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Construction Technology Update No. 51

Acoustical Design of Rooms for Speech

by J.S. Bradley

This Update explains the acoustical requirements conducive to relaxed and accurate speech communication in rooms and gives design criteria for a wide range of room sizes. Some special issues for particular types of rooms and special groups of listeners are discussed.

Rooms such as classrooms and meeting rooms are intended for speech communication, but they are often not designed to optimally support this intended use. When acoustical design issues are ignored, inaccurate communication in a law court or boardroom can result, and the associated costs can far exceed the relatively modest price of an appropriate acoustical design for the room. Similarly, poor acoustical design choices for a classroom can seriously affect children's educational development.

Both excessive ambient noise and inappropriate room acoustics can degrade the intelligibility of speech in rooms. As listeners we often do not realise that we are having difficulty understanding speech because of our quite remarkable abilities to guess the correct word in noisy or reverberant conditions. We are often only aware of more difficult communication situations when the interfering noise stops.

The negative effects of noise and reverberation are usually more obvious when listening in a second language in which we are less able to use context to guess particular words. Of course, listeners with any hearing impairment will be more affected by inadequate acoustics and excessive noise, as will very young and very old listeners with normal hearing. These groups are less capable of processing the speech sounds to correctly determine their meaning. Consequently we should provide these listeners with better listening conditions so that they have equal accessibility to speech communication.

To establish when near optimum conditions for speech exist, we can use carefully controlled speech recognition tests, in which the percentages of correctly heard words or phrases are observed. By determining the related acoustical characteristics for these conditions, we can then derive design guidelines for rooms used for speech communication. This Update is intended to explain the basic principles of designing rooms such as classrooms, meeting rooms, boardrooms and law courts for good speech communication. It is not intended to replace the need for expert guidance when designing such rooms to achieve high quality speech communication.

Some Basic Principles

The louder the speech signal relative to the level of interfering noise, the more intelligible the speech will be. 'Noise' is any kind of unwanted sound. One obvious type of noise is that emitted by heating, ventilating and air conditioning equipment. Other devices such as projectors or computers, and the occupants of the room themselves, also contribute unwanted noise that will interfere with our ability to understand speech.

The level of the speech (signal) can vary with the amount of vocal effort, but increased

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Table 1. Maximum ambient noise levels and optimum reverberation times (RT) for good speech intelligibility

Example Situations	Maximum noise		RT
	dBA	NC	
Primary school classroom Boardroom for elderly adults	30	23	0.5
Law court	30	23	0.5
High school classroom General meeting room	35	28	0.7
Large lecture hall theatre	30	23	0.7

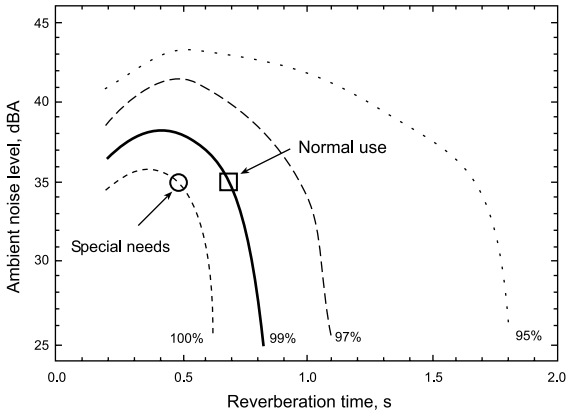


Figure 1. Equal speech intelligibility contours for 300-m^3 (classroom-sized) room and RT design goals

speech levels are usually limited by the human voice mechanism. Although speaking louder is one means of improving the signal-to-noise ratio and hence the resulting speech intelligibility, it can lead to voice strain.[1] The solution to obtaining higher intelligibility and preventing voice stress is to ensure that ambient noise levels are low compared to typical speech levels.

When we listen to speech in rooms, we hear a combination of the direct sound from the talker and many reflections of it. That is, sound travels from the talker to the listener by many different paths that include 'bouncing off' or reflecting from various surfaces. Some of these reflections arrive at the listener very soon after the direct sound but others can bounce around the room for as long as a second or more. It is typically the combination of thousands of different reflections of the speech sounds that the listener hears. In many situations we would not be able to hear the spoken word very well without this added reflected sound energy.

Although some reflected sound is very useful for increasing the intelligibility of speech, later-arriving reflections are undesirable. Reflections that have bounced around the room for longer periods of time (more than 0.05 s after the arrival of the direct sound) cause one word to blur into the next and, in this way, degrade intelligibility. These unwanted later-arriving reflections can be thought of as another type of noise.

For example, in rooms such as a gymnasium there is much later-arriving sound and speech communication is often difficult.

On the other hand, early-arriving speech reflections are very useful because our hearing system adds them together with the direct sound making the voice seem louder and the speech more intelligible. Reflections that have travelled much shorter paths and arrive within 0.05 s after the direct sound are useful early reflections for speech. Thus for optimum speech intelligibility, we need more direct and early-arriving reflections of the speech sound and as little later-arriving speech sounds and ambient noise as possible. The ratio of direct and early-arriving speech energy to later-arriving speech energy and ambient noise has been called a useful-to-detrimental sound ratio. These ratios are related to speech intelligibility scores[2,3] as well as to other more complex measures such as the Speech Transmission Index (STI) and the simplified version of it, Rapid Speech Transmission Index (RASTI)[4,5] (see acoustical terms box).

Because these complex measures are more difficult to calculate and measure, room acoustics criteria are usually given in terms of the conventional reverberation time measure. Reverberation time (RT) is approximately the time it takes for a sound to die away to inaudibility after the sound source has stopped and can be as long as a second or more in large rooms. RT increases with the volume of the room and decreases as sound-absorbing material is added to the room (see sound absorption box). Some examples of ambient noise level and reverberation time design goals are given in Table 1.

Maximising the ratio of early-to-later-arriving speech reflections, and hence intelligibility, is related to achieving an optimum reverberation time. That is, too much or too little reverberation will lead to reduced intelligibility. Only a small range of reverberation times can be considered desirable depending on the ambient noise levels and other details of the rooms.

Figure 1 plots contours of equal speech recognition scores for combinations of ambient noise levels and reverberation times. These were derived from speech studies in many rooms and from measured useful-to-detrimental sound ratios.[6] The 99% contour is used to determine a design goal for normal use. This does not correspond exactly to

Some Acoustical Terms

NC — Noise Criterion — noise rating measure in decibels used for ventilation type sounds.

A-weighted sound level — simple measure for approximating the loudness of sounds with units dBA and about 7 points greater than the NC value.

Sound absorption coefficient — a number between 0 and 1 that describes the fraction of the incident sound that is absorbed by a material.

Sound absorption average (SAA) — average absorption coefficient over frequencies important for speech (replaces the older noise reduction coefficient (NRC) average).

Equivalent sound absorption — the product of the absorption coefficient and the surface area of the absorbing material, m^2.

Reverberation time (RT) — the time it takes for sound to die away to inaudibility after the source is stopped. It is usually measured from the slope of the sound decay and extrapolated to represent a 60-dB decay. RT increases with room volume and can be decreased by adding sound-absorbing material to the room.

Speech transmission index (STI) — a measure of the combined effect of ambient noise and room acoustics on speech intelligibility. It measures how ambient noise and room acoustics reduce the natural amplitude fluctuations in speech sounds.

Rapid speech transmission index (RASTI) — an abbreviated version of the complete STI.

perfectly relaxed listening conditions because the results are derived from speech tests in which listeners strain, to the point of not breathing, to correctly hear each test word. However, a 99% average score on a simple word intelligibility test does represent very good conditions for normal speech communication.

The 99% speech intelligibility contour indicates a range of combinations of ambient noise levels and reverberation times can be expected to lead to the same speech intelligibility score. However, for various practical reasons not all combinations are equally desirable. The point marked with an open square represents a desirable reverberation time design goal. Following the same 99% contour indicates that rooms with higher reverberation times would require much lower ambient noise levels, which would be very costly and difficult to achieve. A lower RT goal on the same contour would require more added sound-absorbing material for minimal additional benefit. Therefore the reverberation time point marked by the open square symbol can be considered optimum because it minimizes both the need to add sound-absorbing material and the need to reduce ambient noise levels.

The point marked by a circle will be used as a design goal for various special needs situations and corresponds to a slightly shorter reverberation time. Similarly, two sets of optimum reverberation time criteria are presented in the following

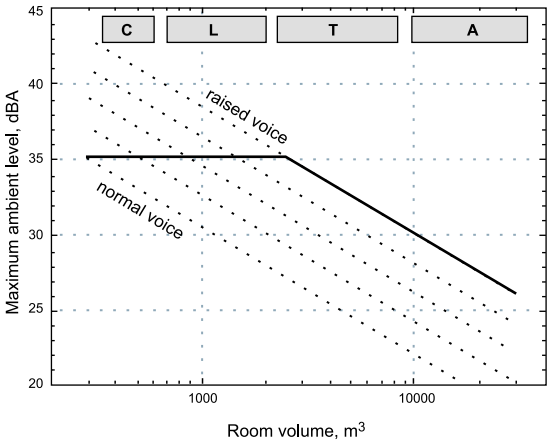


Figure 2. Maximum ambient noise level goals (solid line) (C=classrooms, L=lecture halls, T=theatres, A=large auditoriums)

section. One gives reverberation time goals for normal use and can be considered the most cost-effective approach. The other gives reverberation times that would be preferred for various special needs situations described in the final section.

Recommended Ambient Noise Levels and Reverberation Times

Using plots similar to that of Figure 1, maximum ambient noise level and optimum reverberation time criteria were derived for a range of room sizes. Figure 2 shows maximum noise level design goals and Figure 3 optimum reverberation time design goals.

The solid line in Figure 2 shows the resulting design goals for maximum ambient noise levels as a function of room size and for various levels of vocal effort. The dotted diagonal lines show how expected intelligibility decreases with increasing room volume for particular fixed speech levels. For example, with a 'normal' voice level and a 300-m^3 room volume, a maximum ambient noise level of 35 dBA (approximately NC 28) is required. However, if the same intelligibility is required in a 1000-m^3 room with the same 'normal' voice level, the ambient noise is required to be less than about 30 dBA (approximately NC 23).

In practice we know that talkers raise their voice level somewhat in noisier situations or in larger rooms. (This is known as the Lombard effect.) The design curve (solid line) reflects the fact that talkers gradually raise their voice from a "normal" level to a "raised" level as the room volume increases. For rooms smaller than about 2000 m^3 (most lecture halls and classrooms), the same ambient noise level is acceptable

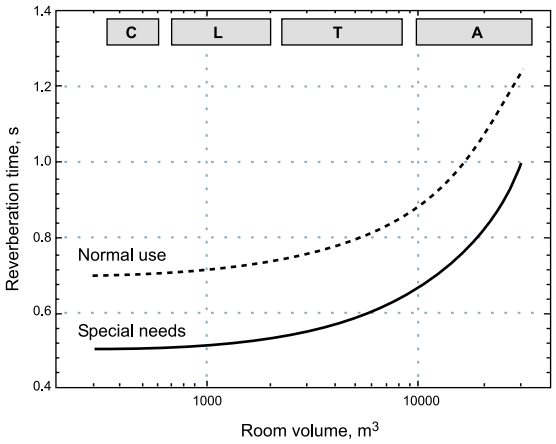


Figure 3. Mid-frequency (500 to 2k Hz) reverberation time design goals (C=classrooms, L=lecture halls, T=theatres, A=large auditoriums)

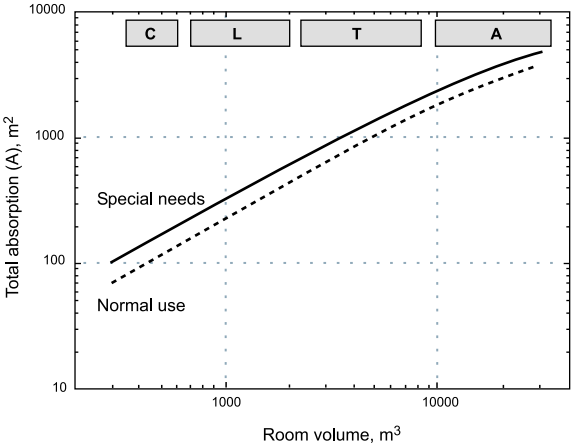


Figure 4. Total sound absorption, A (including that of people) that is required to meet reverberation time criteria (C=classrooms, L=lecture halls, T=theatres, A=large auditoriums)

because voice levels are expected to rise until the 'raised voice' level is reached. Then the design curve follows the 'raised' voice level line for larger rooms. The solid line in Figure 2 provides design goals for ambient noise levels in rooms of various sizes intended for unamplified speech communication. Of course, larger rooms, with more than about 100 people in the audience, may include electronic sound amplification.

Measurements of teachers' voice levels in classrooms suggest that their average vocal effort is about mid-way between 'normal' and 'raised' voice levels even though classrooms are typically only about 300 m^3 in volume. Their use of increased voice levels over extended time periods contributes to the increased incidence of voice impairment in teachers.[1] It is therefore preferable to strive for noise levels that will lead to near-perfect intelligibility without extra vocal effort by the talkers in all but much larger rooms.

In Figure 3, reverberation time design goals are shown for mid-frequency sounds (from 500 Hz to 2 kHz). This range of sound includes the frequencies that are most important for speech. The design criteria for reverberation time vary with room volume, and Figure 3 shows design goals for both normal use and special needs cases as explained in the discussion of Figure 1. It indicates that for smaller rooms, a mid-frequency reverberation time of 0.7 s is optimum for normal use but in some special cases as low as 0.5 s is desirable. Even for larger lecture halls or theatres of a few thousand cubic metres, the preferred reverberation times are only slightly larger.

Although it is preferred that reverberation times for the lower frequency range be not much larger, they will have less influence on speech intelligibility because there is much less speech energy at lower frequencies. Reverberation times at higher frequencies are almost always naturally lower than at mid-frequencies because of increased air absorption and because porous materials are more effective as sound absorbers at these frequencies.

Reverberation time increases with increasing room volume and decreases when sound-absorbing material is added. A calculation example on page 5 illustrates how adding sound-absorbing material to a room can reduce reverberation time.

Figure 4 shows the total sound absorption required for both the normal use and the special needs reverberation time goals. These required total sound absorption values were calculated using the Sabine reverberation equation as illustrated in the calculation example. Although the two lines seem very similar, approximately 40% more sound-absorbing material is required to achieve the lower special needs reverberation times compared to the normal use reverberation time goals.

Because people also absorb sound, it is important to design the room to meet the desired reverberation time goal when the room is occupied as it would usually be. Predicting the amount of sound absorption contributed by each person in various types of rooms is complicated and not well understood. The amount of additional sound absorption provided by one person will vary with the arrangement of the people and the type of seating in the room. For simple practical estimates the following represents the range of possibilities. In a classroom or similar situation with significant spaces between students, the occupants could add as much as 1 m^2 of equivalent

Sound Absorption

The sound absorption of a material is measured in terms of absorption coefficients that describe the fraction of the incident sound that is absorbed. Porous materials (materials that you can blow air through) such as acoustical ceiling tiles, carpets, or curtains and drapes tend to absorb sound best at mid and higher frequencies depending on the thickness and other material properties. Thin panels and other resonant systems generally absorb most at particular lower frequencies.

The total effective sound absorption is the sum of the products of the sound absorption coefficients of each material and their surface areas. For simple estimates, the sound absorption average (SAA) or noise reduction coefficient (NRC) can be used.

Reverberation Time Calculation

The area of the equivalent total sound absorption and the room volume determine the expected reverberation time (RT). The Sabine reverberation time equation can be used to obtain a simple estimate of the sound absorption required to achieve a particular reverberation time,

$$A = 0.161 \text{ volume/RT},$$

where the room volume is in m^3.

For example, to achieve a 0.5-s reverberation time in a 312-m^3 room would require a total of about 100 m^2 of sound absorption. If each person adds 0.75 m^2 of sound absorption, 25 people would add 19 m^2. Thus a further 81 m^2 would be required to meet the 0.5-s RT goal.

To meet a 0.7-s reverberation time goal would require only 72 m^2 of sound absorption or 53 m^2 in addition to the sound absorption of the 25 people.

sound absorption per person at mid-frequencies. The same people located close together in theatre-style seating are expected to add about 0.5 m^2 of equivalent sound absorption per person. An estimate of the expected added sound absorption of the occupants must be included when calculating occupied reverberation times.

Priorities and Special Needs

The previous section gives both maximum ambient noise levels and ideal reverberation time criteria that, if met, should provide near perfect speech intelligibility. While both are important, excessive ambient noise can lead to more serious problems because noise levels are much more likely to deviate greatly from ideal values than are reverberation times. For example, measured noise levels in classrooms frequently exceed the recommended values in Figure 2 by 10 dB or more,[3] corresponding to a factor of 10 times too much noise energy. It is very unlikely that reverberation times could deviate from the recommendations of Figure 3 by such a large factor. Figure 1 further indicates that small excesses in noise levels will reduce intelligibility more than small excesses in reverberation times. This is because the equal intelligibility contours are closer together when one deviates vertically from the design point than when moving horizontally on this plot. It is therefore particularly important to first strive for acceptable ambient noise levels.

Concerning tolerances, an increase of 3 dB above the recommended values is generally accepted as a noticeable difference and 5 dB greater than recommended will correspond to a significant degradation of conditions for speech. Ideally, one should aim to obtain reverberation times between the two recommended values and no more than 10% outside this range.

While the recommended criteria meet the needs of most listeners, there are several special groups of listeners who require better conditions to achieve the same levels of intelligibility. These include normal-hearing younger listeners (10 years old or younger), normal-hearing older adults and hearing-impaired listeners. For these groups, more stringent requirements are needed to provide the same accessibility to speech communication.[7] Noise levels should be 5 dB lower than recommended in Figure 2 and the lower special-needs reverberation time criteria should be used.

Some particular types of rooms also require special considerations. Rooms used for tele- and video-conferencing are intended to function somewhat like recording studios in that speech sounds are picked up by microphones and transmitted to remote locations. The speech is usually transmitted as a single channel or monaural signal, and the listener's ability to discriminate speech from reverberation and noise at the remote location is reduced because the normal benefits of binaural hearing are lost. For tele- and video-conferencing facilities to work well, noise levels should be at least 5 dB below the recommendations of Figure 2 and reverberation times should be as short as possible (0.3 to 0.4 s). Talkers must be facing the microphone and each other and be quite close together.

The shape of rooms for speech and the placement of any sound-absorbing material should be compatible with the directionality of the human voice and the format of communication within the room. For example, in a typical school classroom the person talking might be almost anywhere in the room. In some cases a teacher might be in the middle of the room with some listeners in front and others behind. It is only possible for all of these listeners to hear well if there is adequate reflected sound. For smaller meeting rooms and classrooms, it is therefore usually beneficial that the centre portion of the ceiling be sound reflective.

Any added sound-absorbing material should be more-or-less evenly distributed on the other surfaces of the room.

Other rooms are designed to accommodate a lecture-style configuration where the talker's location is more fixed. In such rooms the surfaces around the talker should generally be sound reflective and those at the opposite ends of the room more absorptive. Again it is usually desirable that the centre portion of the ceiling be sound reflective. For larger lecture halls and theatres, the geometrical design of the room surfaces and the seating locations of the audience must maximise the direct and early-arriving speech reflections reaching all listeners.

Acoustical Design Steps

An acoustical consultant should take the following steps in designing a room for speech communication:

Assess the acoustical requirements. Will the room be configured in a lecture style with a fixed speaker location or will it be a more interactive type of use as in many meeting rooms and classrooms? Will users of the room regularly include those with special acoustical needs such as very young, very old or hearing-impaired listeners who would require superior listening conditions? (Listeners with more severe hearing impairment may require the installation of systems that transmit speech to personal receiving devices.)

Choose a maximum noise level goal. Determine the maximum ambient noise level criterion from Figure 2 and modify it to meet the needs of particular users.

Design to meet noise criteria. Set the maximum noise level criteria for mechanical systems.

Room boundaries must be adequate barriers to intruding noise from outdoors and from adjacent spaces.

Choose the reverberation time criterion. Select the RT design goal from Figure 3 and use the lower (special needs) curve if more critical uses are expected.

Determine the required total sound absorption and amount of material to be added. Figure 4 gives a simple estimate of the total required sound absorption. Calculating the amount of added sound-absorbing material requires knowledge of the sound absorption of various products and an estimate of the absorption of the expected room occupants.

Consider the room shape and the location of the sound-absorbing material. In smaller rooms, sound-absorbing material should usually be distributed evenly over the room surfaces but avoiding the centre portion of the ceiling and surfaces close to talker locations such as fixed podiums. In larger rooms the shape of the room and the location of absorption will also be important.

Summary

In rooms intended for speech communication, good acoustical design is particularly important. Room size and shape, ambient noise level and amount and location of sound-absorbing material all affect how well such a room fulfills its purpose. Expert advice should be sought in order to produce a room environment for good speech communication.

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