reach to shoulder height, with the additional wood surface behind the head serving as a reflecting surface.

The problem of favorable reverberation time, however, should not only be considered in the context of hall size. The question arises to what extent a depen-

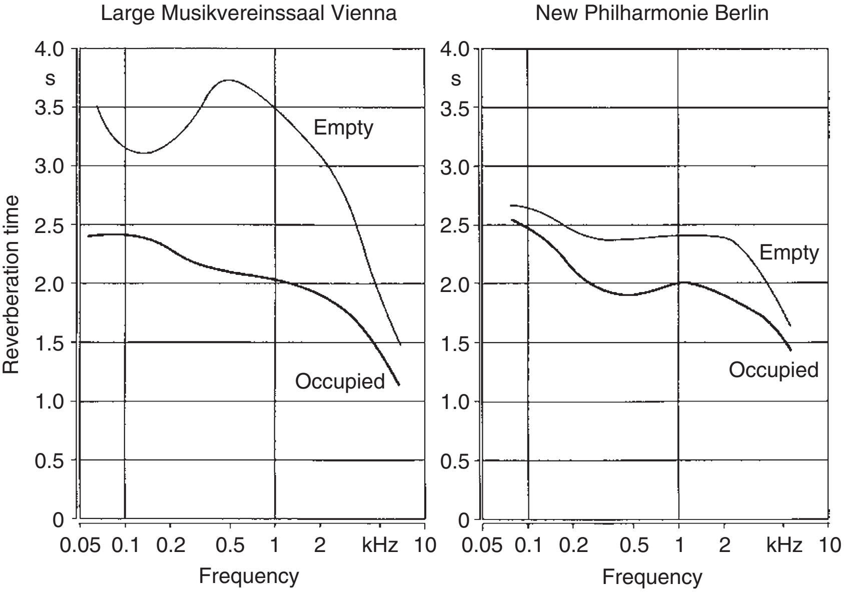

Fig. 6.5 Reverberation curves of two concert halls (after Beranek, 1962, and Cremer, 1964)

dence exists on the character of the music to be preformed in the hall. Should the tonal picture tend more toward a glass-clear transparency or an immersing overall sound, would, within certain limits, likely depend on the style of the work, since composers will be significantly influenced in their sense of tone by the acoustical environment in which they have preformed or heard their pieces (Blaukopf, 1960). Thus, composition styles are influenced by room acoustical conditions, as they are similarly influenced by the technical development of instruments. The performance which is to reproduce the tonal conception of the composer must therefore also be oriented toward the acoustical givens of the "original." It is of course self-evident that a performance under the same conditions as during the time of creation is impossible in most cases, and in most circumstances not even meaningful. It is likely wrong to assume that composers of the great master works considered the acoustical conditions under which they experienced their performances always as optimal.

Reference was already made to the connection between the Vienna Musikvereinssaal and the great masters of the romantic era. Also the other halls which were built at that time have essentially similar characteristics which enhanced the romantic sound ideal; in this context the destroyed hall of the old Philharmonic in Berlin should be mentioned, which, in its acoustics, corresponded to the type of the Vienna Musikvereinssaal. In contrast, the hall of the old Gewandhaus in Leipzig (Fig. 6.6), where premier performances of R. Wagner's Prelude to the Meistersinger and J. Brahms' violin concerto took place, is a relatively small hall. This concert hall was built in 1780 for an audience of approximately 400, and after the addition of the upper balconies provided seating for 570. The size of the hall is 2,100 m^3, the

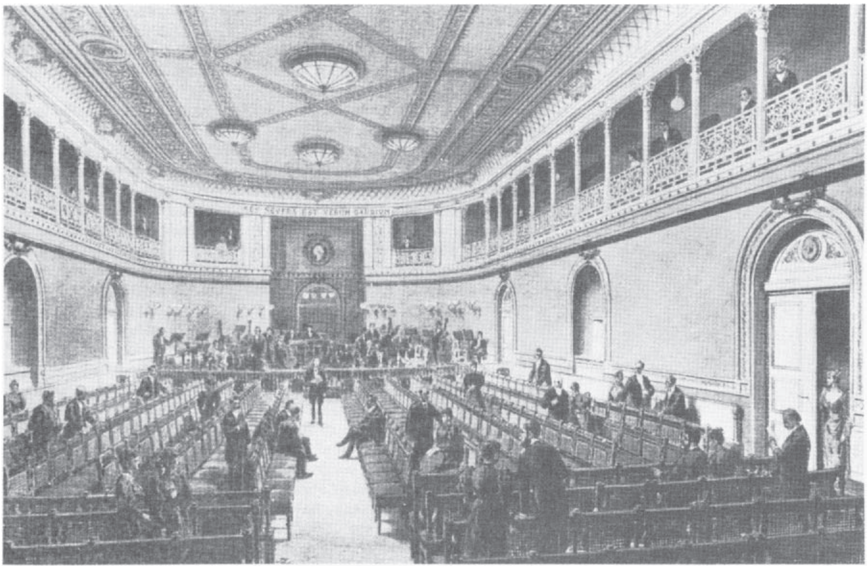

Fig. 6.6 The concert hall of the old Gewandhaus in Leipzig after remodeling in 1842 (Bärenreiter - Verlag Kassel (MGG))

Table 6.4

Concert hall	Volume (m^3)	Reverberation time (s)	
		Mid freq	Low freq
Schloß Eisenstadt	6,800	1.7	2.8
Schloß Esterháza	1,530	1.2	2.3
Hanover Square Rooms London	1,875	0.95	1.6
King's Theatre London	4,550	1.55	2.4
Festsaal der Alten Universität Vienna	5,250	1.7	2.6

reverberation time for occupied circumstances was calculated as about 1.2 s using old drawings (Bagenal and Wood, 1931). Under such circumstances the music naturally exhibited an essentially greater presence than in the halls of much greater volume dating from the second half of the nineteenth century. The works of the classic composers therefore obtained a far more transparent tonal shape.

This also applies – though in different measure – to the concert halls for which J. Haydn composed his symphonies, and in which he preformed them himself. Fortunately two of these halls, i.e., the ones in Eisenstadt and Esterháza (today "Fertöd") have been preserved in practically original condition so that reverberation measurements could be conducted (Meyer, 1978a). Table 6.4 contains the results, which have been recalculated for occupied conditions, along with recalculated reverberation times of two London halls based on literature data (Elkin, 1955; Robbins Landon, 1976), and the values for the festival hall of the old university in Vienna, in which in 1808 the now legendary performance of Haydn's "Creation" took place in his presence.

All of these halls point, or pointed toward a significant rise in reverberation time at low frequencies. The halls in Eisenstadt and Vienna, with their reverberation of 1.7 s at midfrequencies, correspond to our contemporary conception of the reverberation time of early classical orchestral music. The former King's Theater in London comes quite close to this value. Within this context it should be noted that Leonhard Bernstein considered the Beethoven Hall in Bonn, the reverberation time of which also is 1.7 s, as particularly suitable for performances of Haydn symphonies, while it is considered somewhat too dry for romantic music. The hall in Esterháza and the only, slightly larger concert hall in the Hannover Square Rooms in London, were not only significantly smaller in dimensions than the other ones listed in Table 6.4, but their acoustical conditions also were characterized by significantly shorter reverberation times. In today's terms, these halls, as for example the Eroicasaal in the Palais Lobkowitz in Vienna (see page 252), correspond to relatively large chamber music studios.

And in fact, concerts for orchestral works as well as chamber compositions were performed in these halls. The symphonies of J. Haydn, written specifically for these halls of varying reverberation relationships, are especially appreciated under these circumstances. Thus the symphonies written for Esterháza contain rhythmic fine-structures and dynamic jumps from an orchestral *forte* to a *piano* of individual voices, which would have been totally lost in the reverberation of the London halls, and also in Eisenstadt. In contrast, the symphonies written for the king's theater, always have a fermata associated with *forte* breaks, or a following pause. The composition style in these symphonies also frequently utilizes the tonal melting effect of the reverberation (Meyer, 1978a).

The historical development of concert halls, which in this context could only be discussed in a few examples, leads to the conclusion that only a slightly longer reverberation time is appropriate for the works of the classical period in comparison to romantic music. This is especially true since during the classical period orchestral concerts frequently occurred in theaters, which in comparison to the concert halls of that time, had a noticeably shorter reverberation time. Investigations concerning optimal reverberation times have led to similar results. These results will be further considered in the section on studios (Kuhl, 1954a, b).

In two recent concert halls, new approaches have been pursued which, within certain limits are designed to adapt the reverberation time to the compositions to be performed. The halls in Dallas (1989) and Birmingham (1991) not only utilize moveable absorption curtains (not too uncommon), which make it possible to reduce the reverberation time, but also add echo chambers to increase the reverberation time. They are located all around the hall above the highest balcony as well as in the front of the hall at a lower elevation. They can be closed with concrete doors (Forsyth, 1987; Graham, 1992). These, in connection with height-adjustable reflectors weighing more than forty tons, located above the stage, are designed to create acoustical conditions not only appropriate for the standard symphonic works but especially for orchestral works with large choirs written by composers from Berlioz to Mahler which require halls with a cathedral-like character.

A reverberation time of less than 1.7 s in a large hall meets with decided universal rejection, since then even intensity relations become very unfavorable. When, nevertheless concerts under unacceptable acoustical conditions are to be performed in such halls, the utilization of electroacoustic installations becomes an option. This applies especially to halls which are so large that the sound energy of an orchestra or a soloist respectively is no longer sufficient to bring adequate intensity to the distant seats.

If the only concern is to increase reverberation time, then the microphones have to pick up sound contributions of the diffuse sound field, which are then radiated over speakers distributed over the hall. Because of feedback possibilities, limits are set for the degree of amplification. Thus, already during the years 1960–1970, such installations were developed in steps for the Royal Festival Hall in London (Parkin and Morgan, 1965 and 1970). This procedure utilizes a very large number of very narrow band channels and thus a clear limit of reverberation increase can be recognized near 800 Hz. Furthermore, very narrow limits apply to the diffusivity of this artificial reverberation, since each speaker handles only a very narrow tone region.

These difficulties are circumvented by a procedure for which a number of microphones feed each speaker with a broad band signal. Thus, the reverberation time can be uniformly extended, spatially, as well as in respect to frequency, i.e., there is no dependence on the location of the sound source (Kleis, 1979). An ealier example of this procedure is represented by the installation in the Royal Concert Hall in Stockholm, it increases the reverberation time in an occupied room from 1.6 to 2.3 s (Dahlstedt, 1974).

Naturally, it is also possible to limit the individual channels of the electroacoustic instrumentation to an average width without making the band too narrow. Thus a sufficiently large number of channels with the same frequency dependence can result in uniform sound radiation. Such a system, which occupies an intermediate position between the two systems described earlier, is installed in the International Congress Center "ICC Berlin" (Keller and Widmann, 1979).

Finally it is also possible to amplify the direct sound contributions in the framework of an electroacoustic installation. By appropriate choices of delay times for individual speakers, it is possible to achieve the impression that the sound originates with the original source for practically all locations in the audience. This naturally requires a substantial effort, especially for a wide stage. However this can be technically accomplished. For example such an installation is installed in the Palace of Culture in Prague (Ahnert et al., 1986).

6.1.3 Sound Field and Hall Shape

The intensity relationship between the direct sound and the statistical sound field, under given room acoustical conditions, does not only depend on the distance between the listener and the performers, but also on the directional characteristics of the instruments. The more sharply the sound radiation is clustered, the deeper the

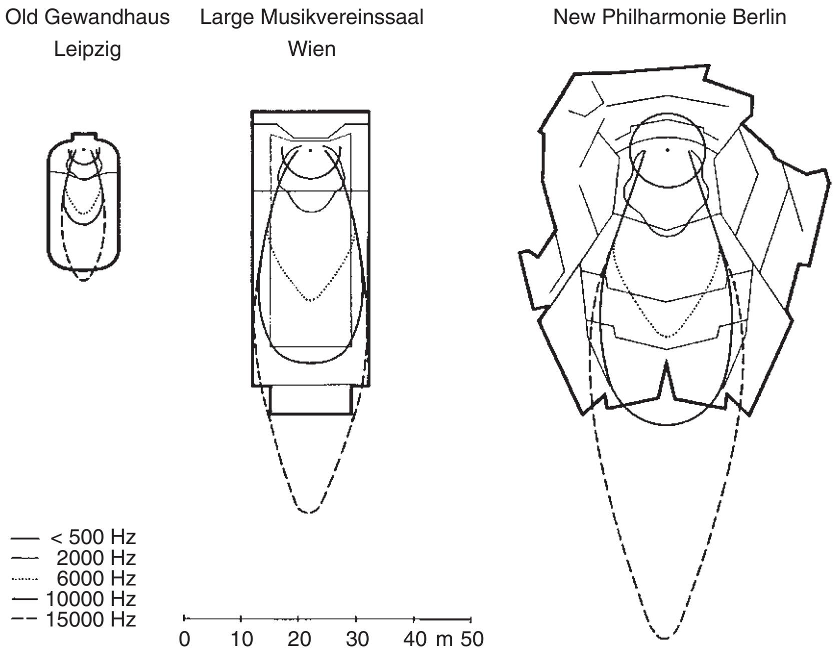

Fig. 6.7 Diffuse-field distance of a trumpet for different frequencies in three concert halls

region of predominantly direct sound reaches into the room in the preferred direction. This effect is all the more important when the diffuse-field distance for omnidirectional sources does not extend significantly beyond the podium. Thus the Vienna Musikvereinssaal has a value of 4.75 m in the midfrequency region. For the significantly larger hall of the Berlin Philharmonie a value of 6.5 m is found, and for the relatively reverberation-poor Royal Festival Hall, a value of 7.0 m. In the old Gewandhaus with its much smaller dimensions, this value amounted to only 2.4 m. Since the reverberation time at very high frequencies is shorter than in the mid-region, this diffuse-field distance is somewhat larger for these tonal contribution; for the highest components it can grow to up to twice this value.

How far this region, for which the direct sound dominates, can be extended for a sound source with pronounced directional characteristics is shown in Fig. 6.7 for several frequency regions in the three concert halls mentioned earlier. This summarizes the effect of the directional characteristics for the reverberation time which decreases for the highest frequencies. Already at 6,300 Hz the trumpet possesses a diffuse-field distance of approximately 27 m in the direction of its axis in the Vienna hall, at 10,000 Hz it increases to 38 m and at 15,000 Hz it reaches a value of 64 m (only theoretical under existing room dimensions). The width of the region enclosed by the diffuse-field distance curve increases only slightly: from 15 m at 6,300 Hz it merely increases to 20 m at 2,000 Hz. As can be recognized from the figure, the Vienna Musikvereinssaal appears to be nearly tailored for the precision of trumpet passages rich in overtones. In contrast, the edge seats in the much smaller old Gewandhaussaal are no longer so advantaged for the brilliance of the trumpet.

Naturally a concert hall design which distributes the audience all around the orchestra leads to a very different tonal effect for trumpets in the hall. The example of the Berlin Philharmonie demonstrates this situation in an extreme manner. However, even for halls with a volume similar to that of the Vienna Musikvereinssaal, whose width exceeds a measure of 20 m significantly, must count on lack of clarity for trumpets-staccato passages.

The different tonal effects created in the audience in front of, to the side of, or behind the orchestra are naturally not limited to trumpets but are more or less pronounced for the other instrument groups. The major considerations are the front to back relationships and the front to side relationship of the directional characteristics. When considering that, for example for the oboe, the front to back relationship for the strongest tone contributions (around 1,000 Hz) amounts to approximately 16 dB, it becomes very clear how difficult it is, to achieve a uniform balance between the individual instrument groups in halls like the Berlin Philharmonie or the Gewandhaus in Liepzig (opened in 1981) (Fasold et al., 1981). It is thus not surprising that for new concert halls the tendency again prevails to move the orchestra from a central position to the proximity of a head-wall, where only choir seats remain behind the orchestra as already utilized in the Gewandhaus.

In addition to the diffuse-field distance, the tonal effect of the direct sound can be supported by reflections with sufficiently short delay i.e., they arrive from not too distant surfaces. A requirement for the effectiveness of such reflection surfaces is that the sound arriving there from the instruments has a sufficiently high level. This condition is particularly met when the relative reflection surface lies within the angular region of principal radiation of the directional characteristic. In the same sense, this naturally also applies for the effectiveness of absorbing surfaces near the orchestra (Meyer, 1976, 1977).

In Fig. 6.8 the principal radiation regions for the group of the first violins and cellos are entered as examples into the schematically represented length-wise section of a hall. The region of the podium in which the relevant instruments are situated is represented as a black bar where a frontal arrangement for the celli in front of the conductor is assumed. The sound rays which delineate the principal radiation region (0–3 dB) emanate from the surface of the instrument. Those parts of the ceiling, rear wall and floor, which lie in the angular region of the strong sound radiation are indicated outside of the room boundaries by bars with specification of relevant frequency regions. In the partial picture for the first violins, the angular region for frequency contributions around 500 Hz are indicated by arrows for clarity. It is noteworthy that this reflection region, important for the brilliance of the violins, is located at the ceiling in front of the podium. In contrast, the reflection surfaces essential for the brilliance of celli are located above the podium.

The multiple divisions of the reflections surfaces for the individual instrument groups show that it is hardly possible to find a comprehensive representation for the entire orchestra, without losing information for the sake of simplification. Figure 6.9

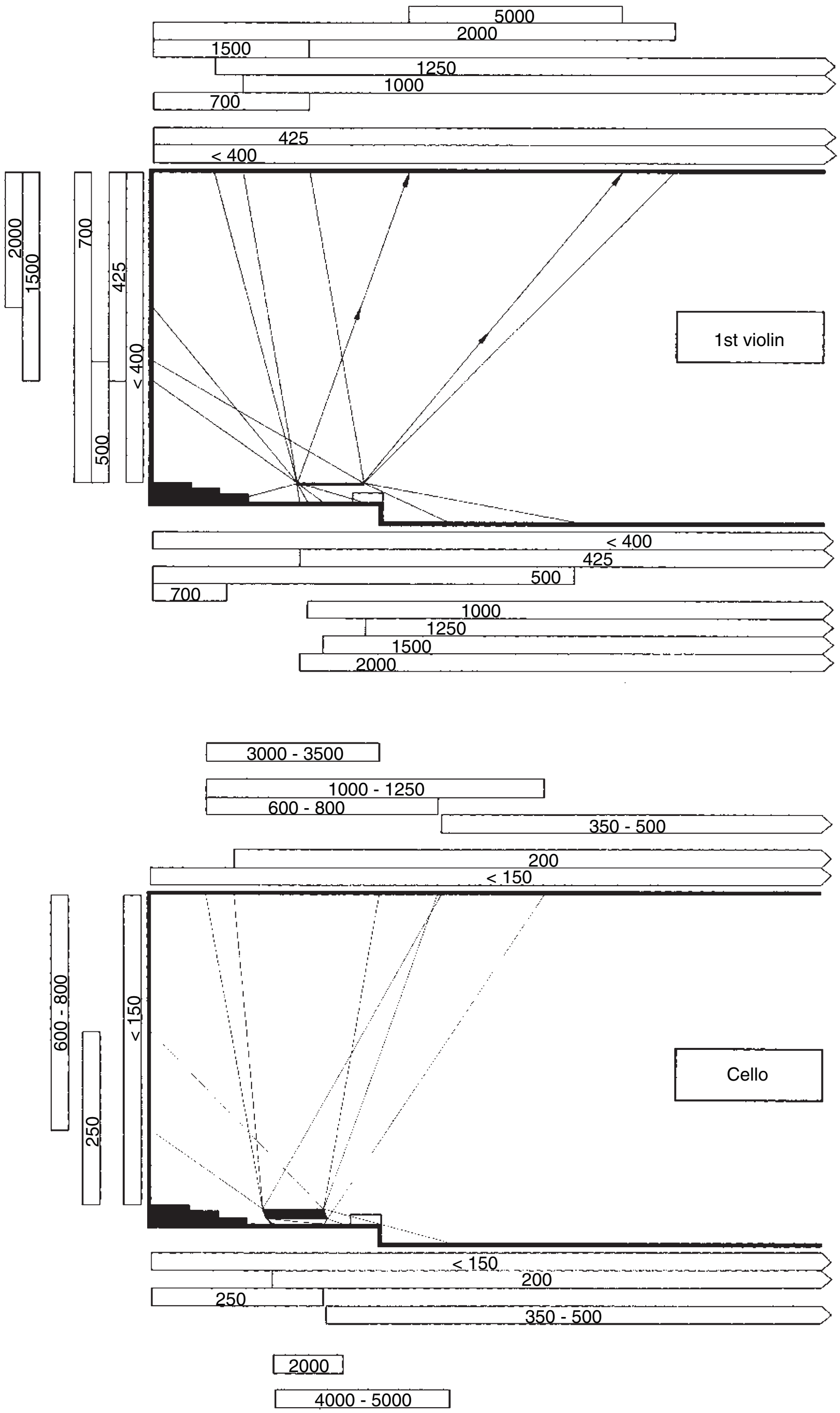

Fig. 6.8 Reflection surfaces on ceiling, rear wall and floor of a concert hall, which lie within the principal radiation regions (0–3 dB) of string instruments. The numbers are frequencies in Hz

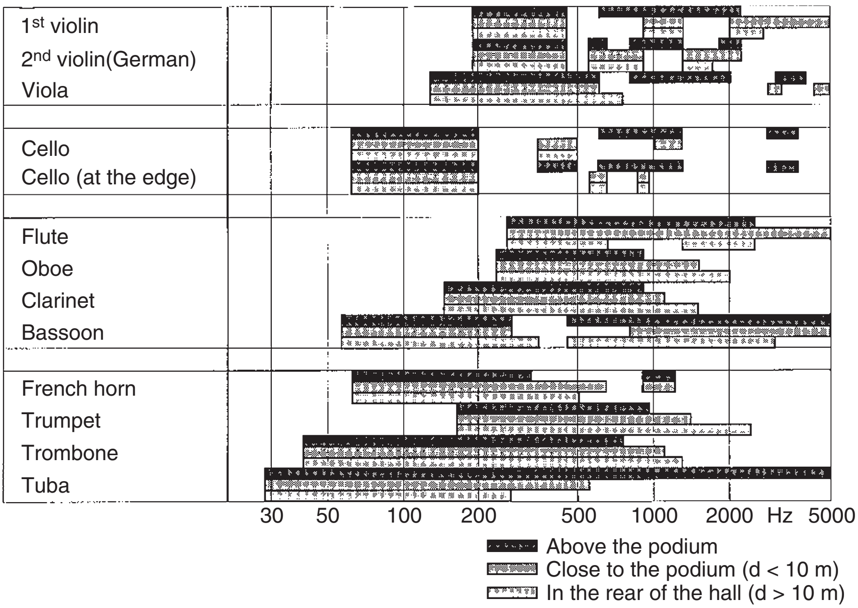

Fig. 6.9 Frequency regions of preferred ceiling reflections for orchestra instruments

shows a schematic representation of the frequency regions for which the ceiling lies either partially or entirely within the principal radiation angle. Here the ceiling is divided into three parts: "above the podium," "in front of the podium" (to a distance of approximately 10 m), "in the distant hall" (a distance greater than 10 m). The spatial relationships correspond to Fig. 6.8; a lower ceiling would bring about changes which would correspond to a shift of the boundary between close and distance audio region in the direction toward the podium. A ceiling rising into the audience would correspond to a shift of this boundary further into the hall.

It is recognized that the ceiling above the podium and also in front of the hall can reflect the sound in relatively broad bands for all instruments and thus it contributes significantly to the loudness impression and also to the brilliance of the tone color. Further into the hall, the high frequencies of most instruments are much weaker as they hit the ceiling, so that here above all the reflections of the lower tone contributions play a role.

In similar fashion Fig. 6.10 visualizes the reflection effect of the wall behind the orchestra, where a distinction is made between the lower region (up to height of 5 m) and the region above that. As can be seen, at low midfrequencies almost all instrument groups utilize the entire height of the wall. Only the lowest strip is not strongly affected for strings because of shadowing by other musicians. At higher frequencies the rear wall is of little significance for winds while the reflections from the upper regions of the wall certainly play a role for the strings.

The side walls lie within the principal radiation region for low and midfrequencies for strings as well as most winds (see also Figure 138 and 150), thus, a priori,

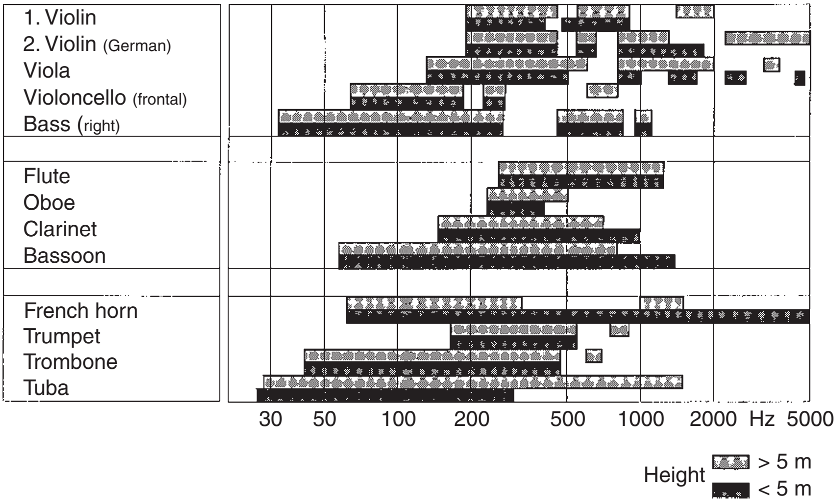

Fig. 6.10 Frequency regions of preferred rear wall reflections for orchestra instruments

they have more influence on the tonal richness than on the brilliance. The fact that the universal validity of this statement has certain limits can be noted for some halls in which large unstructured side walls have such a flat surface that also very high frequencies are reflected with optimal effectiveness. The geometric side wall reflection receives a prominence through the high frequency contributions, which leads to a cutting impression of the violin sound, and the spaciousness of the overall sound obtains a grating component. When the side walls are structured – for example by folding, or the placement of figures – the higher frequencies are reflected diffusely, and this effect becomes inaudible.

The basic hall floor plan and thus the directions of the side walls in the region of the podium and the audience play a decisive role for the acoustical room effects. Thus diverging side walls carry the danger that individual wind groups stand out too strongly in certain regions of the hall because of wall reflections, when the shading by the front rows of performers, and thus that equalizing effect is diminished. Normally an orchestra occupies a rectangular area, so that for strongly divergent room walls, open flanks are created.

The time sequence and the directions of incidence of first reflection are naturally determined by the distances of the reflection surfaces at the ceiling and the walls from the listener. It is therefore notable that three of the five halls identified as optimal in Table 6.1 are rectangular whose height is greater than half the width so that the first reflection in nearly all seats comes from the side and not from above. In Table 6.5, values for the height, the total width of the hall, as well as that width, which is important for first reflections, between boxes or galleries are assembled for several halls with elongated floor plans.

Table 6.5 Dimensions of several concert halls

Concert hall	Height (m)	Overall width (m)	Inner width (m)
Musikvereinssall Vienna	18.5	20	14
Concertgebouw Amsterdam	17.5	28	29.5
Symphony Hall Boston	21	23	17
Meistersingerhall Nürnberg	14	38	27
Sinfonie a. D. Regnitz Bamberg	14	33	22

Among concert halls of the 1960s and 1970s, the Meistersinger Hall approximates conditions for especially good halls relatively closely. For a large number of seats, the reflection from the ceiling arrives after a wall reflection. Many halls of that same period are, however, lower and longer, so that the spatial impression is not created and the width at the top is missing, rendering it less than optimal for Romantic music.

In the Joseph-Keilberth Hall in Bamberg, the side walls form an angle of 10° with respect to the central axis, diverging toward the back, consequently the width measurements are given for the width of the podium where the critical reflection surfaces are located. It is a successful example for the tendency in concert hall construction to achieve sufficiently early side reflections for all seats in the hall. In very wide halls, this can also be achieved by horizontal stepping of the seating regions; a characteristic example for such a design is the Orange County Performing Art Center in Costa Mesa California (Forsyth, 1987).

When calculating the admissible width for a hall, for a condition that the first wall reflection at a location of at least 15 m from the podium should not arrive later than 30 ms after the direct sound, one arrives at a value of 20 m. For larger distances, this condition is also met. The stronger direct sound closer to the orchestra permits a slightly longer delay time. This result is particularly interesting, because the width of 20 m corresponds to the value which is optimal for a sharp trumpet staccato, based on the directional characteristic (see Fig. 6.7).

The shape of the hall, including wall and ceiling structures, crucial for reflection directions, has a decided influence on the level of the sound energy arriving from the side with a delay of 10–80 ms, and thus on the spatial characteristics of the tonal impression. In this context, early sidewall reflections are important, as best realized in rectangular halls or halls with only slightly diverging walls, or by reflections from angular reflection surfaces or correspondingly structured wall features formed by the walls and the underside of galleries (Kuhl, 1978; Wilkens, 1975). A characteristic example is the Gewandhaus in Leipzig, where the wall elements direct the sound partly downward toward the audience and partly up toward the ceiling (see Fig. 6.4). In this way, depending on seating groups, a spatial impression measure of +3.1 to +5.5 dB is achieved (Fasold et al., 1981). For an appropriately shaped ceiling, the radiated sound can be directed to reach the audience from the side after a second reflection (Schroeder, 1979).

This viewpoint, i.e., to create a possibly high measure of spaciousness, can naturally also be taken into account with an electroacoustic reverberation

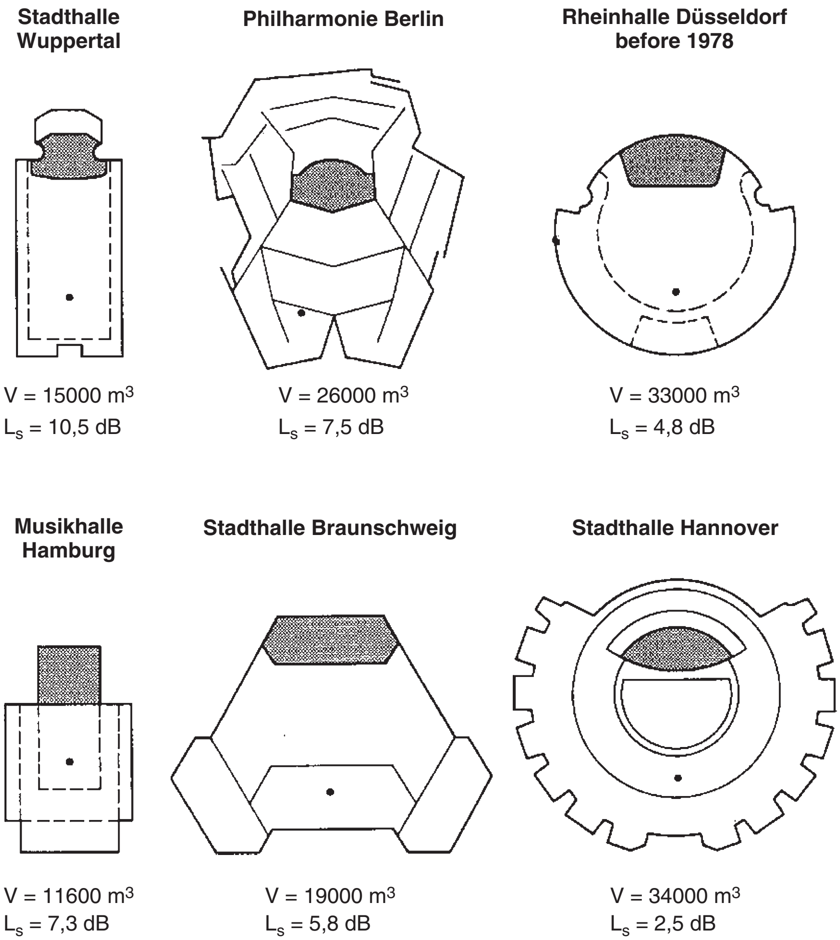

Fig. 6.11 Floor plans of six halls with indication of volume and lateral-sound levels (After Wilkens, 1975 and Kuhl, vor 1978)

installation. However, there is a danger that instruments whose sounds normally reach the audience predominantly in a vertical plane, become estranged by the tonal broadening. This applies particularly to the concert grand piano which ordinarily should distinguish itself from the orchestra sound by spatial precision.

In Fig. 6.11, the floor plans of six concert halls along with hall volumes are assembled. In addition, in each case, a value for the lateral sound level is given. This value is given for a seat in the rear third of the hall with appropriate distance from the wall (Kuhl, 1978; Wilkens, 1975). The advantage of rectangular halls in comparison to long or wide shapes in particularly noticeable. However, one also recognizes that by meaningful structuring of reflection surfaces in the amphitheater-like hall of the Berlin Philharmonie, a high side sound level was achieved for the relevant audience region, while the Braunschweig Stadthalle with its unstructured and angled walls, does not permit a spatial sensation. Thus, it is not surprising that the completely redesigned concert hall in the Lincoln Center in New York was reshaped into a rectangular hall with side walls structured by the presence of gallery boxes (Kuttruff, 1978). This is all the more noteworthy since fan shaped concert hall designs are generally approached skeptically and consideration of strongly structured walls are imperative.

An additional problem for halls with large opening angles or very large width is that a more or less large number of seats on the side are outside the region of optimal direct sound exposure. This is particularly relevant for vocal soloists standing in front of the orchestra: a tonal change is already noticeable outside of a cone of ±40°, and outside a cone of 80° the tonal impression is unsatisfactory. One should not be deceived by a smaller opening angle of a fan-shaped hall. Such a hall opens from a broad basis, the directional characteristic of a singer or an instrument, however, from a point.

Inasmuch as a high ceiling supports the Romantic tone concept, whereas the transparency of classical music is enhanced by a less delayed reflection, i.e., rooms with lower ceilings, which furthermore do not spread, one option is to hang reflectors above the orchestra and to adjust their height to conform to the program. As already mentioned, this however, requires a change of at least 2 m so that the ear can notice the difference in spatial impression. However, it should not be overlooked that, while lowering the reflectors, the regional effectiveness at lower frequencies is broadened (see Sect 5.1.3), so that the tonal color is changed.

This subjective impression of clarity and spaciousness of the tonal picture can be supported by visual impressions. This is less the difference between very austere halls, and rooms, which radiate a more festive character, though the latter possibly stimulate the emotional expectation of the listener more strongly, rather, the distribution of light and color in the hall play a significant role. Illuminated regions stimulate visual attention and raise the concentration of the listener in that direction. In a somewhat darkened room, it is easier to concentrate on an illuminated podium than in a bright hall, particularly when large (not totally immovable) audience regions are in the field of view.

In this context, a comparison of the Leipzig Gewandhaus and the Bamberg Concert Hall are of interest. In Leipzig (Fig. 6.4), the bright podium with its light edge strip, draws the eye. The dark walls retreat in the optical impression: this can strengthen the subjectively sensed clarity, particularly for the distant listener. In Bamberg (Fig. 6.3), the wood framing of the stage extends to the audience region, the white walls are especially noticeable, thus these reflective surfaces play a particular role in the optical impression, in contrast, the blue ceiling is less noticeable. This also corresponds to the directional sensitivity of the ear, which is more sensitive toward lateral reflections than to those from above (Opitz, 1993). This color and light relationship, which is attuned to acoustic processes in the hall, enhances the sensation of spaciousness.

6.1.4 Acoustic Conditions on the Stage

The reflections from the regions close to the orchestra play an important role for aural interaction between musicians. The fact that in some halls musicians hear themselves as loud, and other musicians as insufficiently loud, or not at all, points to the fact that the direct sound is insufficient for mutual communication and must be supported energetically by reflections. When one considers that the accuracy of a rhythmic group performance, at least for chamber ensembles, permits deviations from exact synchronicity of no more than 35 ms (Rasch, 1979), one can derive an upper limit for useful reflections.

The question of time delays for reflections, which aid or hinder mutual listening between musicians, is considered in Fig. 6.12 where results of several authors are assembled: the horizontal axis gives the distance between musicians, and below that, the associated traveling time of the direct sound is noted. The vertical axis gives the ceiling height above the podium. Since the ears of the musicians are located at about a 1 m level, the distance of the reflecting surface should only be calculated from that height, which is included in the measurement of the wall distance. Furthermore, in this coordinate system, the delay times of reflections are indicated in broken lines. The positive or negative effect of reflections on musicians

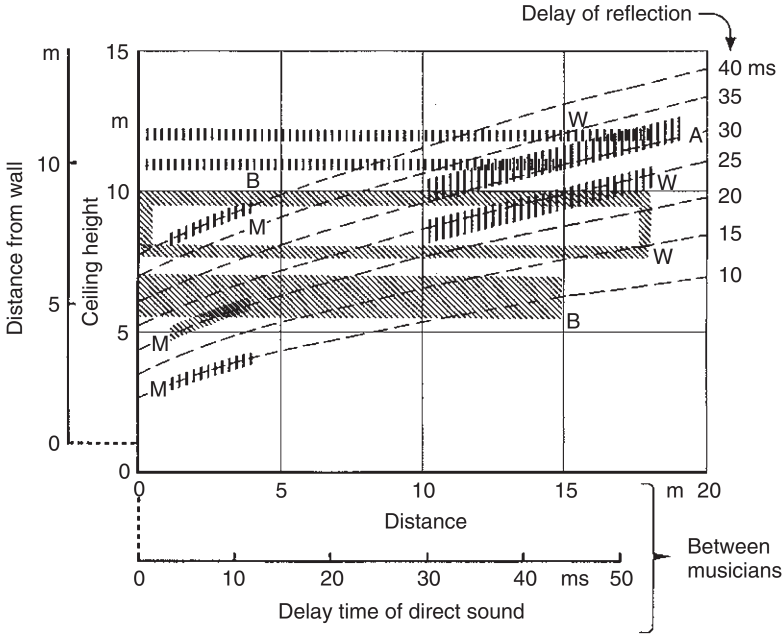

Fig. 6.12 Influence of hard reflection surfaces on mutual hearing (after Allen, 1980; Barron, 1978; Marshall and Meyer, 1978; and Winkler, 1979). *Angled shading*: favorable reflections; *vertical shading*: unfavorable reflections

is indicated by the nature of the shading with references to individual authors (Meyer, 1982b).

Arrival times of approximately 10 ms are sensed as disturbing. This is connected to the fact that the level of reflections becomes too strong and performers can no longer hear their own instruments clearly. Reflections are judged supportive, when the reflecting surfaces are so close to the orchestra, that the delay relative to the direct sound assumes values between 17 and 35 ms (Marshall et al., 1978). This corresponds to a detour of the reflected sound of about 6–12 m. For reflectors above the orchestra, a height of about 8 m is considered optimal. Heights of 12 m are considered as still marginally useful (Winkler, 1979).

For musicians seated only a few meters apart, even ceilings of 8 m heights can bring about disturbing reflections with excessive delay times, which are sensed as separate sounds from the room. These disturbing reflections, however, can be avoided when vertically upward radiated sounds are prevented from being reflected along the shortest path to the neighborhood sound source by folding the reflecting surface. For a very large distance between musicians, the danger of excessively delayed reflections for greater ceiling heights is not a problem, however, for energy reasons the limit of 10 m should not be exceeded when reflections from above are intended to aid mutual hearing.

The lower limit for favorable ceiling height, for small distances between musicians, is between 4 and 5 m. Lesser values lead to reflections which are too loud. This can be counteracted by partial absorption or by folding of the ceiling which affects a reflection of vertically upward radiated sound to distant parts of the stage. Such low ceiling heights, however, are only to be expected in small halls.

Considerations for ceiling heights can also be related to favorable distances for reflecting walls. For chamber music ensembles, distances from 3 to 6 m from the wall are advantageous, for orchestras on the other hand, a surface extension appears to be meaningful, so that the walls enclose the orchestra directly, since otherwise the wall distances become too large for those musicians sitting further in. Excessively large orchestra stages with surrounding reflecting surfaces at distances which are too large lead to situations for which the desks of the front strings and the location of the conductor are acoustically unsatisfactory, because the rear string desks are too weak and many wind groups can only be heard imprecisely. In contrast to that is the undesirable situation for the rear string desks, when they have no rear wall, but instead are located in front of the region of the stage enclosed by the side walls. The minimum required height for the surrounding wall surfaces is indicated by various authors between 1.8 and 3 m, where in the latter case the lower frequency contributions are also strongly reflected, which is of little significance in the rhythmic context. Lateral reflections are also supported by appropriately angled surfaces of gallery enclosures or by angular double reflectors formed by the bottom of the galleries and the wall below them.

The sum of the reflections arriving at the musician should result in a sound level relationship for which the extraneous sound at the ear of the performer should be from 15 dB below to 5 dB above the sound level of the player's instrument; within these limits the performance of the musician is not unduly influenced

(Naylor, 1987). However, independent of that, it should not be overlooked that especially in large halls, strong reflections returning to the orchestra bring the danger that the musicians overestimate the loudness impression in the audience, and consequently do not play a *forte* as strongly as the room acoustical conditions demand, keeping in mind the tonal impression of the listener.

For interactive listening of singers in a choir, considerations similar to those in an orchestra apply, however, the reverberation plays a stronger role than for instrumentalists (Marshall and Meyer, 1985). Reflections with a delay of about 15–35 ms are considered especially favorable. Since the reflected energy should be between -15 and 5 dB in relationship to the level of the voice at the singers ear (Ternström and Sundberg, 1983), reflections rich in energy are necessary: therefore, early reflections are better than later ones, and lateral reflections, by reason of the directional characteristics of the voice, are more effective than reflections from above or behind. An unfavorable region for first reflections appears to lie at delayed times near 40 ms, a phenomenon which has not yet been explained. In contrast, first reflections are again evaluated as better when they only arrive after 60 ms: for such long delay times it is actually better when lateral reflections arrive first.

For a solo vocalist, reverberation dominates even more strongly than for singers in an ensemble in respect to voice control and ease of singing. Early reflections (up to about 25 ms) can affect additional improvement, when coming from the direction of sight, from which also strong reverberation contributions arrive. Reflections from above and behind should only arrive after that (Marshall and Meyer, 1985). In similar fashion, instrumental soloists perceive reflections in a relatively long time range as supportive: the favorable region includes reflections from 20 to 100 or even 200 ms (Gade, 1989a).

Figure 6.13 assembles several floor plans of concert halls, which show different ways of including the orchestra in the total hall, in order to illustrate the aspects of interactive hearing. Furthermore, for these, and two additional halls (included in Fig. 6.11), dimensions are given in Table 6.6 which are important for the acoustical conditions in the area of locations of musicians: concerns are the width of the stage at the front edge, the depth of the stage, the height of the ceiling above the front edge of the stage, or the height of individual reflector hanging at that location, the angles of the side walls of the stage in relationship to the long axis of the hall, and the width of the hall at the end of the stage. See table in text

Overall it is noted from these examples that the ceiling above the stage in most cases is higher than expected from demands of musician-friendly reflections. Reference to tonal advantages of high ceilings for the audience has already been made several times; a further consideration is the tonal impression at the location of the conductor (see Sect. 6.1.5.). The following details for stage design of the individual halls need to be pointed out:

In the Musikvereinssaal in Vienna, musicians receive reflections of short delay from the rear wall and the side walls as well as from the double reflection formed by the surrounding gallery and walls.

In the Symphony Hall in Boston, the orchestra is narrowly enclosed by rear and side walls by the somewhat constricted stage space. The deeply structured ceiling in

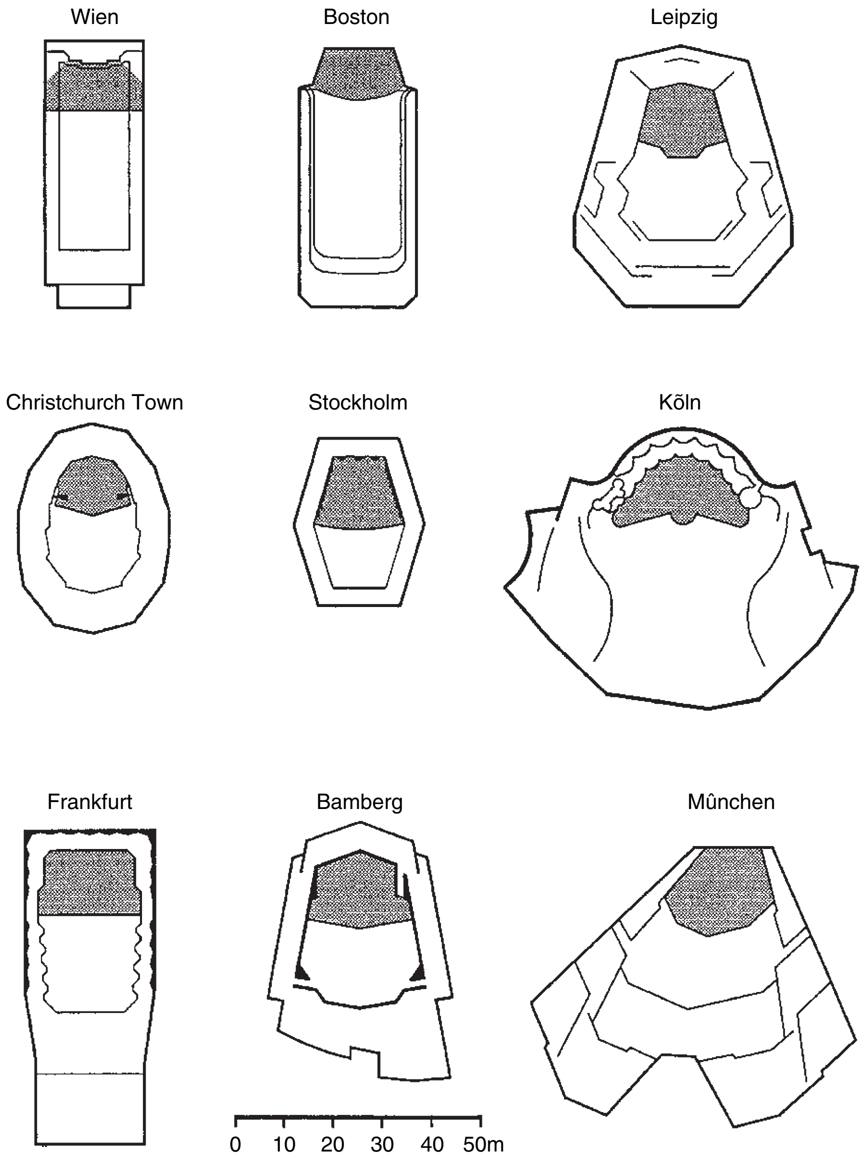

Fig. 6.13 Floor plans of several concert halls. The *shaded areas* identify the stage

the main hall presents a sequence of high frequency reflection into the orchestra which assures a time connection to the subsequent reverberation.

The Philharmonie in Berlin dispenses with a closed rear wall behind the orchestra, which is enclosed by 3 m high walls diverging slightly toward the front. Reflectors hang above the stage, which partially reflect the sound back to the stage.

Table 6.6 Orchestra stages for several concert halls

Concert hall	Year of Constr.	Width depth of podium		Ceiling height above podium	Angle of sidewalls	Hall width in front of podium
		m	m			
Wien	1870	15	9	16	0	20
Boston	1900	17	10	13	18	22,5
Berlin	1963	17	12.5	11	4,5	45/20**
Braunschweig	1965	17	14	10	30	38
Christchurch Town	1972	15	11*	15	–	30
Stockholm	1980	17	13	14.5	17,5	27
Frankfurt	1881	21	13	14	0	25
Leipzig	1981	18	13	15	15	37/21**
München	1985	21	16	14	35	35/25**
Köln	1986	21	10.5	11.5*	20	49/31**
Bamberg	1993	20	17	13	10	31/20**

*Reflector height, **in upper/lower region See table in text.

In the Stadthalle in Braunschweig, early reflections reach the stage area only from the wall behind the orchestra and from the relatively low, folded ceiling, however not from the side walls.

In the Christchurch Town Hall, four large-area unstructured reflection walls of 3 m height are located behind the orchestra stage. Above the front stage area, the front gallery walls are angled, such that they reflect the sound toward the musician. In addition, a reflector hangs above the orchestra, which, however, directs the sound mostly toward the audience.

In the Berwald Hall in Stockholm, rear and side walls of the orchestra stage are designed to absorb low frequencies but reflect middle and high frequencies diffusely, in order to create a clear musical picture for the musicians. Furthermore, the somewhat diverging side walls are folded in such a way that the reflection surfaces are parallel to the room.

In the concert hall of the Alte Oper in Frankfurt, the orchestra is enclosed by parallel wall surfaces extending to the edge of the narrow circumferential gallery. Higher frequencies are also reflected back to the stage by the double-angle reflection surfaces formed between gallery and wall structure.

In the Gewandhaus in Leipzig, the orchestra is surrounded in the back and the sides by walls of approximately 2 m height. Above these is an additional 1 m high railing, which is angled toward the stage. Furthermore, there are additional high frequency reflections from the wall structures above the gallery. In spite of the large room height, reflectors above the musicians are deliberately avoided.

In the Munich Philharmonie, the surrounding walls of the orchestra stage diverge towards the hall. Reflections from these surfaces, therefore, support especially the musicians located relatively closely. Curved reflectors at the side walls throw the sound back to all regions of the stage, thus delay times for the middle of the stage are relatively long. Recently, additional reflectors were suspended below the reflecting ceiling.

In the Cologne Philharmonie the round rear wall of the orchestra stage is structured such that the sound is distributed largely over the entire orchestra. Since the individual surfaces of the wall, as also the railings of the balcony behind the orchestra are inclined, a relatively large amount of sound energy comes back to the orchestra. Furthermore, a nearly horizontal reflector is located above the stage.

In the Joseph-Keilberth Hall in Bamberg, the orchestra is enclosed by walls from the rear and sides, the latter are parallel to the rear of the stage and diverge only slightly toward the front, so that reflections also reach distant regions of the stage. Interactive listening is furthermore supported by the level ceiling as well as angled reflection surfaces at the side walls.

When considering reflections which are effective for mutual hearing, one needs to be aware, that above all, the frequencies in the midrange and possibly the base register are important for intonation. However, for rhythmic ensemble performance the higher components up to a region of 2,000–3,000 Hz are still significant. How strongly these individual contributions to the extraneous sound reaching the performer are perceived, does not only depend on the impinging intensity, but also on the masking of the performer's own instrument, which in turn is directionally dependent (See Sect. 1.2.6). In this context, those reflections are especially important which come vertically from above, while contributions arriving at an angle from above, especially at high frequencies, play a lesser role, particularly when they arrive from the front or the rear. Wind players hear mostly those reflections which they receive from lateral directions; for this, the side walls of the stage are relevant. For strings, these reflections are less useful. For them, reflections from above and from the ceiling in the front of the hall and the rear wall of the stage are more valuable.

The differing directional dependencies, and the threshold of interactive listening for players of different instruments, in addition to the fact that the radiated energy of wind instruments is higher than that for string instruments, is the reason why in many concert halls the balance of the tonal impression for individual player is very poor. Thus, at high dynamic levels, most brass player are themselves relatively loud and are also surrounded by the very loud sound of other brass players, while they hear the sound of the string instruments only weakly or not at all. The strings, in contrast, are located in the angular region of strong direct radiation of the winds, so that they can hear these as very loud, their own instrument very weakly, and the other instruments in their own group even more weakly. The masking by the wind sound, by reason of its spectral composition, goes so far that the violinists can only hear the higher frequency components of there own instrumental sound, and consequently force these contributions by increased bow pressure.

It is precisely this phenomenon which points to the importance of the higher frequency tone contributions for the mutual listening by string players within the individual listening groups. Therefore, ceiling surfaces above the string players should be structured or shaped so that they reflect the sound of the strings somewhat diffusely to the region of the strings. This diffusion characteristic refers predomi-

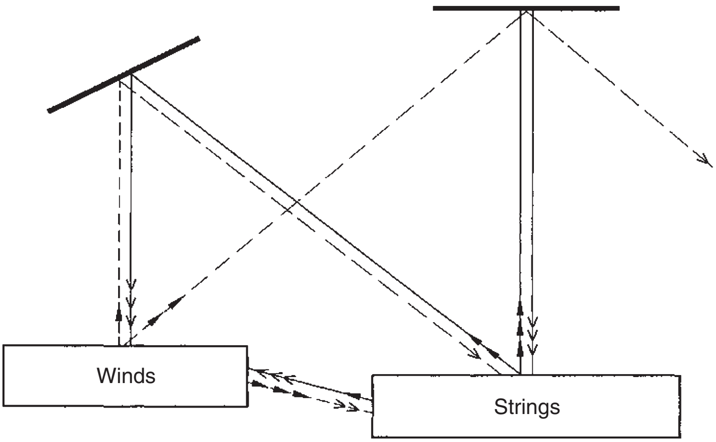

Fig. 6.14 Direct sound and ceiling reflections between winds and strings. *Solid arrows* refer to the intensity of the sound radiation, broken arrows to the sensitivity of the ear for extraneous sound

nantly to the sound contribution over the breadth of the stage, while the reflection surfaces in the direction of the depth of the stage should be practically horizontal. As indicated schematically in Fig. 6.14, these reflectors include directions of strong sound radiation of the instruments, and reflect the sound in such a way that it reaches the players from directions of highest hearing sensitivity. This improves the mutual listening of the string players. In contrast, the sound of the winds is directed toward the audience by these reflecting surfaces.

If, on the other hand, the ceiling surfaces above the wind players are oriented so that reflections from the winds are directed toward the strings, and naturally also in the opposite direction, then the reflections of the string sounds arrive at the winds in a very sensitive direction, which is advantageous to the tonal impression by the wind players. The opposite direction, however, combines a direction of weak radiation by the winds with a direction of low sensitivity for the strings, so that these reflections do not amplify the wind sound for the strings too much. A reflector arrangement, installed with this in mind, has proven very successful in the Hans-Rosbaud-Studio in Baden-Baden, for example.

For large orchestras, the higher dynamic level can lead to phenomena which can influence the clear recognition of the far distant voices, or even make it impossible: the sound not only becomes louder – above all for horns, trombones, and even for the celeste - but also “more dense,” and thus masks the clear contour of other instruments (Schultz, 1981). This effect occurs especially in relatively narrow and low orchestra shells, or when in higher rooms the ceiling reflectors are hung at locations which make them too low or too narrow. A clear explanation for this is not yet found in the literature; however, nonlinear effects in the ear can not be excluded.

It is, however, possible that a special tone impression is created by a large number of slightly delayed wall and ceiling reflections, which prevents locating individual sound sources, and thus a separation in the sense of the "cocktail party effect." As already mentioned, spatial localization of soft sound sources is no longer possible when the sound level at the ear is by less than 10 or 15 dB above the mutual hearing threshold as determined by louder sound sources. This limit is certainly shifted to the detriment of softer sources, particularly in situations which make it increasingly difficult to separate them directionally from louder sources.

The fact that in such cases the addition of sound absorbing surfaces behind the winds (up to head height) can bring effective help without reducing the loudness impression for other players (Schultz, 1981), speaks for this explanation for the intensity of the direct sound, which gives strong dominance over the reflected tonal contributions so that spatial location becomes easier and the transparency of the entire ensemble tone is raised.

Inasmuch as mutual hearing by the musicians depends strongly on the direct sound and the first reflections, players also notice differences in the reverberation distance for different room occupancy. The physical distance between players is precisely in the order of magnitude where already small distance changes change the intensity relationship between the direct sound and the statistical sound field noticeably (see Fig. 5.9). Thus, players in an occupied hall frequently find themselves within the diffuse-field distance of other instruments, while during rehearsal in an empty hall, they are seated outside that distance, because of the narrower diffuse-field distances. Consequently, musicians on stage sense the influence of the audience on the reverberation time (and thus the diffuse-field distance), more strongly than the audience in the hall.

6.1.5 The Location of the Conductor

The conductor differs in several points from the orchestra musicians, not only in the musical task but also from the standpoint of the acoustical environment. The conductor carries the overall responsibility for the tonal shape received by the audience, where the fact should not be ignored that this tonal shape is certainly not always the same for different seats. Technically this means that the conductor has to watch over the tempi and the rhythmic connections, furthermore the conductor must shape a dynamic development as a whole, as well as the balance between the individual musical groups. On the other hand, for practical purposes, during the performance the conductor no longer influences the intonation.

The slightly elevated location of the conductor is already sufficient to reduce the additional attenuation of the sound which occurs for flat spreading above the heads, as seen from Fig. 5.10. The audibility of distant musicians, in comparison to a close player, such as for example the concert master, is therefore better for the conductor. In addition, the masking of sound by the players own instrument, which otherwise is sensitively close to the ear, is not present. A further difference in relation to communications with other musicians consists in the fact that, while the conductor receives acoustical information, information to musicians – at least during the performance – is communicated only optically. Thus information coming from the conductor reaches all musicians without time delay.

While instrumental musicians and singers rely on the correct balance between their own voice and the other ensemble members, the conductor requires a balanced relationship between the direct sound of the orchestra (and the soloist) and the sound in the hall. The optimum for these relationships can be shifted within certain limits depending on the quality of the orchestra: a high degree of rhythmic accuracy in ensemble playing (and thus also better intonation) will allow a stronger hall sound to aid the conductor, and it is precisely this communication with the acoustic room response which enables the conductor to make adjustments for a particular hall. This is certainly very important for an optimal performance.

As already mentioned, the spatial tonal effect generally consists in the fact that the space in front of a listener appears to become filled in a larger or smaller degree with sound; only in rare cases, when the largest part of the hall is located behind the listener, a weak impression of the hall sound is created from behind (Kuhl, 1978). Since the conductor's back is turned toward the main part of the hall only a relatively small spatial tone development becomes noticeable – unless the hall has adequate free space in front and above the conductor.

In this context it is interesting to note that Herbert von Karajan in the 1960s considered the Massey Hall in Toronto, which has a height about 30 m above the orchestra, as one of the most outstanding halls in the world from the standpoint of spatial tone impressions (Winckel, 1962b). Based on previous considerations about mutual hearing within the orchestra this hall must present musicians significant difficulties to maintain rhythmic cooperation. Thus Karl Böhm reported (Winckel, 1974) that he required approximately 10 min in this hall before the orchestra came to a precise ensemble playing after initial floundering; however thereafter he judged the hall as one of the most outstanding from a tonal standpoint. From Table 6.5 it is already evident that halls highly valued for acoustical characteristics have a ceiling height which exceeds by far the measure, which has been found to be favorable from a standpoint of reflections useful for mutual hearing.

Evidently the large hall height conveys to the conductor the spaciousness of the sound from above, which it can not develop from the front by reason of the strong direct sound. This effect is very helpful to the conductor for the overall acoustical impression and thus for the interpretation. A feeling for the spatial tone development evokes within the conductor a sense of the dynamics as determined by the increase of the tonal volume, and prevents forced entrances and dynamic excesses. From this standpoint it is not surprising that regular attenders at Berlin Philharmonic concerts made the observation that reflectors above the orchestras in concerts with H. von Karajan apparently were always located in their top-most position. This consideration also explains why conductors are relatively unanimous in their opposition to placing audience seas behind and partly to the side of the orchestra.

While the hall response gives important information to the conductor about the balance between the individual instrument groups, the effect of the direct sound is also essential. However, differing distances between individual players and the conductor add some difficulties. Aside from the fact, that for most listeners the distance relationships to the instrument groups is different than for the conductor (the differences to the middle string desk and to the brass players is approximately 1:2 or 1:3 for the conductor, however for the listener something like 1:1.2 or 1:1.5), a partial masking occurs for the conductor as a result of the high level of neighboring strings, i.e., a weakening of the sound of the further distantly seated players.

This applies not only to winds, which are sensed by the conductor as increasingly soft in halls with less reverberation, making it difficult to find a correct balance. An example of this is a dry TV studio with large free surfaces within the orchestra (providing free access to TV cameras). This also applies to string desks in the back, so that the conductor predominately hears the front desks, for, at the ear of the conductor, the level from the third desk is already decreased by 7 dB relative to the sound from the first desk, and by 10 to 11 dB weaker from the fifth desk, assuming equal sound power from all players. If there is a wall located directly behind the strings, which, because of its structure sends at least two reflections back to the conductor, the fifth desk (with a level difference from the first of about 7 dB) becomes much more clearly audible at the location of the conductor (Meyer, 1994a). In this connection it should also be mentioned that orchestra musicians value a second reflection of inclined surfaces of the stage edge, since it improves the mutual listening between instrument groups. Particularly woodwinds profit (Winkler and Tennhardt, 1994).

In contrast, when the stage wall is only located 4 m behind the last desk, the equalizing effect is no longer present for the conductor. In this context, reflections from above also have very little effect. On a limited scale stepwise raising of the outer string desks can support a more closed tonal impression of the group for the conductor. However, this is not connected with advantages to the sound in the audience.

The differing demands placed on the acoustical conditions at the podium by the conductor and orchestra musicians has the consequence that there is no absolute optimum for a concert hall. Rather, acoustically good halls will always differ in the fact that they will either favor the intention of the conductor or the tonal impression for the orchestra musicians. The question thus remains open to what extent limitations can be imposed on musicians with regards to mutual hearing in order to make the tonal impression for the audience as good as possible. Driven to an extreme, this leads to the question: must the conductor have the best place in the hall or is the conductor capable of projecting a subjective tonal experience to the perspective of the audience without causing the interpretation to suffer? To this is added the further question: to what degree can the conductor demand additional efforts on the part of the members of the orchestra when acoustical conditions at the podium are tailored to strongly to the position of the conductor? At this point it is certainly relevant to note that the quality of the orchestra plays a decisive role.

6.2 Opera Houses

6.2.1 Reverberation Time and Room Size

The acoustical demands on rooms in which musical stage works are to be performed are significantly more complex than the demands in concert halls. Without loss of significance of orchestra sounds, the effect of the singers is intended to move to the foreground. For this, *bel-canto* passages require sufficient reverberation, possibly even a certain measure of spaciousness, so that the voice achieves a luminous fullness, and the melodic line a tonal continuity. Furthermore, singers want to feel a certain resonance of the hall which transmits a sense of security in development of their own voice, but also security of adjustment to the ensemble. On the other hand, a high degree of clarity is demanded in order to guarantee sufficient understanding of the text, so that the audience can follow the stage action. Therefore, the reverberation time in opera houses must be shorter than in concert halls.

These requirements, however, cannot be generalized by one optimal value depending only on room size. Even more so than in symphonic music, the composition style plays a role. Since the clarity of understanding largely depends on the tempo of sound, it is also influenced by the technique of instrumentation. In fast *parlando* passages, and for spoken texts, the danger exits that the articulation drowns when the reverberation time is too long. This is also relevant for very rapid recitatives, which mostly contain the significant process of the action, while the arias often have a static character in relation to the stage action. The operas of Mozart and Rossini, therefore demand a shorter reverberation than for example, the majority of works by Verdi, Wagner, or R. Strauss.

Thus, in these latter, large "fully composed" stage works, in contrast, the problem of text understanding essentially lies in the fact that singers must not be covered in intensity by the orchestra. This task however, cannot only be mastered by a short reverberation time, but must be accomplished by appropriate reflection surfaces which concentrate the sound energy of the singer into the audience, and by measured dynamics of the orchestra. For energetic reasons, a slightly longer reverberation for the singers than for play-operas is advantageous. Table 6.7 contains a survey of existing reverberation conditions in several opera houses, which in each case can be considered as representative for their time period. In several cases, the year of construction refers to the year of last renovation and the indication of the room volume, relate in each case, only to the audience space. Specifically, this table contains the reverberation time (occupied hall) for midfrequencies as well as for the octave region around 4,000 Hz, since this frequency region includes an important contribution to the singer's formant, which is relevant to the ability to carry the singing voice. In addition, the values for the diffuse-field distance (for omnidirectional sound sources) at midfrequencies and in the 4,000 Hz octave regions are given.

Among the older opera houses, the Festspielhaus in Bayreuth stands out because of its relatively long reverberation time, it is therefore, especially designed for the great flow of Wagnerian music. The frequency dependence of the reverberation

Table 6.7 Acoustical data for several opera houses

Opera house	Year	Volume (m^3)	Number of seats/ standing places	T_m (s)	T_4 (s)	r_{Hm} (m)	r_{H4} (m)
1. GroBe Oper Paris	1875	9960	2131/ 200	1,1	0,9	5,4	6,0
2. Festspielhaus Bayreuth	1976	10300	1800	1,55	1,3	4,6	5,1
3. Scala Milano	1946	11250	2289/ 400	1.2	1,0[a]	5,5	6,0
4. Staatsoper Wien	1955	10660	1658/ 580	1.3	1,1	5,6	6,3
5. Festspielhaus Salzburg	1960	14000	2158	1,5	1,3	5,5	5,9
6. Metropolitan Opera New York	1966	30500	5000	1,8	1,3*	7,4	8,7
7. Semper–Oper Dresden	1985	12500	1290	1,85	1,3	4,7	5,6
8. Opéra National de Paris	1989	21000	2700	1,55	1,25* *estimated	6,6	7,4

Source: 1.–5. Beranek (1962); 6. Tarnoóczy (1991); 7. Schmidt (1985); 8. Müller and Vian (1989)

time was already represented in Fig. 5.8; the rise in the low register favors a round and sonorous tone coloring, which furthermore supports the instrumental sound by the peculiar covering of the orchestra pit. An attempt was made to approach a similar reverberation time in the new Festspielhaus in Salzburg, whose audience space, however, is larger than in Bayreuth. Thus, from an acoustical standpoint, this house also appears to be created for the large opera. Thus, it forms an interesting alternative to Bayreuth as a performance space for Wagnerian music dramas, where the most significant difference is seen in the open orchestra pit.

Opera houses in Paris, Milano and Vienna, built in the typical style of the nineteenth century, with their reverberation times of slightly more than 1 s, represent a compromise between the Festspielhauses designed primarily for tonal fullness, and the demands of good speech understandability. Yet, even these houses are more suitable for the large opera than for the transparent tonal events of Rokoko-works. Already from these examples it becomes clear, that with the passage of time evidently the perception of an optimal reverberation time has undergone slight changes in the direction of more reverberant halls.

While the long reverberation time in the New York Metropolitan Opera is justified by the extremely large audience space, the long reverberation time in the reconstructed Semper-Opera in Dresden is all the more noteworthy, since it is comparable to values of concert halls of corresponding size, and the acoustical characteristics are evaluated as very positive – at least for today's sound impressions (Schmidt, 1985). However, long reverberation times at low frequencies with large orchestras and full instrumentation lead to sounds for singers, or even choirs, which easily become excessively "massive" or "heavy." As an aside, the opera house in Göteborg, (opened in 1994), has a similarly long reverberation time. In contrast, the Opéra National de Paris (formerly Opéra de la Bastille) in Paris corresponds more to the traditional line, as can also be seen from Fig. 6.15.

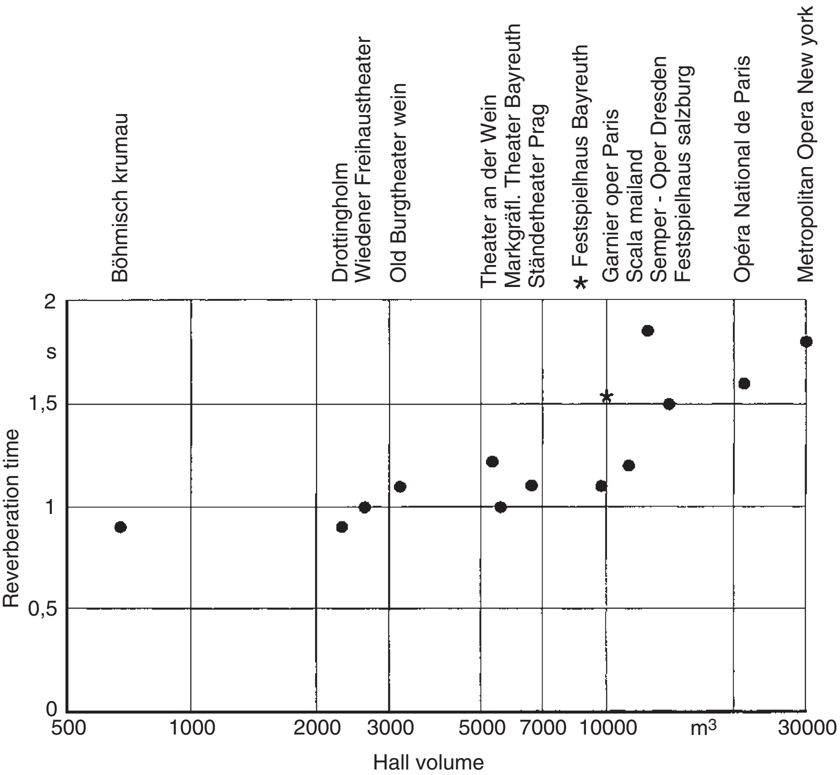

Fig. 6.15 Reverberation times for several opera houses (midfrequencies, occupied hall)

Table 6.8 Acoustical data of historic opera houses (see Table 6.7)

Opernhaus	Year	Volume (m^3)	Number of seats	T_m (s)	T_4 (s)	r_{Hm} (m)	r_{H4} (m)
1. Böhmisch Krumau	1591	670	270	1,0	0,8	1,5	1,6
2. Markgr. Opernhaus Bayreuth	1748	5500	550	1,0	0,8	4,2	4,7
3. Drottningholm	1766	2300	400	0.9	0,8	2,9	3,1
4. Burgtheater Wien	1779	3100	1100	1.1	0,9	3,0	3,4
5. Ständetheater Prag	1783	6600	1100	1,1	0,9	4,4	4,9
6. Wiedener Freihaustheater	1788	2600	800	1,0	0,8	2,9	3,3
7. Theater an der Wien	–	5200	1060	1,15	0,9	3,8	4,3

Source: 1.&5. Januska (1969); 3. Stensson (1968); 4. Singer (1958)

Since many of the great opera houses were built in the same time period in which also the composition of “the great opera” occurred, naturally, the question arises: What was the nature of the halls in which the musical stage works were performed in Mozart's time? Fortunately, a number of theaters from that time still exist. On the basis of existing drawings it is possible to draw conclusions about acoustical characteristics of buildings no longer standing. Reverberation times have been calculated for the old Burgtheater in Vienna, for which Mozart wrote his operas "The Abduction from the Seraglio," "The Marriage of Figaro," and "Cosi fan tutte." Depending on the level of occupancy, these lie between 1.0 and 1.3 s (Singer, 1959). For the Wiedener Freihaustheater, in which the premier performance of the "Magic Flute" occurred, a reverberation time of 1.0 s can be estimated (Meyer, 1986). These calculated values, along with some measured results from several existing theaters from that time are given in Table 6.8. Even though the measured values for the Ständetheater (Stavovské divadlo) in Prague, in which "Don Giovanni" saw its premier and for the "Theater an der Wien" which was an important performance location for Beethoven, in each case the values apply to remodeled conditions, yet approximate original conditions can be estimated. While data of Table 6.8 represents structural and acoustic parameters of that time, it should be mentioned that certainly not all theaters, which in those days were used for performances, were significantly smaller than the average opera houses built in the past century in cities of average size. The opera house built in 1742 in Mannheim has a volume of 7,700 m^3, and the opera house in Esterháza from 1769 with its volume of 9,500 m^3, nearly had the dimensions of the Garnier-Opera in Paris.

A comparison of reverberation curves – however, this time in unoccupied halls – for five opera houses from different time periods is given in Fig. 6.16. The frequency dependence of these curves is noteworthy. The Ständetheater especially emphasizes the low tonal contributions, consequently it does not permit emphasis of the desired brilliance of the orchestra. The Markgrave opera house in Bayreuth, in contrast, with its reverberation maximum at midfrequencies, presents a very light tonal atmosphere, which makes for a nearly ideal performance of Mozart operas. In that context the orchestra does not even need to hold back, but can develop its full brilliance without influencing the effect of the singers. In contrast to concert halls, a drop in the reverberation curves, or at least a flat continuation toward lower frequencies, is advantageous for opera houses.

The stage opening, and the nature of the stage, have an essential influence on the reverberation time. A scene largely devoid of decorations can prolong reverberation significantly, because the room resonances of the stage area are also excited. Sound reflecting props (such as large plywood structures) also increase the reverberation, while curtains and cloth props strongly absorb the sound. Figure 6.17 shows the reverberation curves for two extreme cases of stage scenery structure with the main curtain closed, for the National Theater in Munich (after opening in 1963). The latter is important for the tonal impression during performance of overtures and interludes. This range of variations, which could be used by stage designers to shape the room acoustics, suggests the possibility of utilizing the structure of the stage design to meet the differing demands discussed earlier of a Mozart opera on the one hand or a large music drama on the other.

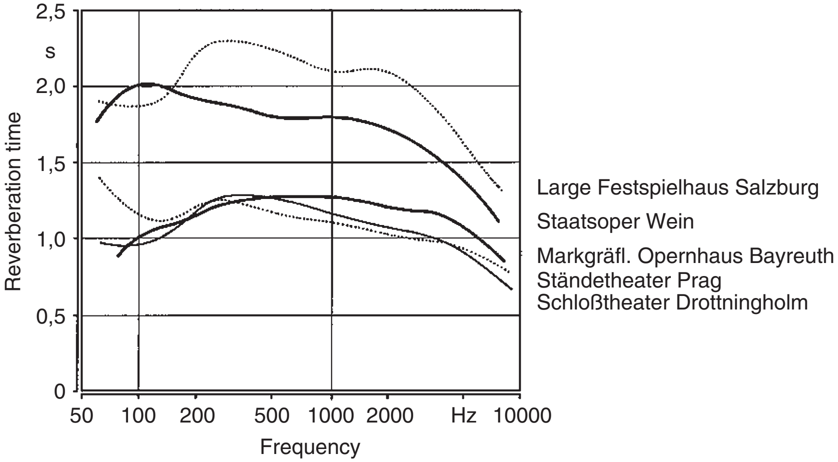

Fig. 6.16 Reverberation curves of several opera houses under unoccupied conditions. Salzburg and Vienna (after Beranek, 1962,) prague (after Januschka, 1969), Drottningholm (after Stensson, 1968)

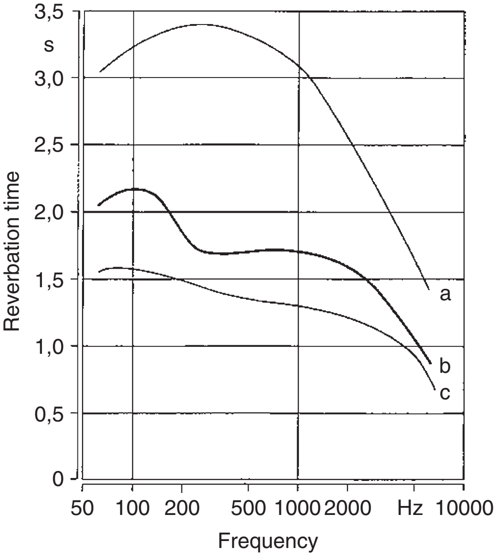

Fig. 6.17 Reverberation curves for the National Theater in Munich (after Müller, 1969). (**a**) for very reverberant scenery, (**b**) with closed main curtain, (**c**) for strongly absorbing scenery

6.2.2 Direct Sound and Early Reflections

The correct intensity relationship between orchestra and stage is a particular problem which will be considered in more detail in Sect. 9.3. In that context the

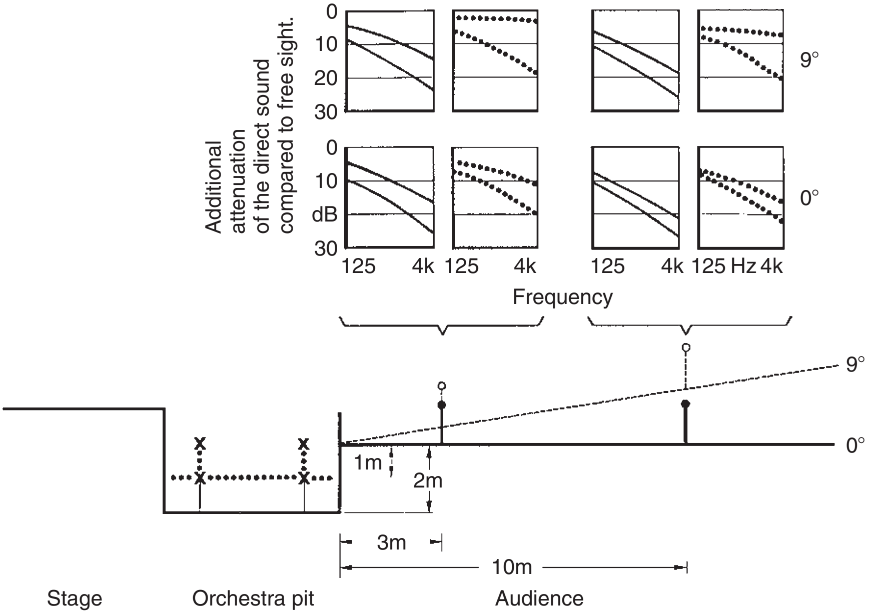

Fig. 6.18 Shading of the direct sound from the orchestra pit into the audience. In the individual diagrams the *upper curve* relates to musicians close to the stage, the lower ones to musicians close to the audience. *Broken*: orchestra location- high. *Solid*: orchestra location – low

nature of the orchestra pit plays an important role. In nearly all old theaters the orchestra pit rarely was located below the level of the front audience rows. Consequently, relatively strong direct sound contributions reach the audience. The sound, therefore, was brilliant and transparent because of the nearly unattenuated higher frequencies. In this respect, the Markgrave Opera House in Bayreuth again represents an optimum. Here the enclosure of the orchestra space is divided by individual pillars, and thus permits the sound to pass through it. The small Baroque Theater in Böhmisch Krumau (Cesky Krumlov) belongs to the few rare exceptions, where the orchestra is located at a level of 2.7 m below the floor of the main hall (Januska, 1969). When the orchestra pit is lowered to some degree, the direct sound is blocked by the enclosure for the audience seated on the first floor of the theater, and is weakened by diffraction around the enclosure.

This effect is represented in Fig. 6.18 for a typical situation; the values are calculated using the curves in Fig. 5.3, and present the frequency dependent level drop which occurs in addition to the weakening with distance (Meyer, 1986). The upper row of diagrams refers to rising chair rows, the lower one to flat chair rows. The left diagrams refer to seats at a 3 m distance from the orchestra pit, the right ones to a 10 m distance. The solid and broken lines refer to an orchestra pit sunk by 2 or 1 m respectively, below the audience floor. In the individual partial pictures, the upper curve relates to a musician sitting at a distance of 4 m from the pit enclosure, and the lower one at a distance of 1 m. As can be seen, the shading

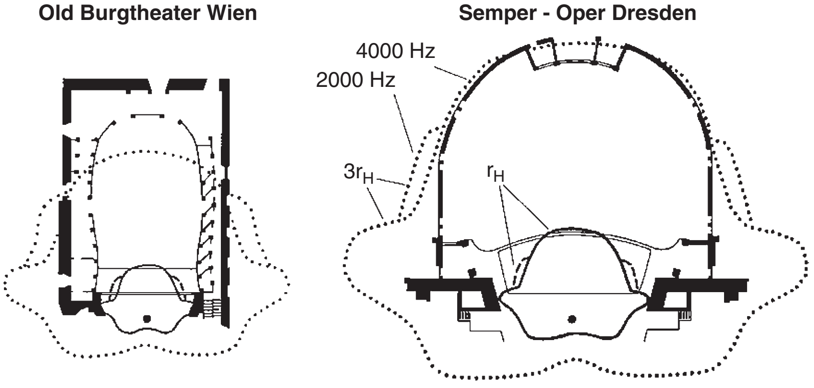

Fig. 6.19 Curves for the simple and threefold diffuse-field distance in the singer's formant

increases strongly with rising frequency. For the lower position of the orchestra, the attenuation at high frequencies can be more than 20 dB. When the orchestra is not lowered that far, the shading can be weaker by 5–10 dB, which is especially noticeable for higher frequencies. The clear sound of a higher seated orchestra effects a particularly advantageous and transparent production of classical operas, or also of many modern works of similar structure, however, it also gives a brilliance to large operas which can not be achieved with deep orchestra pits. Thus, for example, the level of the orchestra pit in the Vienna State Opera is so high that the contra basses in the last row must be lowered by one step so that they don't intrude on the edge of the stage.

While it is possible to keep the overall loudness somewhat lower with deep orchestra pits, particularly for the wind group, this is bought at the expense of a relatively flat string sound on the main floor. Yet, the depth of the orchestra pit has less of an influence on the impression of loudness than on the softness of the attack, because the main part of the energy is shaped for the audience by the strongly delayed reflections. In fact, delays of more than 1/10 s can occur (Reichardt et al., 1972), which naturally makes it easier for the singer to rise above the orchestra through articulation. The total or partial blockage naturally has the strongest influence on the damping of the orchestral sound. The well known blockage in the Bayreuth Festspielhaus (see also Fig. 9.4), does homogenize the tonal impression of the instrument groups, on the other hand, however, it also diminishes the plastic affect of the orchestra. It therefore, supports the classical Wagner sound, as it is most pronounced in the "Ring" and "Parsifal," on the other hand, for example, the "Meistersinger" score, with all its delicacies, is very difficult to realize from a tonal standpoint.

As already represented in Fig. 3.30, it is very important for the singer to rise above the orchestra with the singer's formant. In relationship to the desired clarity, and also the ability to pinpoint location on the stage, it is of fundamental importance for the direct sound to reach the audience with sufficient strength. The determining factor for this is the threefold reverberation distance, this is the distance for which the direct sound drops to 10 dB below the statistical sound field in the hall. Therefore, in Fig. 6.19, the reverberation distances relevant for the singer's formant are given in relationship to the floor plan of two opera houses, where the location of the singer is assumed to be 2.5 m behind the edge of the stage. The basis for the curves is the statistical direction factor, which for 4,000 Hz within an angle of ±20°, remains at a value of 1.6, and for 2,000 Hz, rises above 1.6 in the angular region adjacent to that on each side, so that within an angular region of ±40° from the direction of sight, a pronounced concentrating effect results. It is surprising how well this curve for the threefold reverberation distance fits the Semper-Oper, while in the elongated hall of the former Burgtheater, the rear seats lie outside that region.

As the numbers from Table 6.7 for diffuse-field distance (for omnidirectional sources) at 4,000 Hz show, theaters of current sizes reach values of around 6 m; thus, for a statistic directivity factor of 1.65, a value of 30 m follows for the threefold diffuse-field distance, which should be used as an outside limit for a defensible listening distance. However, this limit should not be considered too dogmatically, particularly when it is possible to reinforce the direct sound with some reflections of only slight delay. The floor, at a distance of 2–5 m in front of the singer, offers an important surface for this purpose, because of the particularly strong tonal contributions of the sound maximum, which are directed downward from the singer. These relatively flat reflections are directed into the hall at an angle of somewhat less than 45°. This floor reflection compensates somewhat for the position of the singer further toward the back of the stage, so that one can defend calculating the "audience distance" from the front edge of the stage.

Inasmuch as the side-walls at the front of the stage are only about one reverberation distance away from the singer, they can be extremely effective as reflection surfaces. To serve in this manner, it is essential however, that they are unstructured and contain no openings for stage lighting or box-seating. Reflections from surfaces near the audience are also effective, because very short delay times can be achieved. This has special application for the under side of the galleries. It is especially relevant, because the ear is particularly sensitive to additional reflections with delays of less than 10 ms, since such reflections lie below the direct sound by a level of 12–20 dB (Kihlman and Kleiner, 1980).

The ceiling above the orchestra can contribute significantly to the balance between singer and orchestra in spite of the relatively long delay times of the reflections. For this, the angle is important, as shown for the example of the Staatsoper Berlin (Fig. 6.20). In the years 1955–1983, the ceiling above the orchestra made an angle of 30° relative to the horizontal. This reflected the sound from the stage mostly into the upper galleries which were already served adequately by the ceiling reflections from the main hall. The sound of the orchestra was reflected toward the main floor so that the sound of the instruments dominated above the singers. Since 1986, the ceiling above the orchestra is angled at only 8°, which reflects the sound from the stage to the main floor, and the sound from the orchestra predominately back into the pit. This results in a more balanced sound level of the singers on stage as perceived on the main floor and in the galleries. It also

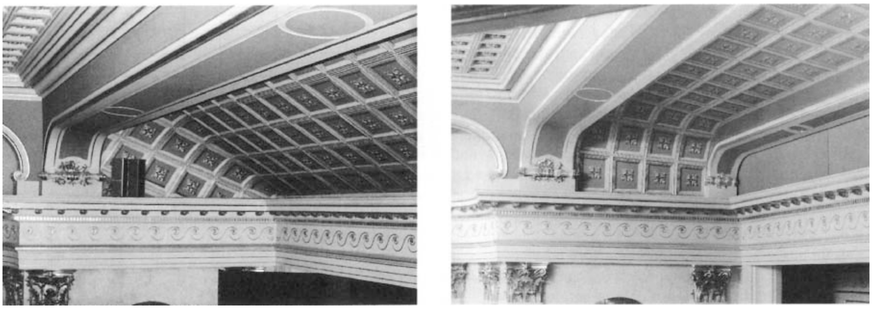

Fig. 6.20 Ceiling above the orchestra in the Staatsoper Berlin (after Marx and Tennhardt, 1991)

improves the balance between the singers and the orchestra on the main floor (Marx and Tennhardt, 1991).

The shape and the arrangement in the audience hall can also have an influence on the balance between singers and orchestra. In theaters with box-seating, the possibility exits that the sound from the stage is reflected by the walls and the ceilings of the boxes in such a way, that it will reach the audience and even the stage. This occurs when the boxes are sufficiently high, and not too deep, so that the singer can still see a small strip of the rear wall. If in addition, the boxes at their full height are separated by sidewalls, so that the reflections return to the stage because of the double angled mirror effect caused by the two angles which approximate 90°, then the singer senses a particularly pleasant resonance of the room in relation to his/her voice.

Using the example of Teatro San Carlo in Naples, Fig. 6.21 shows the sound reflections returning from the boxes, along with the relevant surfaces where they arrive on the stage floor, represented for the right half of the room. The long extended arrival surfaces are created by the superposition of reflections from the rows of boxes located above each another (after Weisse and Gelies, 1979). The many reflections returning to the singer are a help in voice control. The fact that delay times of 80–140 ms are involved clearly should be considered an advantage, since less delayed reflections are covered by the masking due to the singer's own voice (Nakamura, 1992). To a lesser degree, a similar effect is achieved in the Semper Opera by relatively high overhangs below the boxes. This is true because the low frequencies naturally play a lesser role in evaluating tone color variations, consequently, the size of the reflection surfaces only need to be adequate for the middle and high frequencies (Fry, 1978). On the other hand, the sound from the orchestra reaches the boxes at a steeper angle, and is thus reflected more strongly against the front box brim. Therefore, only a small portion is returned to the audience, which is very advantageous for the balance between singers and orchestra.

Open galleries, which are separated only by very low sidewalls, reflect the sound more into the rear portion of the hall. In new theater construction, this effect is

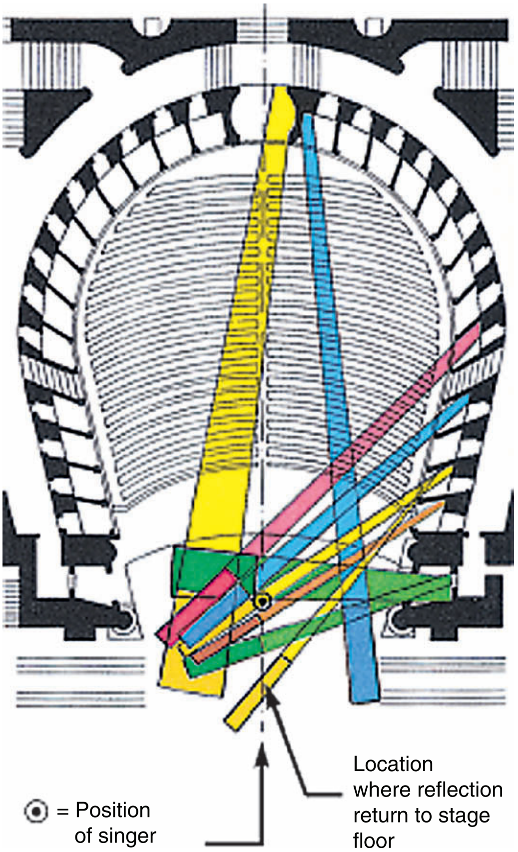

Fig. 6.21 Reflections, originating from a singer, returning to the stage, in the Teatro San Carlo, Naples (after Weisse and Gelies, 1979) (See Color Plate 8 following p. 178)

utilized frequently by appropriate shape and angle of gallery floors and rear walls in order to raise the sound level in the rear portions of the audience (Cremery and Müller, 1978; Fasold et al., 1987). In contrast, very low galleries function as absorbers since even the sound coming from the stage is trapped behind the front rim of the box.

Finally, the stage floor also reflects the sound, which primarily helps the audience in the galleries. As a result, the front seats near the edge of the orchestra pit are not necessarily the acoustically best, from the standpoint of the singer, when a tonal fullness is desired. Corresponding to directional characteristics of the voice, the most effective reflection surface lies in the region of 2–5 m in front of the singer. Of course, proximity to the audience increases clarity of articulation, not even considering the fact that for critical passages (for example, with an accompanying solo instrument), the contact with the orchestra is better.

The depth of the orchestra pit in combination with the angle of the partition separating orchestra from audience plays an important role for auditory communication between singer and orchestra. The reflection from the orchestra to the singers is represented in Figs. 6.22 and 6.23 for several characteristic cases (Meyer, 1988b). If the partition is vertical, instruments close, as well as far from the stage, can be heard from well over 10 m into the audience for a shallow orchestra pit. If the partition is angled toward the inside, the sound transmission from the instruments far from the stage are improved for the singer, the sound of the instruments close to the stage, however, are reflected toward the players, which increases their own loudness impression. If the partition is angled toward the outside, the instruments far from the stage are still easily heard, the sound of the instruments close to the stage are reflected upward above the heads of the singers; however, the singer receives a reflection with relatively short delay of his/her own voice, which can be important since otherwise few reflections are received from the audience.

For a very deep orchestra pit and vertical partition, reflections run more steeply upward and reach the singer only in the front area of the stage; and thus especially the instruments far from the stage are at a disadvantage. Relief can be found in appropriately folded partitions, however, the region of favorable reflections for the singer, don’t reach as deeply into the stage as for a less deep orchestra pit. Another option for supporting the singer, under conditions of insufficient reflections of the orchestra, consists in the use of electroacoustic monitors in the regions of the stage. This however, can be an annoyance to the singers because of the unaccustomed directions of the sound source.

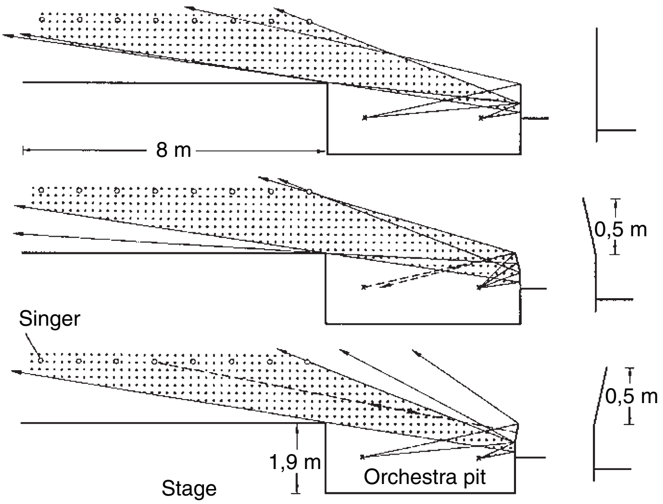

Fig. 6.22 Sound reflections from a shallow orchestra pit to the stage, for differently shaped balustrades

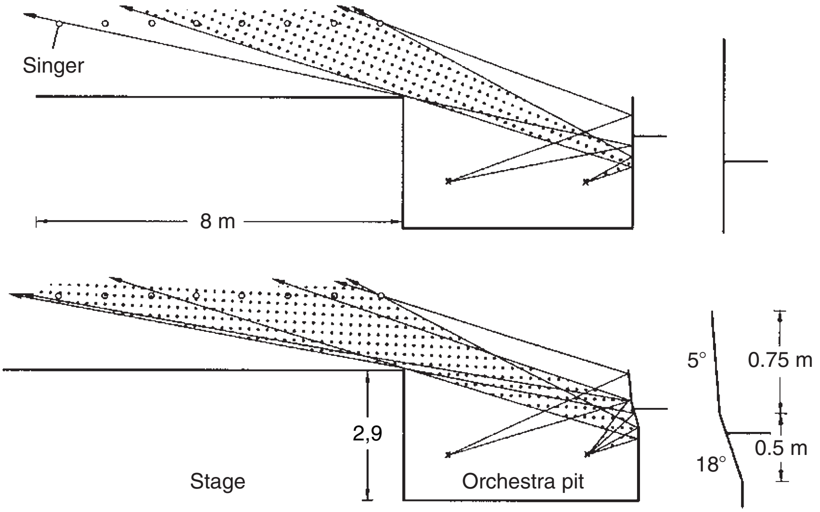

Fig. 6.23 Sound reflections from a deep orchestra pit to the stage, for differently shaped balustrades

6.3 Churches

In many cases, acoustical conditions in churches are characterized by long reverberation times. There are two reasons for this. On the one hand, the walls and the ceilings are frequently highly reflective, on the other hand, in most cases, the ratio of room volume to the volume of persons present is very large, so that absorption effects are not strongly noticeable. Inasmuch as the size of the volume, from approximately 2,000 m^3 in small congregational churches to over 100,000 m^3 for large cathedrals, varies far more than for concert halls and opera houses, the reverberation time also varies in a much greater measure. In addition, the frequency dependence of the reverberation time is closely tied to the architecture style in which the church was built based on the construction materials used (Lottermoser, 1952; Venzke, 1959; Thienhaus, 1962; Meyer, 1977). Thus, acoustical characteristics can be derived, which are typical for church construction styles which not only include the reverberation time, but also the time and directional structure of early reflections (Meyer, 2003).

Three typical reverberation curves for unoccupied church spaces are assembled in Fig. 6.24. Considered here are the Gothic Münster in Ulm, the Baroque St. Michaelis Church in Hamburg, and the small renaissance church of the Darmstadt castle. The Ulm Münster shows a maximum reverberation time at 75 Hz of 12 s. This low frequency of the maximum is characteristic for Gothic churches, as is also shown for other examples in Table 6.9. This is caused by the reflectivity of masonry, which can absorb only higher sound portions because of its roughness; with the exception of leaded glass windows, there are no low frequency absorbers

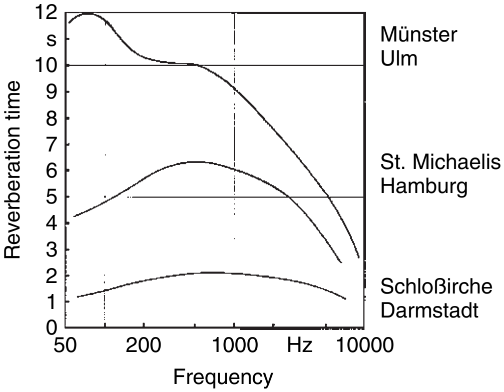

Fig. 6.24 Reverberation curves of several churches

Table 6.9

Church	Style	Volume (m^3)	Maximum reverberation time (s)	At frequency (Hz)
1. Cologne Dome	Gothic	230,000	13.0	100
2. Ulm Münster	Gothic	105,000	12.0	75
3. Freiburg Münster	Gothic	45,000	7.5	90
4. Abtei Church Weingarten	Baroque	53,600	8.5	270
5. St. Michaelis Hamburg	Baroque	32,000	6.3	500
6. Abtei Church Ettal	Baroque	15,000	7.5	750

Source: 1. Winckel (1963); 3.–6. Lottermoser and Meyer (1965)

present. Thus the increase in reverberation time, when comparing midfrequency values to low frequencies becomes greater as the contribution of window area to the totality of walls, ceilings and floors decreases: while a window contribution of 10% results in a ratio of at most 1.1 between low- and midfrequencies, a decrease of window contributions to 2% raises this ratio to1.3 or even more. The reverberation time for Gothic churches in the middle frequencies depends essentially on the volume of the space: A value of 4 s is typical (for an unoccupied room) with a volume of 5,000 m^3, 5 s at 10,000 m^3 and, 7 s at 30,000 m^3. For even larger churches, the reverberation time does not increase significantly and almost never exceeds the value of 11 s (for middle frequencies).

In exceptional cases, Gothic churches have a reverberation time of up to one and a half times the typical values mentioned above. This is the case when the hall in the connection of a "purifying" restoration is too sparsely equipped and above all, the walls and the ceiling are covered with a layer of plaster or paint, which closes the pores. In contrast, the relatively high porosity of materials used in churches of the brick Gothic is very noticeable, particularly when portions of the brick surface are not covered; their reverberation time amounts to only 2/3 of the value typical for natural stone churches with covered walls (Meyer, 2002). The St. Mary church in Lübeck is noted as an example with a volume of 100,000 m^3, it has a reverberation time of only about 6 s. Romanesque churches exhibit reverberation characteristics similar to gothic structures in cases where they possess stone vaulting. However, with a wooden ceiling, the low frequency contributions are dampened somewhat more quickly, so that the maximum of the reverberation time moves to a higher frequency.

In Romanesque and Gothic churches, the pillars or posts play an important role. On the one hand, they block large areas of the side nave. One the other hand, however, they function as valuable reflection surfaces for the audience in the middle nave, provided the sound source is also located in the middle nave. Based on their dimensions, however, they need to be considered as limited reflectors so that their effectiveness becomes significant only above a certain limiting frequency (see Sect. 5.1.3). Depending on the thickness of the pillars or posts, this limiting frequency lies mostly between about 1,000 and 1,500 Hz: complete bending around the pillars can correspondingly be expected only below 200–300 Hz. This is particularly important for the sound of the organ. The high frequency contribution, so important for clarity, including the articulation noise, reaches the listener significantly earlier by diffused reflection from several pillars than the low frequency reflections from side walls and ceiling. This enhances the effectiveness for the direct sound of higher frequencies while the low contributions are perceived as softer than would be expected from their objective intensities, since the initial transient in the hall is slower (Meyer, 2000).

While the reverberation time of middle and low frequencies rises in Gothic churches as a matter of principle, the reverberation time maximum in Baroque churches often shifts into the region of the middle frequencies, since the many wooden structures such as galleries and raised wooden floors underneath the pews, side altars, etc., in most cases largely absorb the low components. This effect is particular strong when the ceiling or the vaulting involves wood. As shown by the example of the St Michaelis Church in Fig. 6.24, a relatively symmetric reverberation curve is created when the maximum is in the region of 500 Hz. Inasmuch as the surface of the walls and additional structures in Baroque churches often exhibit relatively little roughness, the reverberation time at higher frequencies can be somewhat longer in Baroque than in Gothic churches of the same size. Very large Baroque churches with stone vaulting have their reverberation maximum frequently in the region of 250–400 Hz (Lottermoser, 1983), and the difference between Gothic and Romanesque cathedrals is then no longer strongly pronounced. Occasionally however, these large Baroque churches have a second maximum in the reverberation curve, an example of this is the monastery church in Ottobeuren (also known for festival performances), the reverberation characteristics of which are shaped by two maxima at 275 and 1,000 Hz (Lottermoser, 1952). The values for the midfrequency reverberation time typical for this construction style in Baroque churches with volumes of 15,000 m^3, at midfrequencies, lie around 4 s, with 50,000 m^3 around 7 s. This means, that above approximately 10,000 m^3 the reverberation time of Baroque churches is shorter than for Gothic churches with plaster walls, however, longer than for brick churches.

The relatively high frequency location of the reverberation maximum in Baroque Churches leads to the circumstance that the contribution to tone picture in the formant region of the vowels "o(oh)" and "a(ah)" are especially emphasized, and that a clear and brilliant color is created by the fact that the higher components are not very much attenuated, this also corresponds to the optically bright character of the visual impression. This brighter coloration has the additional advantage that the tonal balance between mid and low-frequency contributions is preserved during the reverberation process. Thus, the subjective pitch impression during the decay is not changed for the listener. In contrast, a strong rise in the reverberation time at low frequencies means that the tone coloring during the reverberation becomes increasingly dark. This can lead to the perception of a lowering of the pitch during the decay. The damping of the lower frequency components also avoids the masking effects of the lower voices, so that performance of polyphonic works are possible with sufficient transparency and clarity.

The room acoustic clarity has naturally influenced the instrumental composition style, the development of a polyphonic structure for organ works by Bach can hardly be imagined under acoustic conditions of Gothic cathedrals (Bagenal and Bursar, 1930). These churches especially emphasized the lower registers in their reverberation characteristics and lead to a very dark tonal coloring, which also finds expression in the visual impact made by the somewhat dark rooms on the observer. The duration of reverberations in Gothic churches, therefore, does not permit excessively rapid modulations, and also sets more or less narrow limits on the ability to recognize rapid figures, in spite of the reflections from posts or pillars. The acoustic conditions in these halls are better suited for the slower line sequences of liturgical songs or Gregorian chants. The fact that the Thomas Church in Leipzig, originally a Gothic structure, was suitable for tonal representation of J.S. Bach lies in the circumstance that in its time a multiplicity of additional wooden structures led to acoustic circumstances typical for Baroque churches. The reverberation time in the occupied room was not significantly over 2 s (Keibs and Kuhl, 1959). The harmonically most complicated organ works were created by Bach during his tenure at the so-called Bach-church in Arnstadt, which since Bach's time has been characterized by a reverberation curve with a maximum above 1,000 Hz and a reverberation time at midfrequencies of around 2 s, when occupied.

When churches are fully occupied, as is frequently the case during concert performances, the difference between Gothic and Baroque reverberation characteristics becomes even more strongly noticeably. Since audience absorption is only effective at higher frequencies, the maximum of the reverberation time is lowered and often shifted to a lower register in Baroque churches. A relatively balanced reverberation curve results, which frequently is also not excessively high. An example of this is given in Fig. 6.25 for the reverberation curve of the Frauenkirche in Dresden, which was destroyed during the war and has since been restored. A curve for the unoccupied church was prepared, based on historic tape-recordings form 1943/1944; the curve for the occupied church was subsequently calculated

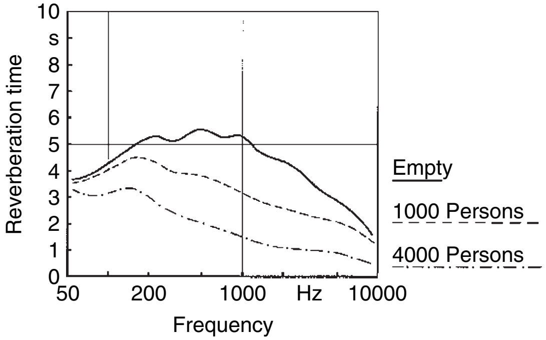

Fig. 6.25 Reverberation curve of the Frauenkirche in Dresden (after Lottermoser, 1960). *Empty*: measured from historic tape-recordings. *Occupied*: calculated from the curve for the empty church (Mozarteum Salzburg)

(Lottermoser, 1960). St. Peters in Rome serves as an additional example, for which at full occupancy values at only 3.5 s were measured (Shankland and Shankland, 1971). In contrast, the maximum for the reverberation time in Gothic churches remains unchanged both in level and frequency location, the drop of the curve for higher frequency regions, however, is steeper. Thus, the coloration of the tone picture has even more emphasis in the low register, however, the clarity of the articulation only suffers slightly since the first reflections from the pillars and posts are not affected by the audience.

Understanding advantages of the Baroque room acoustics has led to an attempt to achieve similar tonal relations by construction measures for numerous newly constructed churches. Alternatively, Many new churches use an architectural conception, which even for relatively small volume, create an excessively large reverberation with preferred low frequency emphasis. This danger can hardly be avoided when using concrete; such rooms are therefore mostly unsuitable for musical performances.

An example of a small church, which lends itself well for musical performances is the Schlosskirche in Darmstadt after restoration in 1969. As shown in Fig. 6.24, with a volume of 1,800 m^3, it has a reverberation time of slightly above 2 s at the midfrequencies and distinguishes itself by a drop toward the lower registers. The tonal effect in this hall is therefore, clear and bright. Many of the small churches constructed in recent yeas, exhibit similar reverberation characteristics. They meet the demands for congregational singing and musical performances of small ensembles and choir (Meyer, 2003).

Long reverberation times in large churches also result in slow initial transients. Since a time period of 1/20 of the reverberation time must pass for the sound level of a sustained note to reach a value of 3 dB below the final value, for a room with a reverberation time of 10 s an initial transient of ½ s can be expected. This naturally leads to a certain "inertia" of the room, and furthermore means that short notes will never reach their final intensity. Thus, they give a softer impression than equally strongly played long notes.

This effect becomes even more significant when the direct sound reaches the audience relatively softly. This is because the diffuse-field distance, by reason of the long reverberation time, is not much larger than for concert halls and opera houses, even though church spaces are usually wider. Thus, even in the Cologne Cathedral, the diffuse-field distance (for an omnidirectional source) for low and midfrequencies is only about 8 m. While first reflections, because of the many pillars and posts in these large churches follow with only very slight delay, the energy density of diffuse reverberations is so high, that it is often impossible to localize the position of the sound source. This applies particularly when the direct sound path of the high frequencies is blocked by pillars. Under such acoustical conditions, a nearly mystical tonal effect is created, which furthermore supports the visual impact of the spatial atmosphere without permitting recognition of precise details of the musical sequences.

6.4 Chamber Music Halls

Today, chamber music is associated with musical performances by small ensembles. From a tonal standpoint, transparent musical performances are expected in which all individual voices are evident. In this context, proximity of audience to the performers fosters immediate contact. These acoustical demands are met by a relatively short reverberation times in rooms which are not too large. This especially emphasizes an intimacy and presence of the tonal impression through very short delays between the arrival of the direct sound and the first reflections. Furthermore, a “chamber- music” tone picture includes the requirement to separate the individual instruments spatially, so that in spite of achieving the homogeneity associated with seamless ensemble performance, a stereophonic effect is perceived.

When considering the historical development of chamber music in the context of the time period during which the works of today’s repertoire were composed, a fundamental change has occurred in the character of the works, as well as in performance practice (Wirth, 1958). In the Baroque era, chamber music was the only alternative to church music. Consequently, instrumentation for those compositions range from one or several instruments for sonatas, clear up to chamber orchestras. These small ensembles consisted predominantly of amateur performers. In approximately 1800, the first chamber music ensembles were organized by professional musicians. These performed in public concerts for a larger audience. For example, from 1803 on we find “the” Gewandhausquartett in Leipzig (Borris, 1969). Naturally, increased performance technical demands were connected with this as well as an evolution of musical content. The expression of both of these is represented especially well in the development of the Beethoven string quartets. At the same time, domestic musical performances developed their own independent form. As determined by the limitations of technical possibilities for amateur performers, this became increasingly removed from concert chamber music.

The chamber music of the Baroque and the early classical era was performed largely in the palaces of the nobility. Thus it was mostly in large rooms or possibly even small halls where a group of performers played for a relatively small number of listeners or occasionally for an audience which filled the hall. According to contemporary artworks, such rooms had a ceiling height of around 4–8 m and a volume between about 200 and 1,000 m^3. Figure 6.26 shows an example of a Paris hall around the middle of the eighteenth century. In such halls, depending on size, the reverberation time should be near 1 s when occupied. Thus the sound should attain the necessary brilliance without losing the individuality of separate voices. In addition, the temporal separation of reflections was sufficiently short for a direct tonal impression.

A hall which played a special role in music history is the so-called Eroica-Hall in the Palais Lobkowitz in Vienna. This hall not only saw the premier performance of the 3rd and 4th symphony by L. van Beethoven but also of many chamber music works by him and other contemporaries. This is a rectangular hall of 8.25 m height and a volume of 950 m^3. In addition to the chamber music podium, it offers seating for approximately 160 people. Its reverberation time is given in Fig. 6.27 both for empty and occupied conditions. When fully occupied, as would have been the case for most of Beethoven's concerts according to contemporary reports, a reverberation time of 1.45 s is determined at midfrequencies, with a steep increase toward

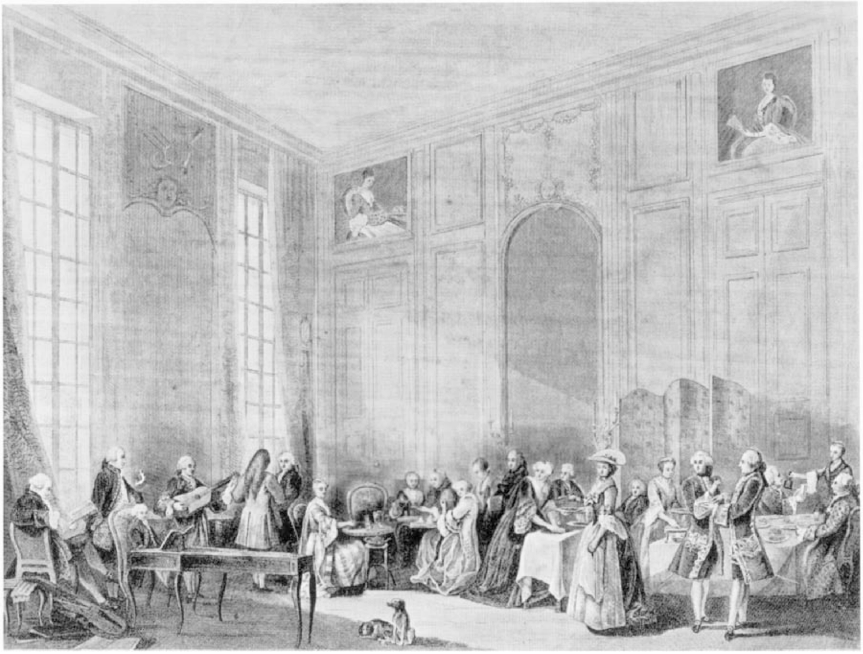

Fig. 6.26 Mozart at the piano in the Palais of Count Conti in Paris, 1763. Oilpainting by M. B. Ollivier (Mozarteum, Salzburg)

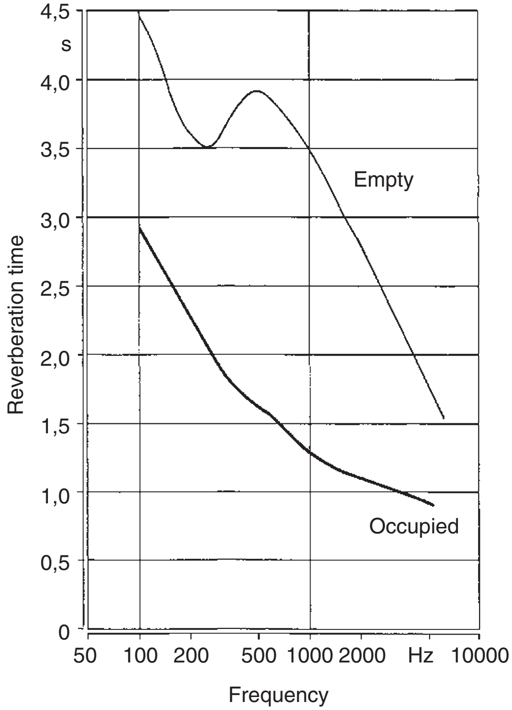

Fig. 6.27 Reverberation curves of the Eroica Hall in the Palais Lobkowitz in Vienna

low frequencies, as a result of the use of marble in the structures. In the empty hall, the reverberation time is significantly longer, thus the number of persons in the audience has a strong influence on the acoustical conditions. The dip in reverberation time at frequencies around 250 Hz can be associated with the wooden podium used today and thus may not reflect the original condition during Beethoven's time.

In this context it is interesting, that in his autobiography, C. Ditters von Dittersdorf (1801) praises a hall of oval design in the castle Johannesberg near Breslau for its especially good acoustics (elliptical halls usually suffer from a disturbing focal point). In this hall, which has a length of 13.5 m, and consequently can not have been much wider than 10 m, the sound concentration evidently must have functioned positively which can only be explained on the basis of a delay time difference between the focusing echo and the direct sound. The direct sound and focus reflections would thus still appear fused to the ear, resulting in a particularly pregnant sound picture. Dittersdorf emphasizes that this construction characteristic contributes much to the amplification of the music without glaring echoes.

The development of house music in common homes, naturally led to the use of smaller rooms in which, determined by the fashion of the times, plush furniture and curtains absorbed the middle and high frequencies strongly. The tone picture, thus lost brilliance, but because of the very short reverberation time, obtained an extremely direct character, which engaged the audience seated close to the performers with a particular immediacy in the tonal procedures. Merely the height of the room, which amounted to at least 3 m, assured that the sound did have some spatial character.

This intimacy of small rooms naturally cannot be transferred to halls for public chamber performances. One can assume that professional quartets use concert halls like the one in the old Gewandhaus for their performances in order to reach sufficiently large audiences. As mentioned, this hall had approximately 400 seats. This already reaches the limit of a meaningful framework for a string quartet; halls, which are larger than the Brahms-hall of the Vienna Musikverein building (with 679 seats and 95 standing places), demand an intensity from the player, which no longer permits a chamber music style and thus already approach a symphonic character. Such halls are only suitable for large ensembles or chambers orchestras, for particularly in chamber music, sufficient loudness is required so that the audience does not sense a disturbing distance.

Modern chamber music halls are therefore usually designed for an audience of 500–600, when acoustics conditions are to be somewhat appropriate for this musical genre. Thus, for example, the small hall of the Meistersingerhalle in Nürnberg, with 500 seats, has a volume of 4,000 m^3. It is thus approximately twice as large as the old Gewandhaus. Under occupied conditions it has a reverberation time of 1.1 s at midfrequencies (Cremer and Müller, 1964). The chamber music hall in the Schauspielhaus in Berlin offers seats for 440 at a volume of 2,150 m^3 and has a reverberation time of 1.3 s. The small hall in the Leipzig Gewandhaus, with a volume of 4,300 m^3 occupied by 450 people has a reverberation time of 1.7 s, with a pronounced rise at the low end, which, at least for small ensembles, is already perceived as too long (Fasold et al., 1981; Fasold et al., 1986). In all three halls, the distance between the center of the stage and the most distant audience row lies between 20 and 25 m. The clarity factor in the Schauspielhaus lies between +1.3 and +3.5 dB, in the Gewandhaus between +0.5 and 1.3 dB. In the latter case, the clarity is already perceived as bordering on insufficient. While the right degree of intensity and, essentially also transparency have been met, the sense of immediate participation is available only in the front portion of the hall, since the distance of 20 m to the last rows already creates a certain separation between the performers and the audience, even when the tone leaves nothing to be desired in brilliance. This does not exclude the possibility that the musicians on the stage have an excellent impression of the acoustics and thus find optimal performance conditions.

The proximity of the audience to the podium is also an essential design criterion for the chamber music hall of the Berlin Philharmonic for which the audience is arranged to surround the stage: 1,064 seats are located within 23 m of the stage. The volume amounts to 12,500 m^3, and the reverberation time at midfrequencies is 1.8 s. This relatively long reverberation time is one of the reasons that the clarity measure lies between -1.3 dB near the podium and -1.6 dB for the distant seats. Numerous reflection surfaces are positioned in the hall to equalize the balance of individual instruments, the surfaces inclined toward the podium reflect the sound toward the player, and thus do not serve to balance the directional characteristics and the blocking by the players for the seats close to the stage (Fütterer, 1988).

As an example of a chamber music hall with a more intimate character, the presentation room of the Schimmel piano Co. in Braunschweig should be mentioned. With a volume of 800 m^3, it offers seats for 80–100, as well as for several upright and grand pianos. Because of its reverberation time of 0.9 s (at midfrequencies in the occupied hall), and a slight drop toward the low frequencies, it provides optimal conditions for the performance of piano and string music for the performer as well as the audience. This was clearly shown, at a comparative demonstration during which the same audience was offered the same program in three halls in immediate succession. The two other halls had a midfrequency reverberation time of 0.7 and 2.7 s respectively, each with a clear rise at low frequencies, for room volumes of 1,750 and 2,750 m^3 (Meyer, 1988a).

6.5 Studios

In a living room, radio transmissions or CD recordings clearly cannot evoke the tonal impression of a public performance. This is particularly true for symphonic music and operas, however, even for chamber music works, certain differences relating to room effects are unavoidable. The reason for this lies primarily in the fact that the reverberation, in essence, is already contained in the recording, while the listening space only adds very damped reflections. In addition, the small size also plays an important role. The spatial representation of a whole orchestra presents great difficulties. Finally, in radio transmission, dynamics are frequently compressed to avoid exceeding loudness levels permissible in residential houses. Recording studios therefore need to take into account the modified sound esthetic demands of such an environment.

The possibility to amplify individual instrument groups selectively, and also control the overall loudness levels, obviates the problem of meeting the listener expectation of conditions for appropriate intensities with suitable combinations of room volume and reverberation times. Thus, the reverberation time can be chosen alone on the basis of tone esthetic view points. For symphonic music, an experiment by W. Kuhl (1954a) with a series of orchestras in 20 different studios had the result that, at least for mono recordings, the optimal reverberation time for orchestra studios, does not depend on their volume, but only on the nature of the music.

The subjective evaluations by over 100 test persons, naturally led to a certain spread of the results, based on the personal tonal conceptions, nevertheless, rather good average values were obtainable. Consequently, the first movement of the Jupiter Symphony, as an example of the classic era gave an optimum of 1.5 s, and for the first movement for the 4th Symphony of Brahms, a value of 2.1 s. Romantic music demanded a significantly longer reverberation; recordings from studios with 1.5 s, almost without exception, were evaluated as too dry. It should be noted that Kuhl, in a discussion, mentioned that for stereo reproduction the possibility of localizing individual voices exists, thus increasing transparency. This allows longer reverberation time in concert halls without diminishing transparency excessively (Kuhl, 1954b).

It is interesting to note, that for an excerpt from the "Sacre du printemps," a reverberation time of 1.5 s was perceived as optimal. In that context, evidently, the transparency of the structure was dominant in the tonal perception. Especially in nonstereophonic recordings dissonant cords can easily obtain excessive hardness, when a separation of voices is no longer audibly possible (the experiment was limited to mono recordings). In contrast, there are, however, conductors, which demand long reverberation times for Stravinsky orchestra works with large ensembles. Thus, Stokowski even speaks of a value of about 4 s for a performance of the "Sacre" (Blaukopf, 1957).

Recordings of symphonic works are usually made in halls, which in size are not much smaller than standard concert halls. These are also used for public performances and also use seating from about 800 to 1,200 people. Accordingly, acoustic characteristics of these large recording halls, at least as far as the interests of the musicians go, are not significantly different from those of normal concert halls. Two examples, which by now have almost become historic, for this type of studio are the larger recording hall in Frankfurt am Main and in Hannover. Both originally had 1,200 seats and had volumes of 12,000 and 15,700 m^3, respectively. The average reverberation time in Frankfurt, (prior to adding the organ) was 1.85 s and in Hannover, 2.0 s; furthermore, the hall in Frankfurt had a low frequency rise up to 2.2 s near 65 Hz (Schreiber, 1958; Kuhl and Kath, 1963). While the radio hall in Hannover has not been subjected to significant changeovers, the hall in Frankfurt was remodeled in the 1980s according to new conceptions: with a volume of around 9,000 m^3 and reduced seating in unoccupied conditions, it offers the same reverberation conditions when occupied, as the concert hall of the old opera in which the public concerts of the radio symphony orchestra are held (Lamparter and Brückmann, 1989).

As far as musicians are concerned, it is advantageous for orchestra recordings in small studios to have the reverberation time not too long and if necessary, add additional reverberation after the recording. An extreme example of this technique is given by a series of performances by A. Toscanini for which he ordered preparation of a studio in New York with extremely short reverberation time. These recordings distinguish themselves by an extreme sharpness of this rhythmically very precise performance. However, they present a very difficult task to the participating musicians relative to the tonal quality.

A reverberation time is viewed as optimal for orchestra studios at 1 s, for a room volume of 1,000 m^3, which increases by 0.2 s for each doubling of the volume (Gilford, 1972). These values can also be considered as advantageous for orchestra practice rooms. Furthermore, the reverberation time at low frequencies should not increase at all, or increase at least significantly less than in large concert halls, since otherwise the bass instruments dominate, which does not correspond to performance conditions in large halls.

Smaller orchestra studios also bring the danger that the weaker instrument groups will be overpowered by those richer in energy. For those cases, one possible solution is not to make the rear wall behind the podium as well as the ceiling above it, fully sound reflecting, as is usually the case, but rather to furnish some surfaces with absorbing elements in order to weaken the intensity of the stronger instrument groups. This must be done with due consideration of the seating of the orchestra and the directional characteristics of individual instruments. It is particularly recommended to place sound absorbing arrangements with appropriate frequency dependence behind the basses and timpani.

Studios for small ensembles, both for entertainment or chamber music, are also partly furnished for public performances and partly for recordings without audiences. The number of listeners is kept small in consideration of the desired room effect on the tonal reproduction. There are rarely more than 300 seats available. The reverberation time for room volumes between 1,000 and 3,000 m^3, for rooms with audience lie in the region of 1.25–1.5 s (Reichardt et al., 1955). The acoustic conditions are thus ideal for chamber orchestras as well as ensembles of several winds and strings. For quartets, trios and sonatas, one obtains a greater intimacy of the tonal picture in studios without audiences which only have a size of 400–1,000 m^3, with reverberation times between 0.8 and 1.0 s. This comes closer to the original atmosphere of producing house music, even though the brilliance no longer reaches the degree desired by some high-fidelity-fans.

6.6 Special Purpose Rooms

In addition to various types of rooms, which serve for artistic performances of musical works for an audience, or for recordings intended for general distribution, there are circumstances for which not the music itself, but the performer or the instrument is the principle interest. This includes rooms for instruction, or for instrumental practice, or for example, tuning cabinets, or intonation rooms in piano factories, as well as performance rooms in which instrument quality is to be judged either directly or in comparison to other instruments. For all of these rooms, the most important acoustic demand is the requirement of a high degree of isolation against sounds from the exterior.

Studios, which are to serve for teaching or practice are usually so small that the internal resonances between parallel walls become particularly disturbing. Thus, wall structure is of great importance. In addition, the reverberation time in such rooms must be kept low, where particularly at low frequencies, a drop in the reverberation curve is desirable. The teaching studios of the music academy in Budapest should be mentioned as examples, the larger ones of these have a volume of 182 m^3 and a reverberation time of 0.9 s at the midfrequencies, at 125 Hz, their reverberation time has dropped to 0.5 s. The smaller studios have a volume of 105 m^3, reverberation values are 0.8 and 0.4 s respectively (Karsai, 1974).

Japanese recommendations give slightly lower reverberation times (Nagata, 1989). As Fig. 6.28 shows, a slight rise is tolerated at least near low frequencies.

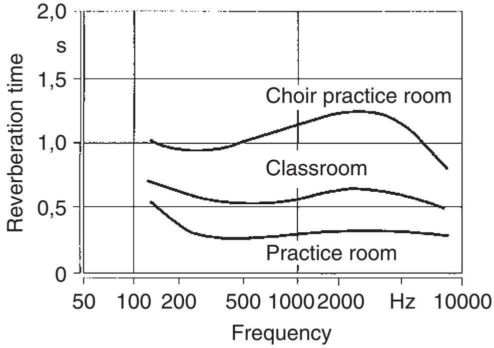

Fig. 6.28 Recommended reverberation times for rehearsal and practice rooms (after Nagata, 1989)

The reason for that may lie in the fact that students do not yet have well shaped sensitivity for tonal changes influenced by the room, on the other hand, performance technical inaccuracies are more clearly recognized in rooms with less reverberation.

Special rooms, which are to serve individuals for practice, usually only have a volume of the order of 30–40 m^3. Based on the fact that in such rooms, tonal impressions comparable to the tonal development in large halls can never develop for the performer, the listening impression should predominately be concentrated on the tonal fine structure. For this, a reverberation time of 0.3–0.4 s is appropriate, where no rise at low frequencies is present, even though the Japanese recommendation (Fig. 6.28) intends that. Wind players prefer slightly longer reverberations than string players, (Cohen, 1992). For percussionist, practice rooms should be largely absorbing. In contrast, experiments in England have shown that in rooms with reverberation below 0.5 s, practice becomes stressful and that rooms with reverberation times of about 0.75 s are preferred for extended practice (Creighton, 1978; Lamberty, 1978).

Reverberation values of the order of 0.3–0.4 s have become accepted for tuning cabinets for pianos. For intonation rooms, the optimum value is slightly higher, i.e., for uprights it is between 0.4 and 0.5 s at a volume of up to 1,000 m^3, and for concert grands, between 0.5 and 0.6 s at approximately the same room size. In order to judge a concert grand accurately, a larger room is needed, which should have a volume between 400 and 600 m^3. However, a reverberation time of 0.6 s for this size is noticeably too short. The optimum lies in the region from 0.8 to 0.9 s. Values above 1 s already increase the difficulty of judgment. Furthermore, these rooms should have no rise at low frequencies.

Practice rooms for orchestras pose a particular problem. If the volume is too small, unacceptable loudness occurs for normal playing intensities; if they are damped excessively, the articulation and sharpness of staccatos cannot be balanced accurately. Therefore, in general, a "tonally appropriate" reverberation time cannot be achieved. Thus, in a room of a volume of 1,200 m^3, a reverberation time of 1.2 s at midfrequencies with a slight low-frequency rise, is perceived as too long for an orchestra with 90 musicians. In such a room, mutual listening can only be assured by strong damping behind the winds and by lowering the reverberation time at low frequencies below the value for the midrange. Völker (1988), therefore, recommends a volume of 50 m^3 per musician (!) with a reverberation time of 1.3–1.5 s. Similar values are included in Japanese recommendations for choral practice rooms (see Fig. 6.28).

Tennhardt and Winkler (1994) recommend a room size of 25–30 m^3 per musician, where for average orchestra size the volume should not be below 2,000 m^3. To the degree that practice rooms are also used for warm-up in production recordings, the average reverberation time in an occupied room should be between 0.5 and 0.7 s, and in other practice rooms, between 0.8 and 1.1 s. A low frequency reverberation rise up to about 1.3 s is still defensible, the reverberation time around 4,000 Hz, should not sink to below 0.6–1.0 s. For smaller orchestras, or section rehearsals, variable sound absorbers, as for example curtains at a distance of 20–30 cm from the wall, are recommended to match the reverberation time to the value of the full occupied room. Sidewalls should be fitted with low frequency absorbers at a level up to 3 m. The wall behind the orchestra is particularly suited for surfaces, which absorb also the middle and high frequencies; absorption surfaces on the ceiling should only cover 30%, since otherwise, at lower dynamic levels, performers tend to compensate for an uncertain tone onset by playing too loudly.

6.7 Open Air Stages

For performance in the open, acoustic conditions are largely determined by the direct sound. Generally this is followed only by a few individual reflections. Since sound energy can escape in nearly all directions, in contrast to closed rooms, a diffuse sound field is not formed, thus there is no reverberation in the usual sense. It is however, easily possible, that individual reflections from distant reflection surfaces are perceived as a discrete echo, which influences the otherwise extremely pronounced clarity of the tonal picture.

To this day, the partly well preserved Greek amphitheaters are admired because of their exceptional ability to make speech understood to the last row. These theaters, which offer seating for many thousands, were frequently built into a mountain with rounded rows of seating, and in those days also had a rear wall behind the stage. The so-called “orchestra” was located between the stage and the audience, which, as a free surface, furnished an energetically important ground reflection. The rise of the seating rows was determined in such a way that each viewer had a clear view of the “orchestra” and thus could receive these reflections without obstructions. A further reflection from the rear wall of the stage, as well as a double reflection from the rear wall and stage floor, completed this package of sound reflections (Canac, 1967).

Measurements on the amphitheater of Epidaurus, which has an audience potential of 14,000 people, showed that all these reflections had a delay of less than 30 ms in comparison to the direct sound, which explains the extreme clarity. The fact that the sound energy of a single voice is sufficient for such a wide auditorium is related to the fact that the low level of extraneous noise, due to its location far from common traffic, makes it possible to hear even very soft tones (Cremer et al., 1968). Such acoustics however, cannot necessarily be designated as optimal for musical performances. Certainly, the extreme transparency of the orchestra's sound can present a unique experience for the listener, which is furthermore enhanced by the extraordinary atmosphere of the location. However, frequent attendance at such concerts can quickly diminish the novelty of this effect.

In contrast, conditions for an opera performance in a Roman arena, as for example, during the festivals in the well known structures in Verona, are significantly different. Due to the fact that the room, which was certainly not originally intended as a theater, forms a closed circle open at the top, a large number of reflections result. This certainly can give the impression of reverberation. Thus the level drop after the first 160 ms corresponds to a reverberation time of 0.85 s at midfrequencies and 1.25 s at low-frequencies (Kurtovic and Gurganov, 1979). Furthermore, for operas, particular clarity in relations to singing is advantageous so that the arena meets the acoustic demands very well. However, one should not overlook that the critical intensity question is solved in Verona by contracting only first class singers and by using large orchestras. The level a singer can create in the upper ranges of the arena lies by 15 dB lower than the value which can be achieved in an opera house with a reverberation time of approximately 0.8 s (Pravica, 1979).

A different type of open air performance is presented by the types of concerts which are performed from a more or less closed orchestra shell to a public sitting in the open. The walls and roof of the music pavilion ensure sufficient loudness for mutual listening by performers and that furthermore, the energy radiated in the outward direction is concentrated in the direction of the audience (Furrer, 1972). In health resorts a variety of shapes for such concert shells are found.

Relative to acoustical effects, structures which have a foundation layout and cross section approximating a parabolic mirror are particularly unsatisfactory since they present varying directions of concentration for the individual instrument groups as already explained in Sect. 5.2.1., and thus, do not present a balanced tone picture to the audience. An example of this shape is given by the music shell at the beach promenade in Westerland on the island of Sylt (Fig. 6.29).

In contrast, pavilions, which have an outwardly directed trapezoidal foundation with a roof directed slightly upward toward the public, are advantageous. When the walls, furthermore, create necessary diffusion by subdivision into small elements, the acoustical conditions are good for both the performer and the listener. The concert pavilions on the island Norderney for example, correspond to this type (Fig. 6.30).

When the region in which the audience sits or walks is spread over a large area, frequently loud speakers are mounted in the frame or on the roof of the music shell in order to achieve sufficient intensity even for large distances. Thus, either a central speaker group can radiate the entire sound, or by using several speakers distributed over the width of the pavilion, which correspond to the seating arrange-

Fig. 6.29 Concert shell in Westerland on the island of Sylt

Fig. 6.30 Concert shell in health resort facilities of the island Norderney (Norderneyer Badezeitung (Foto Kühnemann))

ments of the instrument groups, their sound can be stereophonically projected from the stage. For highly directional speaker amplification, however, it is important that there be no house walls in the neighborhood, which could reflect a disturbing echo, since, for transmission times of an order of magnitude directly related to the musical tempo, very undesirable effects can occur. In this context, facades with contain a number of balconies or other protrusions are especially undesirable since the sound is mirrored back to the source by double reflections from two mutually perpendicular surfaces (see Fig. 5.1b).

The danger of disturbing wall echoes also exists for serenade concerts in interior courtyards or similar spatial situations. For excessive distances between reflecting walls (more than 20 m) so that sound reflections are no longer joined into a relatively well contained reverberation, a solution can be given by having the audience rows rise relatively steeply. The sound which reaches the rear wall above the heads of the audience is consequently reflected upward due to its angle of incidence, and thus no longer influences the perceived sound.

For opera performances and concerts, with an audience of several thousand, increasingly electroacoustic sound installations are utilized, which are intended to coordinate the tonal picture at the location of the audience with a corresponding optical directional impression. For this, numerous microphones and speakers are employed, which are interconnected by delay circuits to ensure that for all audience locations the sound signal of the respective speaker group, which has the shortest distance from the connecting line between the listener to the original sound source arrives prior to the sound from other speakers, however, later than the original sound. In this way, both directional and distance impressions are preserved. Typical examples include the opera performances on the 50 × 60 m Lake Stage in Bregenz (Ahnert et al., 1986) or the Berlin Forest Stage (Schlosser and Krieger, 1993). In these cases, some microphones are permanently positioned and some are affixed to the singers as micro-portable systems. In open air concerts, occasionally microphones are used, which are introduced into the corpus of the string instrument itself at the point where the strings are connected to the body (Winkler and Kaetel, 1990).