8. Office acoustics

How to effectively design the room acoustics of offices.
### TOPICS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foreword</td>
<td>3</td>
</tr>
<tr>
<td>Room acoustics versus building acoustics</td>
<td>5</td>
</tr>
<tr>
<td>Fundamental principles of acoustics</td>
<td>7</td>
</tr>
<tr>
<td>Sound pressure</td>
<td>7</td>
</tr>
<tr>
<td>Decibel scale</td>
<td>9</td>
</tr>
<tr>
<td>Frequency</td>
<td>13</td>
</tr>
<tr>
<td>Wavelengths of sound</td>
<td>17</td>
</tr>
<tr>
<td>Sound level values</td>
<td>18</td>
</tr>
<tr>
<td>Subjective room acoustics</td>
<td>21</td>
</tr>
<tr>
<td>Room acoustic parameters</td>
<td>22</td>
</tr>
<tr>
<td>Reverberation time</td>
<td>22</td>
</tr>
<tr>
<td>Sound absorption</td>
<td>27</td>
</tr>
<tr>
<td>Acoustic design of offices</td>
<td>32</td>
</tr>
<tr>
<td>Acoustically effective materials</td>
<td>32</td>
</tr>
<tr>
<td>Sound absorber types</td>
<td>38</td>
</tr>
<tr>
<td>Adjusting the reverberation time</td>
<td>40</td>
</tr>
<tr>
<td>Speech intelligibility</td>
<td>40</td>
</tr>
<tr>
<td>Sound barriers</td>
<td>42</td>
</tr>
<tr>
<td>Design examples</td>
<td>44</td>
</tr>
<tr>
<td>Individual office</td>
<td>44</td>
</tr>
<tr>
<td>Two-person office</td>
<td>45</td>
</tr>
<tr>
<td>Multi-person office</td>
<td>46</td>
</tr>
<tr>
<td>Lecture room/meeting room</td>
<td>47</td>
</tr>
<tr>
<td>Cafeteria</td>
<td>48</td>
</tr>
<tr>
<td>Annex</td>
<td>49</td>
</tr>
<tr>
<td>Index</td>
<td>49</td>
</tr>
<tr>
<td>Bibliography</td>
<td>53</td>
</tr>
</tbody>
</table>
Foreword

The desire for quietness and comfort is becoming more and more important not only in private life but also at work and, therefore, in offices. Unpleasant sounds, or noise, at the workplace are increasingly perceived as stressful. On the other hand, there are the current trends in the design and building physics of modern office building architecture which make it much more difficult to create appropriate acoustic conditions in a room. The use of thermoactive components (e.g. concrete ceilings), for example, requires a new approach to the positioning of acoustically effective elements in a room. Office furniture with sound absorbing properties often proves to be a useful tool in designing the acoustics of modern office working environments.

Whether a room is acoustically suitable for particular uses, i.e. its acoustic quality, is influenced by many factors. In addition to the acoustic characteristics of the boundary surfaces of a room, furnishings can also have a major influence on the speech and listening conditions in the room.

Finally, office acoustic design is a predictable activity with an outcome which can be precisely measured: ideally, an acoustic quality is achieved which suits the use of the room, which makes us feel comfortable and allows us to communicate without any effort, and which we do not perceive as too loud or too quiet.
8. Office acoustics

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Notes/Key

= rules of thumb

= for the experts

The index provided in the annex contains a short explanation of some terms used in acoustics. These terms are not marked any further in the text of this brochure.

This brochure includes several references to German standards and regulations. Comparable regulations exist in many other countries. The German ones may give a guidance how a suitable office acoustic quality can be achieved.
Room acoustics versus building acoustics

At first glance the fields of room acoustics and building acoustics seem to deal with similar aspects; the essential difference becomes clear only when we take a closer look.

In building acoustics, the question always is:
What portion of the sound reaches the other side of the partition in question?
The key property is the sound transmission loss of the partition separating two rooms. Essentially, it is about the ability of components – walls, ceilings, doors, windows, etc. – to minimise the sound transmission between two rooms. A high degree of sound transmission loss is usually achieved using solid, heavy components which hinder the propagation of sound.
The question in room acoustics, on the other hand, is: What surfaces help to create optimum listening conditions in a room?

The key property in this case is the sound absorption provided by the materials used in the room. Sound absorption describes the ability of materials to absorb sound or to convert the incident sound energy into other forms of energy. Sound absorption is achieved by means of sound absorbers which can be a variety of different materials: foamed materials, resonant panels, perforated panels containing non-woven fabrics, acoustic plasters, etc. The properties and varieties of sound absorbers will be described in more detail later.

Thus, the terms “sound insulation loss” and “sound absorption” have a completely different meaning. If we feel annoyed by noise from an adjacent room, increasing the sound insulation essentially helps to improve this situation. Sound absorption, in contrast, improves the acoustic quality inside a room.

For sound transmission loss values within office buildings the recommendations of national regulations should be followed if applicable. As this brochure mainly covers the aspects of the acoustic design of rooms, issues concerning the noise control in buildings are not dealt with more extensively here.
This chapter introduces the fundamental quantities of acoustics, which will serve as a basis later when we have a closer look at some office acoustic applications.

> **Sound pressure**

Sound can comprise harmonious tones, music, bangs, noise, crackling, but also speech. All of these sound events cause a slight variation in air pressure which propagates within the surroundings of its source. We therefore refer to the sound pressure of a tone, of noise, speech or music. The louder the sound event, the heavier is this pressure variation and the higher is the sound pressure.

Figure 3 shows this variation in air pressure as a function of time. Figure 4 illustrates schematically the propagation of sound from a point source.
As a rule, sound always propagates into all three directions of space. With many sound sources the sound radiation depends on the orientation of the source; in most cases it is sufficient, however, to assume roughly a uniform, omni-directional sound radiation. Sound sources of this type are referred to as omni-directional sound sources. Today it is also possible to select very tightly restricted sound radiation directions by means of special loudspeakers so that the radiated sound can be directed specifically to a particular position. This method is used, for example, when fitting lecture rooms with electroacoustic equipment. Here, it has to be taken into account that the sound energy decreases considerably with increasing distance from the sound source. In the areas occupied by the audience, however, the sound distribution should be as uniform as possible. To achieve this effect, a larger number of loudspeakers may have to be used.
> **Decibel scale**

If we compare the quietest sound event which human beings can perceive (the smallest perceptible sound pressure) with sounds at our auditory pain threshold, we find that the sound pressure changes by a factor of one hundred billion within this range. Representing and handling such a large range of sound pressure values proved to be cumbersome, and so a logarithmically defined quantity, i.e. decibel, was introduced along with the sound pressure level, which has hardly any effect on small sound pressure values, but reduces the high values to a convenient size. This provides us with a scale of between 0 decibel (abbr.: dB) and about 140 dB. The arbitrary determination of the value for 0 dB is based on the sound pressure which is just about perceivable by humans. Figure 5 shows some examples of common noise situations on the decibel scale.
The logarithmic properties of the decibel scale result in some special calculation rules for sound pressure levels, which are explained in detail in the relevant literature. Some useful rules of thumb can be summarised here, however:

### Sound pressure increase for identical sound sources

An increase in the number of sound sources by a factor of two always results in an increase of the level by 3 dB, a factor of ten in an increase by 10 dB, and a factor of one hundred in an increase by 20 dB.

<table>
<thead>
<tr>
<th>Sound pressure increase for identical sound sources</th>
<th>Example: Copy machine/printer</th>
<th>Increase in the dB value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>62 dB</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>$62 + 3 = 65$ dB</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>$62 + 5 = 67$ dB</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>$62 + 6 = 68$ dB</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>$62 + 7 = 69$ dB</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>$62 + 10 = 72$ dB</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>$62 + 12 = 74$ dB</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>$62 + 13 = 75$ dB</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>$62 + 17 = 79$ dB</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>$62 + 20 = 82$ dB</td>
<td></td>
</tr>
</tbody>
</table>

Noise caused by 10 identical copy machines, each with a sound pressure level of 62 dB = 72 dB ($62 + 10$)

Noise caused by 2 identical copy machines, each with a sound pressure level of 62 dB = 65 dB ($62 + 3$)
What is more common in practice, however, is that the total sound perceived is caused by different noise sources of different sound levels. If there are two sound sources in a room, the following simplified calculation applies:

### Sound pressure increase for two different sound sources

First of all, the difference between the two levels has to be determined. This difference specifies the column. Then the level increase value given in the second row of the respective column is added to the larger one of the two level values:

<table>
<thead>
<tr>
<th>Level difference between two levels</th>
<th>0 to 1</th>
<th>2 to 3</th>
<th>4 to 9</th>
<th>more than 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level increase (to be added to the larger value)</td>
<td>+ 3 dB</td>
<td>+2 dB</td>
<td>+1 dB</td>
<td>+ 0 dB</td>
</tr>
</tbody>
</table>

**Example:**
For two sources of 50 dB and 57 dB, respectively, the difference of 7 dB means an increase by 1 dB, which is added to 57 dB and thus results in a total level of 58 dB.
The following formulae are used for adding and multiplying any number of level values:

### Adding levels

Due to their logarithmic notation, sound pressure levels cannot be simply added and subtracted; first, they have to be converted from their logarithmic representation. This results in the following formula which can be used for adding or subtracting any number of level values.

\[ L_1 + L_2 + \ldots + L_n = 10 \log(10^{10^{L_1/10}} + 10^{10^{L_2/10}} + \ldots + 10^{10^{L_n/10}}) \text{ dB} \]

**An example from practice:**

In an office room, a printer (sound power level 60 dB), a fax machine (sound power level 54 dB) and a copy machine (sound power level 62 dB) are arranged together on a work surface. What is the total sound pressure level which is to be expected?

\[ L_{\text{Printer}} + L_{\text{Fax machine}} + L_{\text{Copy machine}} = 10 \log(10^{10^{60/10}} + 10^{10^{54/10}} + 10^{10^{62/10}}) \text{ dB} = 64.5 \text{ dB} \]

### Multiplying levels

If, instead of adding different levels, one single level merely multiplies, the above formula is simplified as follows.

\[ L_{\Sigma} = 10 \log(n \cdot 10^{L_0}) \text{ dB} \]

**An example from practice:**

In an office room, two copy machines are to be added to a copy machine already present in the room (sound power level 62 dB), the two new machines being of identical construction as the first one. What is the total sound pressure level which is to be expected?

\[ L_3 = 10 \log(3 \cdot 10^{62/10}) \text{ dB} = 67 \text{ dB} \]
Frequency

Human beings perceive the sound pressure level as the volume of sound, i.e. its loudness, making it an important property of sound. Equally important is the frequency content of the sound, i.e. its spectrum. Pure tones are sound events of a single frequency. The superposition of tones of different frequencies is referred to as noise or sound, depending on the frequency mix.

The sensitivity of the human auditory system is highly dependent on the frequency. It is particularly perceptive in the frequency range of human speech between 250 Hz and 2000 Hz. This is very useful when we listen to someone speak, but disruptions in this frequency range are perceived as particularly annoying and can strongly affect communication. Towards higher or lower frequencies, our hearing ability decreases.

The following figure contains so-called isophones, i.e. equal-loudness contours. The figure shows, for example, that a 100 Hz tone requires a loudness of approximately 25 dB in order to be perceived, whereas at 1000 Hz, 5 dB are sufficient for a tone to be heard. In addition to the threshold of hearing, the figure shows the equal-loudness contours based on 1000 Hz for different level values. The top curve in the following figure indicates the progression of the pain threshold as a function of frequency.

At such high levels the auditory system can be permanently damaged even by a noise event of a very short duration, e.g. a bang lasting only a few milliseconds.
Acoustic design always needs to take into account the frequencies of sound relevant for the human ear creating optimum conditions for human perception.

A noise loudness rating which is to meet the demands of the human auditory system needs to take into account the frequency characteristic of the human auditory system. The medium frequencies, at which the human auditory system is particularly sensitive, are weighted more heavily than the high and low frequencies. This weighting results in the term dB(A) for sound pressure levels, i.e. the so-called A-weighted sound pressure level. Nearly all regulations, guidelines, standard values, limit values, recommendations and references to sound pressure levels use values expressed in dB(A).
**Frequency ranges relevant for room acoustic design**

The frequency range to be taken into account when planning a room is based on the human auditory system on the one hand and what is technically sensible and feasible on the other. Frequencies above 5000 Hz are attenuated by the air to such a degree that it is not sensible to take them into account when designing the acoustics of a room. Below 100 Hz, other physical implications of sound propagation need to be taken into account.

The internationally standardised test methods for determining the sound absorption of materials are based on the frequency range from 100 Hz to 5000 Hz. Correspondingly it has been decided to focus room acoustic planning on the frequency range between 100 Hz and 5000 Hz.
**Frequency steps: one-third octaves and octaves**

Many room acoustic parameters, such as reverberation time, sound absorption or sound pressure level, depend on frequency, i.e. they assume different values at different frequencies. Therefore, the corresponding frequencies or frequency ranges also have to be stated when indicating these parameters.

As shown in Figure 8, the relevant frequency range in room acoustics is between 100 Hz and 5000 Hz. This range can be subdivided into six octave bands (125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz) or 18 one-third octave bands (100 Hz, 125 Hz, 160 Hz, ..., 4000 Hz, 5000 Hz), depending on how precisely the relevant parameter is to be represented.

The step from one octave to the next is always obtained by doubling the frequency. One octave comprises three one-third octaves; the increments are correspondingly smaller and are, therefore, more significant and precise. When solving issues related to room acoustics by measurements, a resolution of one-third octave bands should thus be selected, because many acoustics-related problems occur in narrow frequency ranges and require precisely tailored solutions. The figure below shows the sequence of the octave and one-third octave values within the frequency range relevant for room acoustics.
> Wavelengths of sound

Each frequency of sound is associated with a sound wave of a particular wavelength. In air, a 100 Hz wave has an extension of 3.40 metres, whereas a 5000 Hz wave has an extension of only about 7 centimetres. Accordingly, the sound waves relevant for room acoustics have a length of between 0.07 m and 3.40 m. As we can see, the dimensions of sound waves are well within the range of the dimensions of rooms and furnishings. The following figure shows the range of all sound wavelengths relevant for room acoustics.
> **Sound level values**

**Rating level**
The relevant parameter for an objective assessment of the noise impact at a workplace is the so-called rating level, which consists, on the one hand, of the measured, time-averaged sound pressure level in a room and, on the other hand, of adjustments in accordance with the characteristic of the noise as well as its duration of impact. Potential adjustments are made for the impulsiveness and tonality of a noise. If the noise to be assessed comprises bangs or similar impulses or if individual tones are clearly discernable, adjustments are made in addition to the measured value, and the sound is effectively assessed as louder. The rating level is usually based on a rating period of 8 hours.

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**Level values regarding the sound impact at the workplace**

The action value in accordance with the directive of the EU legislation on noise exposure of workers (2003/10/EG) is 80 dB(A).

Details regarding the maximum allowable sound pressure level in work rooms are also contained in the German regulation VDI 2058, to which reference is made in German VDI 2569. In terms of the rating level, these values are:

- \( L_r \leq 55 \text{ dB}(A) \) for intellectual activities
  - Examples: scientific work, designing, examining, calculating, meetings, etc.

- \( L_r \leq 70 \text{ dB}(A) \) for simple or largely mechanised office work:
  - Examples: scheduling, data collection, working with word processing devices, selling, working in operations offices

A continuous sound level of 80 dB(A) and above and an impulse noise of 130 dB(A) and above may irreversibly damage the auditory system.
The following figure shows the result of a sound pressure level measurement in a call centre, which gives a rating level of 58 dB(A) based on a time interval of 8 hours. Usually, it is sufficient to measure short, representative periods of time.

**Determination of the rating level**

The rating level $L_r$ is calculated using the following equation in accordance with the German Standard DIN 45645-2:

$$L_r = L_{Aeq,T} + K_I + K_T + 10 \log \frac{T}{T_r}$$

with:
- $L_{Aeq,T}$ = the equivalent continuous sound pressure level of the corresponding work shift
- $K_I$ = the impulse adjustment
- $K_T$ = the tone adjustment
- $T$ = the duration of the work shift, usually 8 hours
- $T_r$ = the rating time interval, usually 8 hours
8. Office acoustics

Background noise level
High background noise levels in office rooms will likely affect the intellectual efficiency. For this reason, several regulations and standards contain recommendations regarding the maximum permissible background sound pressure level.

The following table shows the values of the recommended background noise level in accordance with the European standard EN 11690:

<table>
<thead>
<tr>
<th>Type of room</th>
<th>Maximum background noise level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conference room</td>
<td>30 dB to 35 dB(A)</td>
</tr>
<tr>
<td>Individual offices</td>
<td>30 dB to 40 dB(A)</td>
</tr>
<tr>
<td>Open-plan offices</td>
<td>35 dB to 45 dB(A)</td>
</tr>
<tr>
<td>Industrial workplaces</td>
<td>65 dB to 70 dB(A)</td>
</tr>
</tbody>
</table>

The background noise level in a room is determined by the structural conditions inside the building and the acoustic equipment of the room. In addition to heating, ventilation and air conditioning systems, office machines also contribute to the sound level of a room.
Subjective room acoustics

How we perceive and evaluate noise also depends on subjective aspects. A listener’s subjective reaction to sound events depends on their personal attitude and expectations with regard to the sound source. Airport staff and residents living close to an airport, for example, are annoyed by aircraft noise to an entirely different degree. In an office environment, people who are used to working in an individual office often have problems dealing with the unfamiliar noise situation or different listening environment of an open-plan office, even if the acoustic conditions in the room are very similar.

Psychoacoustics as a branch of acoustics, or also noise effect research, deals with the relationship between our subjective perception and the sound signals which are objectively present. In general, it can be assumed that even noise with a sound pressure level as low as 30 dB(A) may be experienced as annoying.

The objective parameters
• sound pressure level in dB(A),
• frequency composition or sound spectrum,
• progression in time and
• noise duration
allow us to infer the degree of subjective annoyance.

Moreover, the subjectively experienced annoyance caused by a noise or a noise environment – e.g. in an open-plan office – is also influenced by individual factors such as personal attitude or experience. A quantitative compilation of these factors influencing the subjective annoyance can be achieved only by a detailed surveying of the individuals concerned. A reliable forecast of the degree of subjective annoyance cannot be made.
Reverberation time

Whether a room is perceived by its users as acoustically comfortable or not can be calculated very precisely in the process of designing the acoustics of this room. Similarly, it can be estimated which treatments will lead to a certain result, what surface area needs to be equipped with sound absorbers and how these are to be positioned in the best manner. For this purpose, the reverberation time as an essential room acoustic parameter will now be explained in detail. Afterwards, the functioning of sound absorbers will be described.

We all know how impressive organ music sounds when played in a church. But what does this reverberation – which can be often felt even physically – have to do with the acoustics of an open-plan office or a concert hall?

The reverberation time can be determined for each enclosed space, and it thus provides the basis for assessing the acoustic conditions in a room. Put simply, the reverberation time indicates the period of time it takes for a sound event to become inaudible. Technically, the reverberation time $T$ has been defined as the time required for the sound pressure level in space to decay by 60 dB. This means that, if a room is excited with an impulse of 95 dB, the reverberation time indicates the period of time within which the noise level drops to 35 dB. This can be a few tenths of a second up to several seconds.
This objectively measurable quantity allows different rooms to be compared with each other and their room acoustic quality to be assessed. While a reverberation of 4 to 8 seconds is adequate for a church, the values aimed at for the reverberation time in conference or office rooms are quite different. The following table provides an overview of the typical reverberation times of different room types.

<table>
<thead>
<tr>
<th>Type of room</th>
<th>Reverberation time (example)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Church</td>
<td>approx. 4 to 8 seconds</td>
</tr>
<tr>
<td>Swimming pool</td>
<td>max. 1.7 seconds</td>
</tr>
<tr>
<td>Concert hall for classical music</td>
<td>approx. 1.5 seconds</td>
</tr>
<tr>
<td>Class room, medium-sized</td>
<td>0.6 seconds</td>
</tr>
<tr>
<td>Conference room</td>
<td>depending on size</td>
</tr>
<tr>
<td></td>
<td>approx. 0.8 to 1.2 seconds</td>
</tr>
<tr>
<td>Office room</td>
<td>depending on size</td>
</tr>
<tr>
<td></td>
<td>between 0.5 and 0.8 seconds</td>
</tr>
</tbody>
</table>

The reverberation time is the “fingerprint” of a room. It provides a quick and objective indication of the acoustic quality of a room. Complaints regarding poor acoustics are typically linked to inappropriate reverberation time values; an optimum reverberation time, however, does not automatically guarantee optimum acoustic conditions. The reverberation time thus provides acoustic designers with a clearly defined parameter which can be easily handled.

It has a direct effect on speech intelligibility in a room. In general, speech intelligibility in a room decreases with increasing reverberation time. This does not mean, however, that the shortest possible reverberation time is always the best solution! Very poor speech intelligibility usually does suggest, though, that the reverberation time is too long.

The subjective impression of the sound quality of a room allows even non-experts to draw conclusions as to how the reverberation time progresses within the different frequency ranges. If, for example, speech in a room sounds blurred, and if it is very difficult to understand each other, it can be assumed that the reverberation time is too long. Acoustically “dry” in this context means that the sound is absorbed unnaturally fast. If this happens only at high frequencies, the room sounds “hollow” or “booming”, whereas at low frequencies it sounds “piercing” and “sharp”.
The larger the room, the longer is usually the reverberation time. The more absorption there is in a room, the shorter is the reverberation time. A room usually becomes more reverberant with increasing height. Absorbing surfaces – such as carpets, curtains and sound absorbing ceilings, but also furniture or people present in the room – reduce the reverberation time. A fundamental task of office acoustic design is to achieve a good balance between these two quantities, i.e. the volume and the absorption area. In a second step it has to be determined how to position reflecting and absorbing surfaces in the room in an optimum manner.

The shape of a room is usually of minor importance for the reverberation time. Only if the room acoustic requirements are very high (e.g. in concert halls) or if the shape is very unusual, e.g. vaulted surfaces or heavily varying room heights, does shape become an essential factor.
Optimum reverberation time
The German standard DIN 18041 “Acoustic quality in small to medium-sized rooms” forms the basis for the recommendations regarding the acoustic design of small to medium-sized rooms. The recommendations given in DIN 18041 should always form the basis for any room acoustic design.

With regard to the optimum reverberation time, DIN 18041 distinguishes between three different room categories: “music”, “speech” and “communication and teaching”. Rooms of the usage type “music” are music class rooms and halls for music presentations. “Speech” in the broadest sense comprises all rooms where a speaker speaks to an audience. “Communication and teaching” comprises all types where several people speak at the same time, i.e. teaching rooms as well as conference rooms, multiple occupancy offices, service points, call centres and rooms with audiovisual presentations or electroacoustic uses. Figure 13 indicates the medium reverberation time which should be aimed at depending on the volume and use of a room.

Example 1: A conference room (usage type: “communication and teaching”) with a volume of 250 m³ should have a reverberation time of 0.60 s.

Example 2: A courtroom (usage type: “speech”) with a volume of 650 m³ should have a reverberation time of 0.90 s.
Reverberation time as a frequency-dependent quantity

The reverberation time is a frequency-dependent quantity whose values normally change with frequency. Therefore, the reverberation time is usually expressed in frequency increments of octaves or one-third octaves.

DIN 18041 provides a clear recommendation for the progression of the reverberation time over frequency: reverberation time values which are as constant as possible at all frequencies where speech and communication are concerned, and a slow increase towards low frequencies below 250 Hz for rooms used for music.

Figure 14 shows the tolerance ranges for the usage types “speech”, “teaching and communication” and “music” with reference to the optimum reverberation time $T_{\text{opt}}$. Ideally, the reverberation time curve should be within these ranges.
Sound absorption

To achieve optimum reverberation time values sound absorbing materials are used when designing office rooms. In the following, the functioning of sound absorbers will be explained. Afterwards, several materials with sound absorbing properties will be introduced.

The sound absorption coefficient $\alpha$ as a tool for room acoustic design

The sound absorption coefficient $\alpha$ describes the property of a material to convert incident sound into other forms of energy – e.g. thermal or kinetic energy – and thus to absorb it. An ideal sound absorber which “swallows” 100% of the incident sound has a sound absorption coefficient of 1.0 (Figure 15) – a fully reflective surface, on the other hand, has a sound absorption coefficient of 0 (Figure 16). Both extremes are almost impossible to achieve: real materials always have a sound absorption coefficient of between 0 and 1 (Figure 17).

Fig. 15

Case 1: Sound completely absorbed (sound absorption coefficient $\alpha = 1$) no reflection

Fig. 16

Case 2: Sound completely reflected (sound absorption coefficient $\alpha = 0$)

Fig. 17

Case 3: Sound partly absorbed (sound absorption coefficient $\alpha = \text{between 0 and 1}$)
The sound absorption coefficient \( \alpha \) of a material is highly dependent on frequency. For this reason, the absorptive effect of materials has to be considered in the context of frequency as well. A material may have a sound absorption coefficient of 0.1 at 125 Hz, i.e. it reflects 90 % of the sound, whereas, at 4000 Hz, it may have a sound absorption of 1, i.e. it absorbs the entire incident sound at this frequency. This is the case, for example, for many porous absorbers such as mineral fibres, foams, curtain fabrics, etc.

The damping of low frequencies (with long wavelengths) requires either very voluminous sound absorbers made of porous materials (rock wool, glass wool, foamed materials, etc.) or installations making use of a resonance mechanism, e.g. an enclosed air volume or a vibrating surface. Sound absorbers of this kind usually reach their maximum within a restricted frequency range, i.e. the frequency which excites vibrations in their air volumes or surfaces. The physical process involved is referred to as resonance; the corresponding absorbers are called resonance absorbers. Many of the traditional sound absorbers – e.g. acoustic ceilings or wall panels – make use of combinations of both absorber types (porous absorbers and resonance absorbers) so as to extend the capacity of the material to a wide frequency range, i.e. to achieve broadband absorption.

**Frequency-dependent effect of sound absorbers**

The following generalised rule applies: High frequencies can usually be damped by sound absorbers of a small thickness. For low frequencies, in contrast, sound absorbers of a greater thickness or large dimensions are required.

**How to determine the sound absorption coefficient**

The frequency-dependent sound absorption coefficient of a material is determined by means of a special acoustic test method – the so-called reverberation chamber method. For this test, a material sample is placed into the reverberation chamber, whose reverberation time has been determined previously without the sample. From the change in the reverberation time with the sample present in the chamber, the sound absorption coefficient \( \alpha_S \) can be determined for each one-third octave band between 100 Hz and 5000 Hz (cf. Fundamentals of acoustics, page 15).

This yields 18 one-third octave band values which uniquely describe the absorption behaviour of the material, i.e. to what extent and at what frequencies the material absorbs the sound. These properties essentially determine the area of application of the respective sound absorber.
Equivalent sound absorption area
It is not only the choice of material, however, which is responsible for the sound absorption in a room. What is most important is the total area of this material present in the room. The equivalent sound absorption area has been introduced to provide a measure for the sound absorbing performance of a sound absorber actually present in the room. It is defined as the product of the sound absorption coefficient $\alpha_s$ of a material and the surface area of this material.
A sound absorber of 10 m² with a sound absorption coefficient of 0.50 has an equivalent sound absorption area of 5 m² and thus has the same effect as a sound absorber of 20 m² with a sound absorption coefficient of 0.25 or a sound absorber of 5 m² with a sound absorption coefficient of 1.00.

In a fully furnished room with different surfaces, for example, each material (e.g. carpets, plaster, acoustic ceiling, curtains, windows, shelves, etc.) can be allocated a sound absorption coefficient, and by multiplying this coefficient by the surface of this material, the equivalent sound absorption area can be calculated. The equivalent sound absorption areas of all materials are then added to determine the total equivalent sound absorption area of the room.

Calculation of the equivalent sound absorption of surfaces in a room:

$$ A = s_1 \alpha_1 + s_2 \alpha_2 + s_3 \alpha_3 + \ldots + s_n \alpha_n $$

- $A$ – total equivalent sound absorption area in a room
- $s_1$ – surface size of material 1, e.g. acoustic ceiling
- $\alpha_1$ – sound absorption coefficient of material 1
- $s_2$ – surface size of material 2, e.g. carpet
- $\alpha_2$ – sound absorption coefficient of material 2
- $\ldots$
- $s_n$ – surface size of material $n$
- $\alpha_n$ – sound absorption coefficient of material $n$
Sound absorption coefficient and reverberation time
The reverberation time of a room can be derived from the calculated total equivalent sound absorption area using the Sabine formula.

\[
T = 0.163 \cdot \frac{V}{A}
\]

- \(T\) – reverberation time in seconds
- \(V\) – volume of the room in cubic metre
- \(A\) – total equivalent sound absorption area in square metre

Effect of sound absorbers

- The larger the sound absorption coefficient of a material, the more this material reduces the reverberation time in a room.

- Even a sound absorber with a high sound absorption coefficient shows the desired effect only when using a certain surface area of it.

- On the other hand, a sound absorber with a relatively low absorption coefficient can achieve the desired effect if its surface is large enough.

- Either a single sound absorber or a combination of many different sound absorbers can be used for damping a room.

- The decisive factor for the reverberation time of a room is always the total sum of all equivalent sound absorption areas.
Choosing the right absorber
Depending on the furnishings of a room, a well-balanced acoustic pattern in a room may be achieved with a variety of different sound absorbers. The requirements a sound absorber has to fulfil may be very different for a carpet than for a smooth floor covering, for example. The same applies for differently furnished rooms. The task of office acoustic design is to match the surfaces and the elements of a room in the best possible manner.
### Acoustic design of offices

> **Acoustically effective materials**

Basically, every surface has an acoustical effect. A smooth, hard surface such as a concrete wall or a tiled surface is almost fully reflective. A thick textile pad, a highly absorptive acoustic ceiling or a special acoustic wall panel have a relatively high sound absorption coefficient. For each material the frequency-dependent sound absorption coefficient can be determined. These values can be used in the planning process to adjust the reverberation time of a room in the best possible manner. The following list describes materials commonly used in different sound absorption products. The list is not comprehensive.

**a) Glass and mineral fibre panels**
Glass and mineral fibre panels are porous absorbers which are mounted either directly on a reverberant surface or, more frequently, at a certain distance from this surface. Common examples include different types of tiled ceiling systems. The air space behind the ceiling plates is particularly important for the sound absorption. A narrow distance or a small air volume behind the absorber panel usually limits the absorption at low frequencies.

**b) Foamed materials**
Open pore foams with a common thickness of several centimetres are most effective at high frequencies. Foams are also used as coverings on punched or slotted panels or expanded metal surfaces. To improve the sound absorption – particularly at low frequencies – the foam surface is covered with a non-woven or woven fabric or a thin layer of an acoustically hard material. This provides for many different areas of application.

**c) Perforated gypsum plaster boards**
Perforated gypsum plaster boards are available as jointless systems or as tiled ceiling systems. In both cases, the acoustic effect is mainly achieved by the perforation in combination with a non-woven fabric arranged in front of an air cavity. If required, the effect is increased further by applying a mineral fibre mat. This is an example of a resonance absorber. The absorption performance of the installation changes with the cavity depth.
d) Slotted or perforated wooden panels
Wood panels are typically resonance type sound absorbers with sound absorption resulting from the combination of a perforated panel, a non-woven fabric and an enclosed air volume behind it. As in the case of the perforated gypsum plaster boards, an additional porous absorber is often introduced into the air volume to enhance the sound absorbing effect to a broader frequency range. Wooden panels have the advantage of being mechanically robust, which enables them to be used even in places under heavy load. For this reason, wooden panels are predominantly used as absorbers in wall areas, but also for office furniture such as cabinet surfaces.

e) Acoustic plasters
Acoustic plasters are porous absorbers of different types: they can be either sprayed directly onto the surface of an object or first applied to smooth, porous or punched substrates which are then mounted on the object. In the latter case it is possible to suspend the construction, which may have a positive effect on the absorption behaviour of the material. From a visual point of view, acoustic plasters are advantageous in that they provide a jointless appearance and are, therefore, hardly noticed at all. Especially for modern buildings, smooth surfaces without any noticeable grids are often desired.

f) Layered materials
Layered sound absorbers are mainly used where the installation depth or the suspension height is very small. Normally, in layered sound absorbers porous absorbers are combined with resonance absorbers. There are combinations of plasters or plate resonators and mineral wool. They are optimised to achieve sound absorption values at a small installation height which would otherwise be possible only with systems of a large installation depth.

g) Micro-perforated sound absorbers
Micro-perforated sound absorbers are materials made of acrylic glass, wood or foil. The sound absorption results from a very fine perforation and the air volume behind the panel or foil. By varying the distance, the sound absorbing properties of the material can be specifically influenced to match the requirements of the object. Micro-perforated sound absorbers are particularly attractive, because they provide new areas of application: the sound absorbers can be manufactured also transparently or transluscently and thus be arranged in front of windows and lighting equipment. Moreover, sound absorbing luminous ceilings are also possible with these types of absorbers.
For each material the frequency-dependent sound absorption coefficient can be determined.

The following figures contain examples of the sound absorption coefficients and equivalent sound absorption areas of selected materials. Figures 18 and 19 show the sound absorption coefficients of planar sound absorbers (such as acoustic ceilings, plasters, carpets). The equivalent sound absorption area can be calculated by multiplying the sound absorption coefficient by the surface of the respective material (see page 29).

Figure 20 shows the equivalent sound absorption area for individual objects (such as cabinets, movable partitions, chairs) and occupants.

![Fig. 18](image1)

![Fig. 19](image2)

Illustrations of the sound absorption coefficients of different materials:
- **marble, tiles, smooth concrete**
- **glazing, large, heavy panes**
- **parquet on concrete**
- **heavy carpet on concrete**

Figures:
- **Fig. 18**
- **Fig. 19**
Excursus: Single number ratings

In the previous sections the advantages of looking at the sound, the reverberation time and the sound absorption coefficient in a frequency-dependent context have been explained in great detail. Several interested parties have, however, expressed their desire for simplified values, which might not permit sophisticated planning, but would allow rough comparisons to be made between different sound absorbers or preliminary statements regarding the basic suitability of products for particular applications. Such values should also enable a simplified planning of rooms with low requirements regarding their acoustic quality.

Against this background, single number ratings of sound absorption have been defined in Europe and the US which differ slightly. The most common single number rating of sound absorption in Europe is the so-called weighted sound absorption coefficient $\alpha_w$, whereas in the anglo-american world it is the Noise Reduction Coefficient (NRC) or the Sound Absorption Average (SAA).
Single-number ratings commonly used in Europe

Weighted sound absorption coefficient $\alpha_w$ (according to the European/International standard EN ISO 11654): In order to determine the weighted sound absorption coefficient $\alpha_w$, the mean value for the octave frequency band between 125 Hz and 4000 Hz is determined from three one-third octave band values. 18 one-third octave band values are thus converted into 6 octave band values. The mean value of the respective octave is then rounded to the nearest 0.05; it is referred to as the practical sound absorption coefficient $\alpha_p$. The practical sound absorption coefficient $\alpha_p$ between 250 Hz and 4000 Hz is compared to the reference curve given in EN 11654. This comparison gives a single number of the weighted sound absorption coefficient $\alpha_w$. Deviations by more than 0.25 between the curve and the reference curve are indicated by means of the shape indicators L, M or H, depending on whether they occur at 250 Hz (L), at 500 Hz or 1000 Hz (M), or at 2000 Hz or 4000 Hz (H). The resulting values are, for example, $\alpha_w = 0.65$ (H), $\alpha_w = 0.20$ or $\alpha_w = 0.80$ (LM).

Single-number ratings commonly used in the US

NRC (ASTM 423): The NRC (Noise Reduction Coefficient), which is widely used in the US, is determined by calculating the mean value from four one-third octave band values of the sound absorption coefficient (250 Hz, 500 Hz, 1000 Hz and 2000 Hz) and rounding the result to the nearest 0.05. If the number is at the exact mid-point of the numbers divisible by 0.05, the value is always rounded up (example: 0.625 => 0.65; 0.675 => 0.70).

SAA (ASTM 423): Another value used in the US is the SAA (Sound Absorption Average). It is determined by calculating the mean value from twelve one-third octave band values of the sound absorption coefficient between 200 Hz and 2500 Hz and then rounding the result to the nearest 0.01.
Based on the $\alpha_w$ value, sound absorbers can be classified into different sound absorber classes. $\alpha_w$ values of more than 0.90, for example, belong to sound absorber class A, values of between 0.15 and 0.25 belong to class E.

<table>
<thead>
<tr>
<th>Sound absorber classes</th>
<th>$\alpha_w$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.90 – 1.00</td>
</tr>
<tr>
<td>B</td>
<td>0.80 – 0.85</td>
</tr>
<tr>
<td>C</td>
<td>0.60 – 0.75</td>
</tr>
<tr>
<td>D</td>
<td>0.30 – 0.55</td>
</tr>
<tr>
<td>E</td>
<td>0.15 – 0.25</td>
</tr>
<tr>
<td>not classified</td>
<td>0.00 – 0.10</td>
</tr>
</tbody>
</table>

**Advantages and disadvantages of single-number ratings**

*Advantage:* Sound absorbers can be roughly classified and thus compared with one another.

*Disadvantage:* A single-number sound absorption value is always an extremely simplified value. Sound absorbers with very different absorption spectra can have identical single-number ratings. This may sometimes result in the use of a sound absorber which is not suitable for the existing conditions. Frequencies below 200 Hz are not taken into account.
> **Sound absorbers**

When planning the acoustics of an office, sound absorbers can be used in a variety of places in the room. Three groups can be distinguished:

a) **Sound absorbers for the design of ceilings**
Acoustic ceilings represent the largest group of sound absorbing materials. Most of the time there is sufficient surface area available for these materials, which is a clear advantage. With thermoactive ceilings, however, acoustic ceilings can usually not be installed on a larger surface. In this case, special baffle systems can be used, which allow the bare ceiling to continue to radiate thermally, but which provide at least part of the sound absorption required in the room. Moreover, there are sound absorbers which are installed specifically at the edges of the ceiling of a room to ensure that the low frequencies in particular are damped. In Figure 21 these sound absorbers are referred to as edge absorbers.

b) **Sound absorbers for the design of walls**
In addition to sound absorbers for the design of ceilings, there are sound absorbers which have been developed mainly for their use on walls. These types of absorbers should be extremely robust, particularly if installed in areas which are touched or hit in everyday use. However, textile materials such as curtains or panels with textile surfaces can be used for sound absorption as well. In some cases, absorbers on walls can be used as an alternative to acoustic ceilings. Usually, these two absorber types are combined, however, because, from a room acoustical perspective, it is always advisable to damp all three dimensions of the room, since the sound also propagates into all three spatial directions.

c) **Floor coverings**
Due to several different effects, floor coverings contribute to the impact sound protection between rooms within a building as well as to the acoustic optimisation and the reduction of the noise level in a room. This is particularly the case with textile floor coverings. The room acoustic or sound absorbing properties of carpets and other textile coverings result substantially from their porous structure. Their generally small thickness, however, makes floor coverings mainly efficient in the medium and upper frequency ranges only.
d) Sound absorbers integrated into furniture

The fourth group includes furniture elements which have been optimised as to their sound absorbing efficiency. On the one hand, there are movable partitions with sound absorbing surfaces. In addition to this, there is now available a wide range of sound absorbing cabinets, desk elements or even entire room-in-room systems, which can be taken into account when planning the acoustic design of offices. Luminaires containing special baffles or radiators and the like can also have sound absorbing properties if provided with appropriate surfaces.

Furniture elements with integrated absorbers are advantageous in that they can be used in a very flexible manner if constructional measures cannot be carried out on a building. Moreover, they can be positioned very closely to sound sources and, therefore, also be used specifically for noise protection.
Adjusting the reverberation time

In accordance with the recommendations given in German standard DIN 18041, the optimum reverberation time of a room is related directly to the size and use of this room. The surface of the sound absorbing materials which is required for achieving the optimum reverberation time can be calculated using the Sabine formula. First of all, the surfaces which are present in any case have to be taken into account, such as windows, doors, floor coverings, etc.; then the surfaces of additional materials are determined. The sum of these values yields the required reverberation time value. One single material may be sufficient for achieving this value; otherwise, a combination of different sound absorbers may be used. In practice, different sound absorbers are frequently applied for ceiling and wall surfaces, but also sound absorbing elements such as movable partitions or cabinets are becoming more and more common.

Speech intelligibility

In addition to the reverberation time as a parameter of room acoustics, there are also other parameters, among which speech intelligibility is an example where office rooms are concerned. Even if the reverberation time is identical in different rooms, there may be a very different degree of speech intelligibility. In general, the following rule applies: the shorter the reverberation time, the better the speech intelligibility. However, this applies only if speech intelligibility is not affected by high background noise or other interfering sounds.

Speech intelligibility plays a major role in the design of office rooms. Employees often feel distracted by distinctly audible conversations their colleagues may have with each other or on the telephone. The task of office acoustic design is then to reduce speech intelligibility. On the other hand, without any optimising treatments speech intelligibility in conference rooms and auditoriums is often insufficient.

The traditional method for measuring speech intelligibility in a room is to systematically survey a sufficiently large number of persons using standardised lists of syllables and phrases. This procedure involves considerable effort, however, and is usually only applied in research contexts.
On the basis of such subjective studies, physical deduced quantities have been developed to describe speech intelligibility. One widely used value is the STI (Speech Transmission Index). The STI value, or also its simplified version, the RASTI (Rapid Speech Transmission Index), takes into consideration both the influence of reverberation and the sound level of interfering noise. In the following table, measurable STI or RASTI values are associated with the corresponding speech intelligibility.

<table>
<thead>
<tr>
<th>STI range of values</th>
<th>Speech intelligibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75 … 1.00</td>
<td>very good</td>
</tr>
<tr>
<td>0.60 … 0.75</td>
<td>good</td>
</tr>
<tr>
<td>0.45 … 0.60</td>
<td>satisfactory</td>
</tr>
<tr>
<td>0.30 … 0.45</td>
<td>poor</td>
</tr>
<tr>
<td>0.00 … 0.30</td>
<td>very poor</td>
</tr>
</tbody>
</table>

The STI measurements are based on a recording of the transmission between a sound source (speaker) and a reception point (listener). The more the transmission is affected by the influence of the room (reverberation, shielding, echoes, …) or the acoustic environment (background level, other sound sources, …), the lower the speech intelligibility or the smaller the STI value.

In unfavourable acoustic conditions, poor speech intelligibility is compensated by increasing the speech intensity (level increase).

In some specific applications, a speech intelligibility which is too high can be reduced by artificially playing recorded sounds (usually noise signals). From a technical point of view, this effect is achieved by using so-called “sound masking” systems. For office rooms, sound shields are a more suitable solution. They are available in a variety of different shapes, e.g. as partition screens or cabinets. Their function will be described in the following.
8. Office acoustics

> Sound barriers

To optimise the acoustics in office rooms, the local acoustic environment of the work stations is to be designed such that annoyance caused by noise from the surrounding work stations is kept to a minimum.

Sound propagation

For this approach we should have a look at the basic paths of sound propagation in a room. Figure 22 is a schematic representation of the various sound propagation paths in a room. Apart from direct sound, sound is transmitted by reflections from the walls and ceiling. Depending on the sound absorption coefficient of the ceiling and walls, part of the incident sound always reverberates resulting in a repercussion of the emitted sound by reflection or scattering.

The direct transmission of sound from a source to a receiver can be interrupted by using sound barriers. Examples of sound barriers are movable partitions, attachments to be placed on desktops, a free-standing cabinet or even a free-standing wall.

When planning and selecting suitable sound barriers, the phenomenon of “sound diffraction” needs to be taken into account. The so-called diffracted sound is not reflected at one of the boundary surfaces; instead, it diffracts “around” the edges of an obstacle (e.g. a sound partition). Thus, at a work station behind a sound barrier (listening position), sound arrives both in the form of reflections from the ceiling, walls and floor, and as diffracted sound (see Figure 23). Its sound pressure is always lower, however, than the sound pressure of direct sound without any sound barriers. To what extent sound arrives as diffracted sound depends on the height of the sound barriers on the one hand and its shape on the other. Moreover, diffraction and reflection are generally highly frequency-dependent, which must be taken into account when using sound barriers.
**Blocking sound**

Sound barriers should have a certain mass per unit area, and their surface should be impermeable to air to achieve at least a minimum degree of sound insulation. In addition, sound absorbing material may be applied to one or both sides of the sound shields. If this is the case, the level in the room is reduced not only by the sound barrier effect, but also by sound absorption.

If only one side of the sound barrier is provided with sound absorbing material, this side should face the noise source to prevent the sound from propagating into the room early on.

The height of the room is of particular importance when determining the optimum height of a sound barrier. The relationship between the barrier height and the room height influences the shielding effect to the same extent as the distance between the source and the receiver. High partitions are most efficient with short distances between the source and the receiver. Ideally, the partition height/room height ratio should be greater than 0.5. Particularly with short distances between the source and the receiver, the level can be reduced by up to 10 dB by installing a sound partition.

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**Rules of thumb for using sound shields**

- The sound barrier should be positioned as closely as possible to the “sound source” emitting the noise.

- Sound barriers are to be preferred which do not simply represent a wall (I-view), but rather change their direction in space, thus “enclosing” the sound source at least partially (H or L-view).

- Sound barriers are fully efficient only if the surfaces surrounding them are not reflective themselves. The effect of a movable partition is relatively smaller if positioned below a heavily reflecting ceiling or next to an unframed window. Boundary surfaces adjacent to a sound barrier should, therefore, also be sound absorbing, where possible.

- Where possible, sound barriers should be flush with the adjacent boundary surfaces or furniture elements. Gaps and openings reduce the sound barrier effect considerably. For an optimum effect, the barrier height should be at least half the room height.
8. Office acoustics

Design examples

> Individual office

The foremost requirement which has to be fulfilled in a one-person office is that the reverberation time value is designed in accordance with the size of the room. This can be achieved either by applying sound absorbing materials to the ceiling or by using other types of sound absorbers.

A carpet can contribute to the office acoustic concept in a beneficial manner and, moreover, has a positive effect on noise resulting from footfalls, objects falling to the floor, etc. As the only office acoustic treatment, however, carpets are inadequate, because their absorption behaviour is highly frequency-specific. This basically also applies to all of the subsequent examples. Furthermore, the furnishing should ensure that there are no smooth walls facing each other. Parallel smooth walls in a room can result in clearly audible reflections, so-called flutter echoes, no matter how big or small the room is. This can lead to unpleasant effects in noise perception and, as a consequence, may restrict the usability of the room to a large degree. Larger continuous reflecting surfaces can be avoided, for example, by furnishing the room with cabinets, shelves, picture frames, pinboards, curtains or louvre blinds, coat racks, plants, etc. Therefore, a systematic arrangement of sound absorbers in normally sized individual offices is usually not required.
Two-person office

Once an office is occupied by more than one person, and if the occupants need to communicate verbally, the positioning of the sound absorbers and the application of sound barriers measures need to be taken into account in addition to an appropriate reverberation time. The most suitable location of sound absorbers is the ceiling area above the work stations. If it is not possible to install an acoustic ceiling, a sound absorbing baffle can be installed above the work stations instead. Moreover, the transmission of direct sound between the employees should be prevented by installing a separating attachment between the two work stations opposing each other, as illustrated in the figures. For this purpose, the attachment should have sound absorbing properties and a height of at least 0.70 m, so that the direct connection between the speaker and listener is interrupted. If walls are to be part of the acoustic design of a room, the surfaces most suitable for arranging sound absorbers are the ones close to speaker positions, i.e. the wall surfaces behind the employees or the wall surfaces flanking the add-on meeting unit. When planning the interior design of a two-person office, larger smooth wall sections opposing each other should be avoided as well.
8. Office acoustics

> Open-plan office

What applies to a two-person office also has to be taken into account in the design of an open-plan office. Adjusting the reverberation time to a value appropriate for the size of the room is of first priority. Installing sound absorbers in the ceiling area is also recommendable for open-plan offices; above the work stations and above very noisy areas such as the printer, fax and copy machine tables it is absolutely necessary, however. To reduce direct sound, opposing desks should be shielded from each other by a, preferably sound absorbing, separating attachment of a height of at least 70 cm. Furthermore, closed shelves, cabinets, movable partitions or special room partition systems can be used to achieve an acoustic separation of individual work areas. At the same time, these elements can ensure privacy at the workplace and shield off any unwanted light, if necessary. Sound barriers should always be arranged flush with any boundary surfaces, since even a small gap reduces the sound insulating effect of such elements significantly.

As a whole, the office acoustic design of an open-plan office should always weigh the visually open design usually intended against the acoustic separation to be achieved, two goals which appear to exclude each other. At the end of the planning process, a compromise should be found which leaves enough room for both aspects.

In an open-plan office, the furniture present usually reduces the risk of having larger sections of parallel smooth walls which might cause a flutter echo. However, this aspect should also be given attention.
**Lecture room/meeting room**

The distinctive feature of a lecture room is that the position of its screen, beamer and, if applicable, speaker’s desk define a spatial direction which should also be reflected in the acoustic design of this room. The arrangement of sound absorbers and reflecting surfaces should help the listeners in any seat in the room to understand the speaker without any effort. Sound absorbers in the ceiling area should, therefore, be positioned predominantly in the rear area of the room and on the sides, while the surface above the speaker position and, where possible, also the central ceiling area need to remain reflective in any event. The rear wall of the room should be sound absorbing, at least at the height of the speaker and listeners. The reason for this is that, for the perception by the listeners, it is better to have only the direct sound emitted by the speaker and the reflected sound from the side walls arrive at the listeners and not any reflections from the rear wall.

In terms of the reverberation time, for a lecture room the usage type “speech” should be used as a basis, which usually allows for higher reverberation times than the “teaching and communication” type. This is due to the fact that in such a room only one person speaks at a time, and it is generally desired that this person is understood by all other persons present.

If, in a meeting room, conversations are held in a “round table” manner instead, i.e. there are several speaker positions and sometimes people speak simultaneously, this should be reflected in the design of the ceiling, which should be sound absorbing to all sides and have a reflective area above the table at most. Furthermore, in this case the reverberation time has to be based more on the usage type “communication and teaching”.

![Examples of lecture room, meeting room](Fig. 27)
> Cafeteria

In cafeterias, the foremost priority is to achieve the optimum reverberation time. In accordance with the recommendations of DIN 18041, a simplified method can be used for this purpose. DIN 18041 contains a table specifying the percentage of the ceiling or wall surface areas to be covered as a function of the height between floors and the weighted sound absorption coefficient $\alpha_w$ (see page 35) of the sound absorber used. For a cafeteria with a typical height of 2.50 m, for example, 70 % of the ceiling surface is to be covered with a sound absorber having a weighted sound absorption coefficient of 0.70. If the sound absorber has a weighted sound absorption coefficient of 0.50, the entire ceiling has to be covered. For rooms with a height of 3.00 m and a sound absorber with a sound absorption coefficient of 0.70, also nearly the entire ceiling has to be covered with this sound absorber.

Shielding the tables from each other is not generally required, but should be provided for areas which need to fulfil certain requirements regarding privacy.

If heavily reflecting surfaces (e.g. two glass fronts) oppose each other, as illustrated in the example below, sound absorbing curtains should be provided, which interrupt these continuous reflecting surfaces at evenly spaced distances. Corresponding measures have to be taken for the opposing wall surfaces unless the furnishing of the room already represents an interruption of the smooth surfaces. It is generally favourable to have one quarter to one third of the sound absorbing surfaces in the wall area.

Fig. 28

Example of cafeteria
Annex

> **Index**

A-weighted sound pressure level – dB(A)
The A-weighted sound pressure level is the weighted average value of the sound pressure level (dB) as a function of the frequency of a sound. The weighting takes into account the ability of the human auditory system to perceive sound pressure levels or tones of different frequencies to a different degree. This sensitivity is particularly pronounced in the medium frequency range, i.e. the range of human speech. Nearly all regulations and guidelines indicate values expressed in dB(A).

Acoustic quality
The acoustic quality of a room refers to its suitability for a particular use. It is influenced by the properties of the boundary surfaces (walls, ceiling, floor) and the furnishings and by persons present in the room.

Auralisation
Auralisation is a method for simulating the acoustic properties of a room. With this method, the effects of certain acoustic treatments can be “auralised” as early as the design stage.

Background noise level
Usually, sounds which do not contain any meaningful information are referred to as background noise (e.g. noise from air conditioning or traffic). The background noise level is measured in dB or, by weighting its frequencies in accordance with the human auditory system, in dB(A).

The background noise level indicates the sound pressure level which has been exceeded during 95% of the measurement period. It has a direct effect on speech intelligibility.

Building acoustics
Building acoustics is a branch of building physics, or acoustics, which deals with the effect of the structural conditions on the propagation of sound between the rooms of a building or between the interior of a room and the outside of the building.

Diffracted sound
When a sound wave encounters an obstacle its direction changes at the boundaries of this obstacle. Part of the sound energy thus enters the shadow region behind the obstacle. This portion of the sound, which is basically “deflected” at the edge, is referred to as diffracted sound.

Decibel (dB)
Logarithmically defined unit of measurement which expresses the sound pressure level. The relevant scale for human beings is 0 dB to 140 dB. 0 dB refers to a sound pressure of 20 µPa.

Equivalent sound absorption area
The equivalent sound absorption area A is defined as the product of the sound absorption coefficient \( \alpha \) of a material and the surface S of this material.

Flutter echo
A flutter echo occurs when a sound signal moves back and forth several times between at least two heavily reflecting surfaces. It can be perceived subjectively: a shot or the clapping of hands sound like machine gun fire which becomes weaker and weaker. Flutter echoes are usually perceived as annoying and should be avoided. This can be achieved by the geometrical design of the room and/or by covering part of the reflecting surfaces with absorbing material.
**Office acoustics**

**Frequency**
Frequency indicates the number of sound pressure changes per second. Sound events with a high frequency are perceived by the human ear as high-pitched tones, sound events with a low frequency as low-pitched tones. Sounds such as noise, road traffic, etc., normally comprise a great number of frequencies. The measurement unit of frequency is hertz (Hz), \(1 \text{ Hz} = 1/\text{s}\). Human speech is in the range between 250 Hz and 2000 Hz. The audible range of human beings is between 20 Hz and 20000 Hz.

**Isophones**
Isophones are "equal-loudness contours". They describe which sound pressure level is required at which frequency for a single tone in order for a person to perceive it as equally loud.

**Noise**
Noise comprises all sounds which, due to their loudness and structure, are considered as harmful or annoying or stressful for human beings and the environment. It depends on the condition, preferences and mood of a person whether sounds are perceived as noise or not. The perception of sounds as noise and the way in which people are affected by it depend, on the one hand, on physically measurable quantities such as the sound pressure level, pitch of a tone, tonality and impulsiveness. On the other hand, certain subjective factors also play a role: at bedtime noise is perceived as extremely annoying. The same is true for activities which require a high level of concentration. If we like certain sounds, we will not perceive them as annoying even at high volumes; sounds which we do not like are annoying to us even at low volumes (e.g. certain types of music). Furthermore, how we feel at a particular time also influences our sensitivity to noise. If an activity is disrupted or disturbed by one or more sounds, this is referred to as noise pollution. We are particularly sensitive to noise if verbal communication is affected, e.g. if a loud conversation at the neighbouring table makes it difficult for us to listen, and if we have to concentrate or want to sleep.

**Octaves**
Acoustic parameters such as the sound pressure level or the sound absorption coefficient are usually expressed in increments of octave band and one-third octave band. The precise knowledge of acoustic properties in the smallest possible frequency steps of sound is a prerequisite for a detailed acoustic design. For room acoustics the relevant octave band centre frequencies are 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz. The octave bands are obtained by doubling the previous frequency. Each octave comprises three one-third octave values (see also single number ratings).

**Omni-directional sound sources**
Spherical sound sources are basically those sound sources which radiate uniformly into all three directions of space. Since hardly any loudspeaker exhibits an omni-directional characteristic in its near field, for certain applications in acoustic measurement technology there are special measurement loudspeakers, so-called dodecahedron loudspeakers, which incorporate twelve individual loudspeakers in a nearly spherical arrangement, thus forming an approximately omni-directional sound source between 100 Hz and 4000 Hz.

**Porous absorbers**
Porous absorbers comprise, for example, mineral fibres, foams, carpets, fabrics, etc. The effect of the porous absorbers is due to the fact that sound is able to enter the open structures of the material where, by the friction of air particles, the sound energy is converted into thermal energy at the surface of the pores. Porous absorbers achieve their best effect at medium and high frequencies.

**Psychoacoustics**
Branch of acoustics or noise effect research which deals with the subjective perception of objectively present sound signals. Furthermore, psychoacoustics studies the influence of a listener’s personal attitudes and expectations on the perception of sound events.

**Rating level \(L_r\)**
The rating level \(L_r\) \((L\ for \ "level", \ r\ for \ "rating")\) is the relevant parameter for objectively assessing the noise impact at a workplace. Apart from weighting the sound pressure level as a function of the frequency (see A-weighted sound pressure level), a determination of the sound pressure level takes into account certain adjustments which depend on the characteristic of the sound (e.g. impulsiveness or clear prominence of individual tones) and its duration of impact. The rating level is also expressed in dB(A).
Resonant absorber
This term comprises all types of absorbers using a resonance mechanism such as an enclosed air volume or a vibrating surface. Resonant absorbers are mainly suitable for absorbing sound of medium to low frequencies. The maximum effect of resonance absorbers is usually restricted to a certain frequency range (see also “porous absorbers”).

Reverberation chamber
Reverberation chamber are special laboratory rooms with walls which reflect the incident sound waves to a very high degree. Reverberation chamber have particularly long reverberation times across the entire frequency range.

Reverberation chamber method
The reverberation chamber method is used for determining the frequency-dependent sound absorption coefficient. A sample of the material to be tested is placed into the reverberation chamber. The sound absorption of a material can then be calculated from the change in the reverberation time of the room.

Reverberation time
Put simply, the reverberation time indicates the period of time it takes for a sound event to become inaudible. Technically, the reverberation time $T$ has been defined as the time required for the sound pressure level in space to decay by 60 dB.

Room acoustics
Room acoustics is a branch of acoustics which deals with the effect of the structural conditions of a room on the sound events occurring in this room. Rooms in terms of this definition may be concert halls, theatres, class rooms, studios, churches, but also office rooms, call centres or conference rooms, in which acoustic presentations (speech and music) or communication generally occur. The central issue of room acoustics is to determine which surfaces can be used to create optimum listening conditions. In this context, the most important property of the materials is their sound absorption.

Sabine formula
If the volume and the total equivalent sound absorption area of a room are known, the reverberation time can be estimated using the Sabine formula, where “$T$” is the reverberation time, “$V$” is the volume of the room and “$A$” is the total equivalent sound absorption area.

The close relationship between the volume of a room, the sound absorption of the surfaces of this room, and the reverberation time was discovered the physicist Wallace Clement Sabine (1868 – 1919). He found out that the reverberation time $T$ is proportional to the room volume $V$ and inversely proportional to the equivalent sound absorption area $A$: $T = 0.163 \times \frac{V}{A}$ (in metric units).

The equivalent sound absorption area $A$ is the sum of all surfaces $S$ present in the room, each multiplied by its corresponding sound absorption coefficient $\alpha$:

$$A = \alpha_1 S_1 + \alpha_2 S_2 + \alpha_3 S_3 + \ldots + \alpha_n S_n$$

Single number ratings of sound absorption
So-called single number ratings are used for a simplified representation of the frequency-dependent parameter of the sound absorption coefficient as well as for a rough comparison of different sound absorbers. In Europe, the “weighted sound absorption coefficient” $\alpha_w$ in accordance with the European/International standard EN ISO 11654 is commonly used. In the US, the NRC and SAA values are widely used. All of the above values are based on measurements of the sound absorption in one-third octave and octave bands. For a detailed acoustic design of a room it is necessary to know these sound absorption values precisely in one-third octave or at least in octave bands (see “octaves”).

Sound absorbers
Sound absorbers are materials which attenuate incident sound or convert it into other forms of energy. A distinction has to be made between porous absorbers and resonant absorbers or combinations of these absorber types.

Sound absorption coefficient $\alpha$
The sound absorption coefficient $\alpha$ of a material indicates the amount of the absorbed portion of the total incident sound. $\alpha = 0$ means that no absorption occurs; the entire incident sound is reflected. If $\alpha = 0.5$, 50 % of the sound energy is absorbed and 50 % is reflected. If $\alpha = 1$, the entire incident sound is absorbed, there is no longer any reflection.
Sound attenuation
Sound attenuation describes the ability of materials to absorb sound or to convert the sound energy present into other forms of energy, i.e. ultimately into thermal energy (see also "sound insulation").

Sound barriers
A sound barrier is basically an obstacle which interrupts the direct propagation of sound from a source to a receiver. It can consist in a movable partition or an attachment to be placed on top of a desk. Cabinets and other large-surface pieces of furniture can also function as sound partitions. Sound partitions can be provided with a sound absorbing surface which additionally reduces the propagation of sound.

Sound events
General term for tones, music, bangs, noise, crackling, etc.

Sound masking
Sound masking specifically uses natural (e.g. birds’ twittering) or artificial (e.g. noise) sounds in order to blanket other sounds. This method can be used, for example, to drown out information-containing sounds if the other background noise is too weak to mask them.

Sound pressure
All sound events have in common the fact that they cause slight variations in air pressure which can propagate in elastic media such as air or water. We therefore refer to the sound pressure of a tone. The heavier the pressure variations are, the louder is the sound event. The faster the variations occur, the higher is the frequency.

Sound pressure level (Lp)
The sound pressure level (L for level and p for pressure) is a logarithmic quantity for describing the intensity of a sound event. The sound pressure level is often also referred to as “sound level”, which is actually not quite correct. The sound pressure level is expressed in decibels (abbreviated as dB). Sound pressures are measured using microphones. The measurable level range starts at just below 0 dB and ends at approximately 150 to 160 dB.

Sound spectrum
The sound spectrum describes the frequency composition of the sound. Pure tones are sound events of a single frequency. A superposition of tones of different frequencies is referred to as noise or sound.

Sound transmission loss
Sound insulation refers to the restriction of the propagation of sound through the boundaries of a room. Sound insulation is, therefore, a measure to separate rooms acoustically from unwanted sound from adjacent rooms or the outside. This has nothing to do, however, with the required acoustic sound attenuation within a room (see also "sound absorption"). Sound insulation or sound transmission loss is a fundamental parameter of building acoustics. A distinction has to be made between airborne sound and impact sound. Airborne sound is created by sound sources present in the room which are not immediately connected to the boundary surfaces, e.g. people who are talking. Impact sound, on the other hand, results from structure-borne sound (footfalls, knocking), which in turn excites the walls or ceilings to radiate airborne sound. Airborne sound insulation and impact sound insulation both have to fulfil the requirements established in relevant building laws.

Sound waves
Variations in air pressure which are caused by sound events are referred to as sound waves. The length of the sound waves defines the frequency and their height defines the level. Long sound waves have a low frequency and are perceived as low-pitched tones. Short sound waves have a high frequency and are perceived as high-pitched tones. In air, a 100 Hz wave has an extension of 3.40 metres, whereas a 5000 Hz wave has an extension of approximately 7 centimetres.
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International/European origin

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Further information

The information of buero-forum is a service of bso Verband Büro-, Sitz- und Objektmöbel e. V., the association of office furniture industry in Germany.

Further information on the topic office acoustics and to other topics on office design and furniture can be obtained from the bso and its member companies:

- AOS Akustik Office Systeme GmbH
  www.akustik-office-systeme.de
- ASSMANN BÜROMÖBEL
  GMBH & Co. KG
  www.assmann.de
- A + Z Bürosysteme GmbH
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