Architectural Acoustics

Mathematical and physical foundations

Christian Frick

Course agenda

FS 2024

22.02.24	Introduction	all
29.03.24	Human perception	CFR
07.03.24	Listening	JST
14.03.24	**Math and Physics**	**CFR**
28.03.24	Basic room acoustics	CFR
11.04.24	Acoustics and arts	THE
18.04.24	Room acoustic design	JST
25.04.24	Guidelines and standards	CFR
02.05.24	Office spaces	DOU
16.05.24	Final presentations	all

Agenda

- 15:45 - 16:00 Auditory perception: Demonstration of selected examples
- 16:00 - 17:15 Basic Math and measurement of acoustical properties.
    - dB addition of identical sources (pressure addition), dB addition of different sources (energetic summation)
    - Inverse square law for point sources, distance law for line sources
    - Weighting functions (Z, A, C)
    - Room acoustics: Reverberation time, absorption values (Sabine, Eyring)
    - Reverberation time and sound pressure level
- 17:15 - 17:45 Exercises 1 and 2 - discussion of the assignments, intro to exercise 3
- 18:00 - 18:25 Sound walk on the campus
- 18:25 - 18:30 Wrap up

Wrap up: human perception

- **Spectral Dimension:** Describes the frequency content of the sound, including the distribution of frequencies and their amplitudes. It helps us identify the pitch and timbre of a sound.
- **Temporal Dimension:** Encompasses aspects related to the timing and duration of sound events. This includes the onset, duration, and temporal envelope, which describes how the sound evolves over time.
- **Amplitude Dimension:** Refers to the intensity or magnitude of the sound, often measured in decibels (dB). It indicates the loudness or volume of the sound.
- **Spatial Dimension:** Describes the location and directionality of sound sources in a three-dimensional space. This dimension is particularly important for understanding sound in immersive or spatial audio contexts.
- **Textural Dimension:** Accounts for the overall texture or complexity of a sound, considering elements like density, layering, and the presence of simultaneous sound events.
- **Emotional Dimension:** Considers the emotional or psychological impact of a sound on a listener, including associations, mood, and affective responses.
- **Cultural and Contextual Dimension:** Recognizes that the interpretation and significance of a sound can vary based on cultural, social, and contextual factors, adding a layer of meaning beyond its physical properties.

Spectral and amplitude dimensions

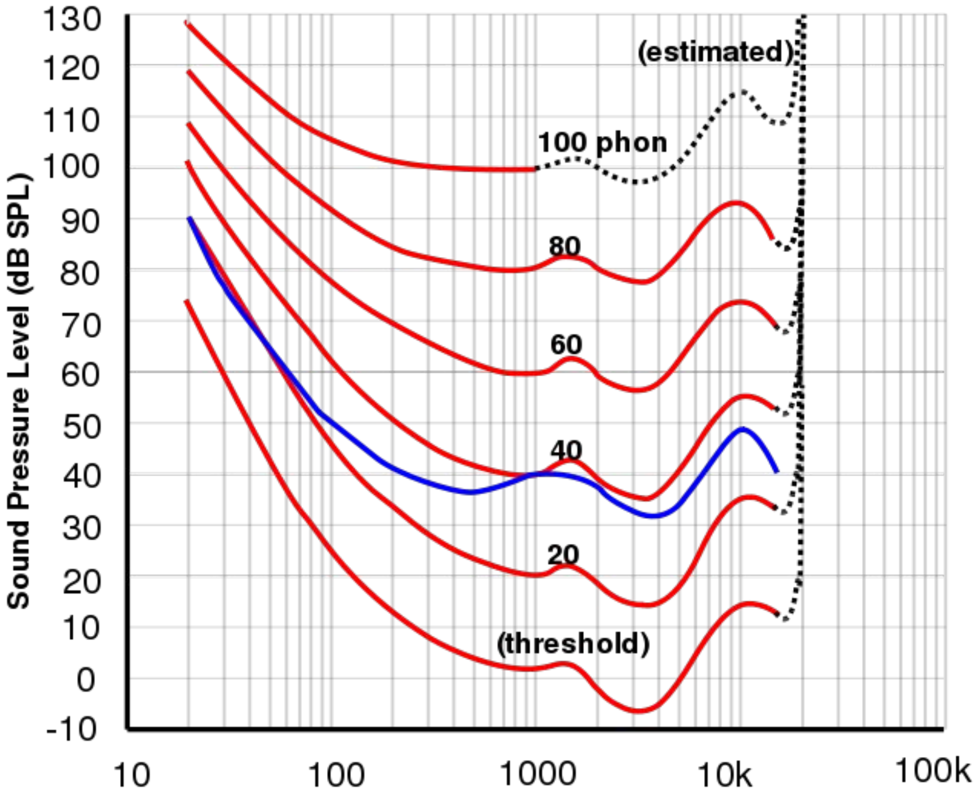
Different species hear different frequency ranges.

The human frequency range extends from approximately **20 - 20000 Hz**, from low to high frequencies.

The sensitivity of the ear varies (is not constant) over the entire perceptible frequency range.

Regarding the measurement of sound pressure level this sensitivity is depicted in weighting functions.Where

- the A weighting is deduced from the 40 phon contour,
- the C weighting curve from the 100 phon contour.



Equal-loudness contours (red) (from ISO 226:2003 revision)
Original ISO standard shown (blue) for 40-phons

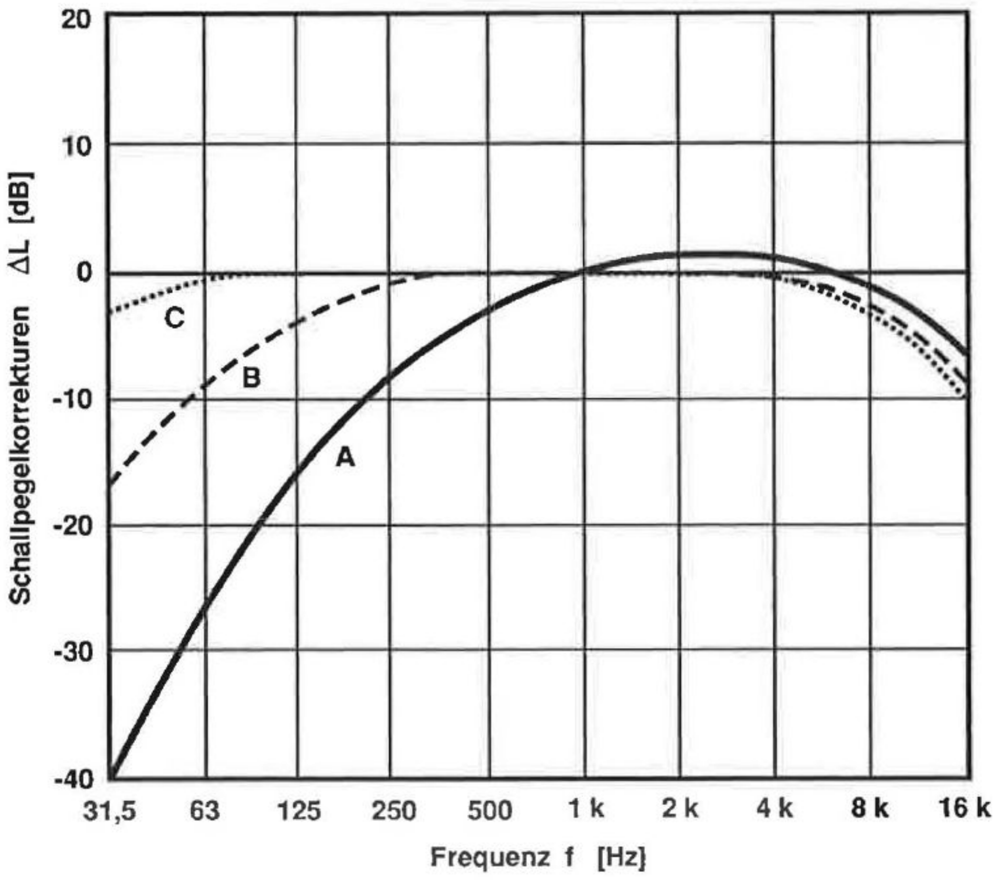
Spectral dimension - weighting functions

A-weighting and C-weighting are filter curves applied to sound measurements to account for the sensitivity of the human ear at different frequencies and sound pressure levels.

A-weighting relates to the 40 phon curve, which reflects the ear's sensitivity at lower sound levels,

while C-weighting relates to the 100 phon curve, which is associated with higher sound levels.

These weightings help provide more accurate assessments of how humans perceive sound in different contexts.



dB as a logarithmic value

As discussed in the last lecture, the dB value is a logarithmic, dimensionless unit of measurement.

As a rule of thumb, these rules apply:

- A doubling of the **sound energy *W*** causes an increase of +3 dB, a halving corresponds to -3 dB.
  (Linear relationship to sound intensity.)

- A doubling of the **sound pressure *p*** causes an increase of +6 dBSPL, a halving corresponds to -6 dBSPL.

- **Perception**:
  An increase of 10 dBSPL is perceived as 'twice as loud', a reduction of 10 dBSPL as 'half as loud'.

$$L_w = 10 \cdot \log\left(\frac{W}{W_0}\right)$$

L_w	sound intensity level [dB]
W	sound intensity in [W/m^{-2}]
W_0	10^{-12} W/m^{-2} (reference intensity)

$$L_p = 20 \cdot \log\left(\frac{p}{p_0}\right)$$

L_p	sound pressure level [dBSPL]
p	sound pressure in [Pa]
p_0	$2 \cdot 10^{-5}$ Pa (20 μPa) at 1 kHz (hearing threshold)

Sound propagation, distance laws

For a point source:

A doubling of the distance R causes an dispersion of the sound energy on a quadratically increasing surface (4*A).

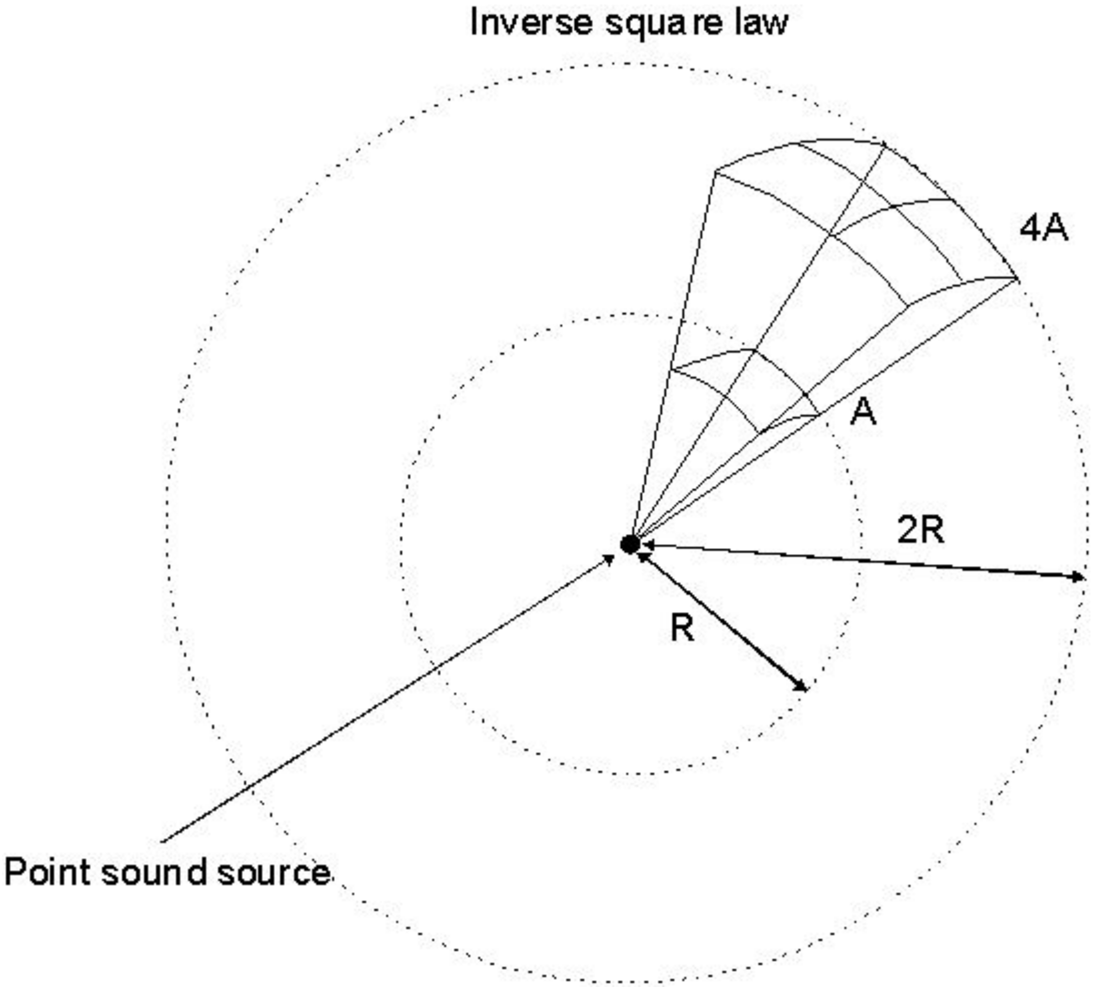
This corresponds to a reduction of the sound intensity of **-6 dB**.

This holds for sources with or without directivity.

For a line source:

The surface of the cylinder grows linearly with the radius. Therefore a doubling of the distance corresponds to a doubling of the (cylinder) surface.

This corresponds to a reduction of the sound intensity of **-3 dB**.



Sound propagation, distance laws

For a point source:

A doubling of the distance R causes an dispersion of the sound energy on a quadratically increasing surface (4*A).

This corresponds to a reduction of the sound intensity of **-6 dB**.

This holds for sources with or without directivity.

$$L_2 = L_1 - 20\log\left(\frac{r_2}{r_1}\right)$$

L_n sound pressure level at distance r_n

For a line source:

The surface of the cylinder grows linearly with the radius. Therefore a doubling of the distance corresponds to a doubling of the (cylinder) surface.

This corresponds to a reduction of the sound intensity of **-3 dB**.

$$L_2 = L_1 - 10\log\left(\frac{r_2}{r_1}\right)$$

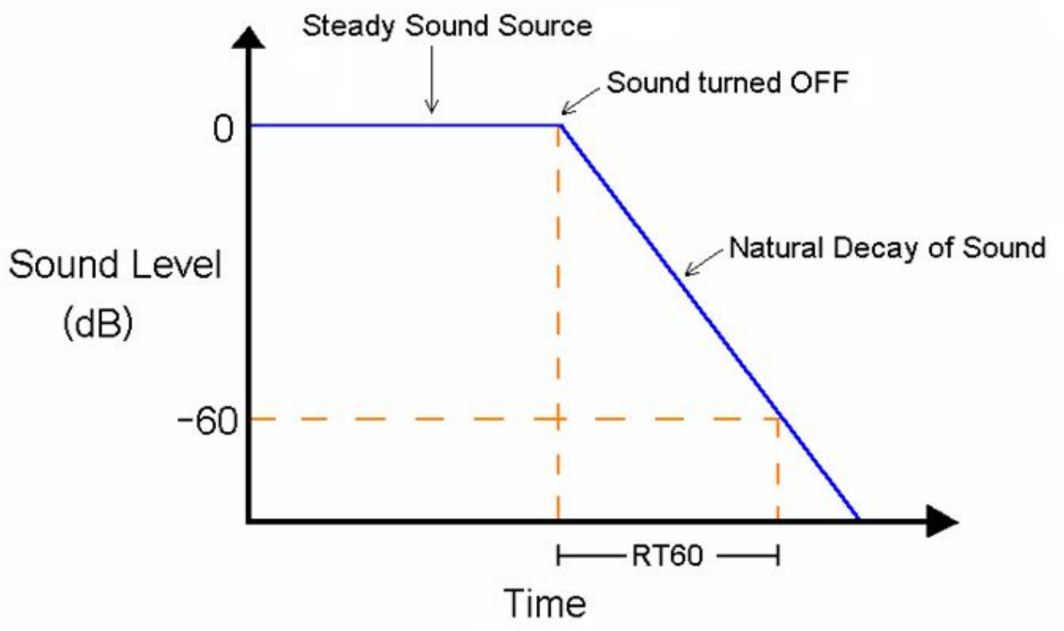
L_n sound pressure level at distance r_n

Reverberation time, RT_{60}

W.C. Sabine

In 1898, Wallace C. Sabine (1868 - 1919) developed the reverberation time equation, but the article "Collected Papers on Acoustics" appeared only in 1922.

Sabine's equation is valid if the absorption is homogeneously / stochastically distributed in the room.



$$T = \frac{K \cdot V}{A}$$

T	*RT_{60}*, time for a 60 dB decay [s]
A	total sound absorption surface [m^2]
V	room volume [m^3]
K	Coefficient = 0.161 $s^{-1}m$

Source and further information:

http://www.sengpielaudio.com/calculator-RT60.htm

Reverberation time, RT_{60}

C.F. Eyring

In 1930 Carl F. Eyring proposed an equation better suited for smaller rooms. In contrast to Sabine's empirical equation, Eyring's equation was based on the Image Source Model.

Source and further information:

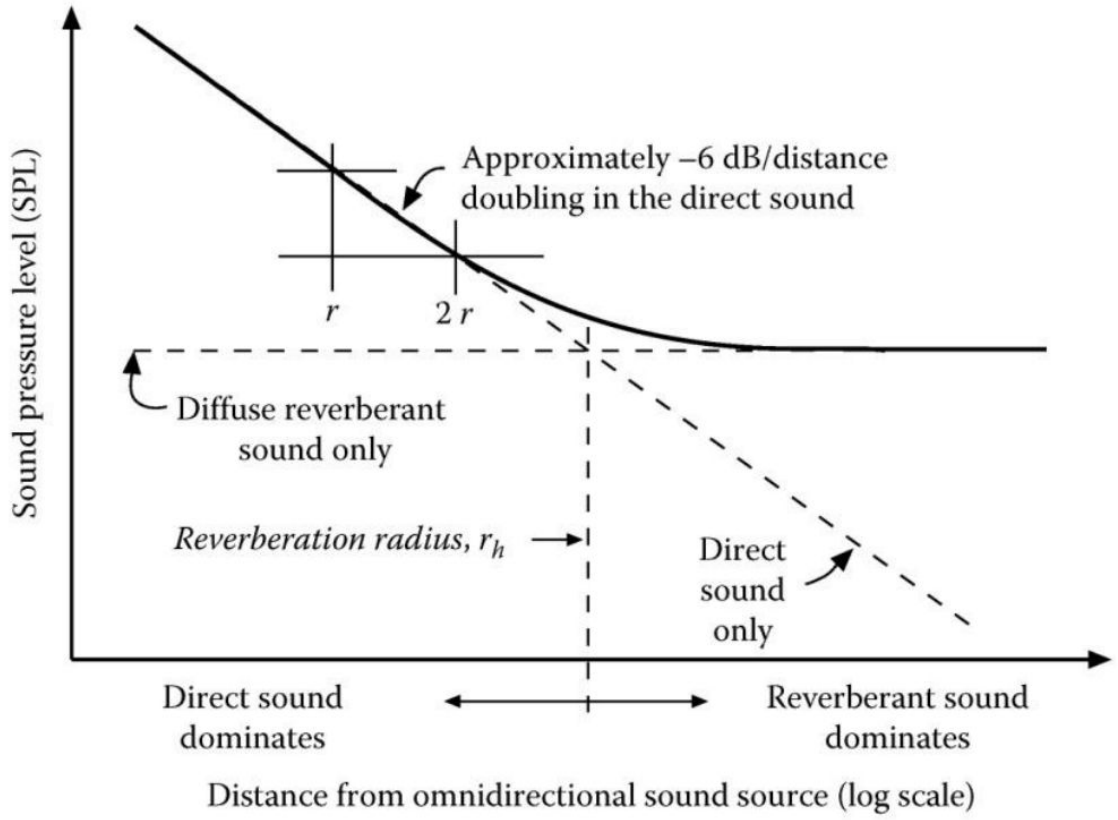
https://en.wikipedia.org/wiki/Reverberation#

$$T = 0.161 \frac{V}{-A \cdot \ln(1-\alpha_m)}$$

T	reverberation time [s]
A	total of all room surfaces [m^2]
V	room volume [m^3]
α_m	average degree of absorption (per frequency)
K	Coefficient = 0.161 $s^{-1}m$

Reverberation radius, r_H

The reverberation radius is the distance from a sound source to a point in a room where the direct sound and the reflected sound have the same energy, meaning they are of equal intensity.
This point is significant for understanding the balance between direct and reflected sound in an acoustic environment.



Reverberation radius, r_H

The reverberation radius is the distance from a sound source to a point in a room where the direct sound and the reflected sound have the same energy, meaning they are of equal intensity.
This point is significant for understanding the balance between direct and reflected sound in an acoustic environment.

$$r_H = 0.141\sqrt{A}$$

$$r_H = 0.057\sqrt{\frac{V}{T}\cdot Q}$$

r_H	reverberation radius [m]
A	total sound absorption surface [m^2]
V	room volume [m^3]
T	RT_{60}, reverberation time [s]
Q	quality factor of sound source []

Temporal resolution and speech intelligibility

Sound absorbers in room corners help improve speech intelligibility by reducing late corner reflections and echoes that disturb perception. Absorbing sound in corners reduces these late reflections, leading to clearer and more intelligible speech.

Placing sound absorbers in the middle of the ceiling can reduce speech intelligibility by absorbing early reflections. These early reflections help our brains process speech and understand it more clearly.

The choice of where to place sound absorbers depends on the specific acoustic characteristics of the room and the desired acoustic outcome.

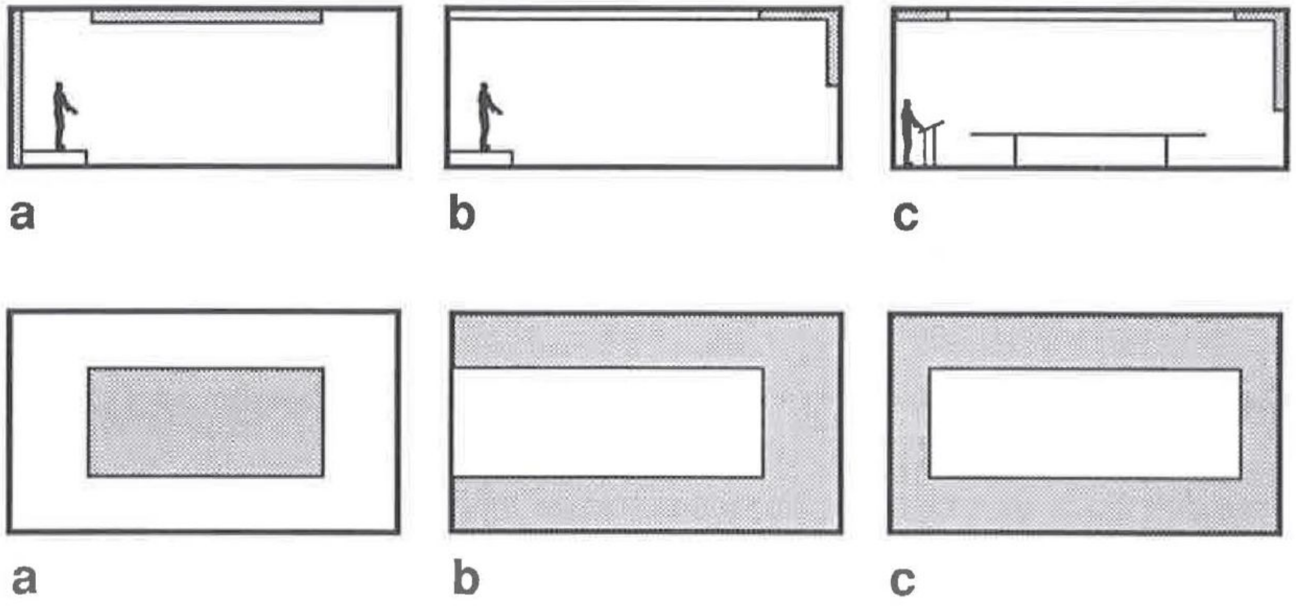


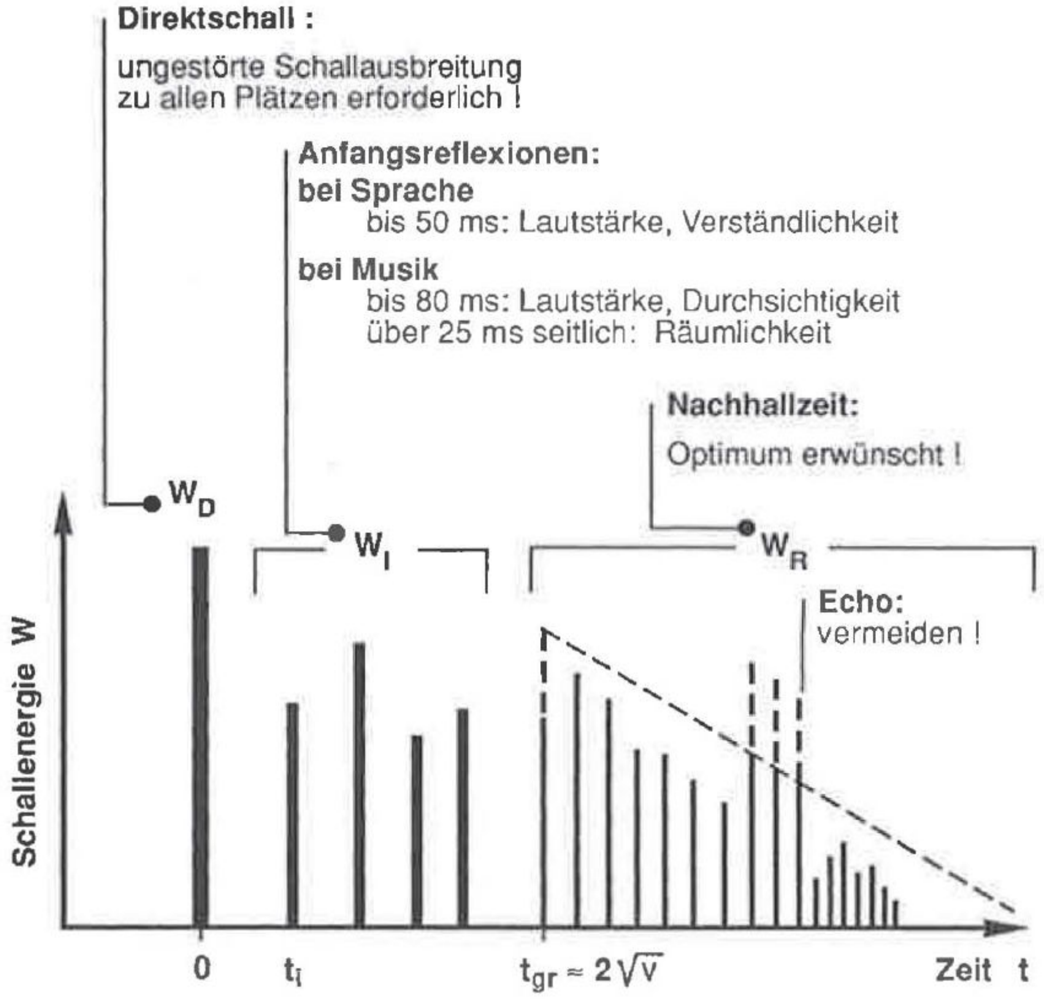
Bild 4.83 Unzweckmäßige und zweckmäßige Verteilung von breitbandigen Schallabsorbern [630]
oben: Längsschnitt; unten: Deckenansicht
a) unzweckmäßig: nützliche Reflexionsflächen werden unwirksam gemacht
b) c) zweckmäßig: nützliche Reflexionsflächen bleiben erhalten

Temporal resolution and speech intelligibility

Sound absorbers in room corners help improve speech intelligibility by reducing late corner reflections and echoes that disturb perception. Absorbing sound in corners reduces these late reflections, leading to clearer and more intelligible speech.

Placing sound absorbers in the middle of the ceiling can reduce speech intelligibility by absorbing early reflections. These early reflections help our brains process speech and understand it more clearly.

The choice of where to place sound absorbers depends on the specific acoustic characteristics of the room and the desired acoustic outcome.



Reverberation time and diffuse field sound pressure level

What's the difference between between 'loud' and 'comfortable' restaurants?

$$L_p = L_W + 10\log\left[\frac{Q}{4\pi r^2} + \frac{4}{A}\right]$$

Assuming identical sound sources and distances L_W, Q and r^2 are identical for loud and comfy restaurants.

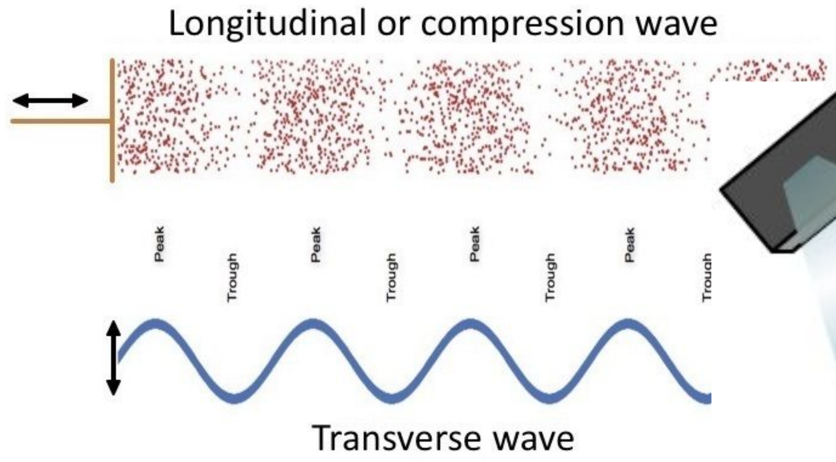
With identical volumes V and Sabine's Equation the change in the sound pressure level L_p is only dependent on the reverberation times:

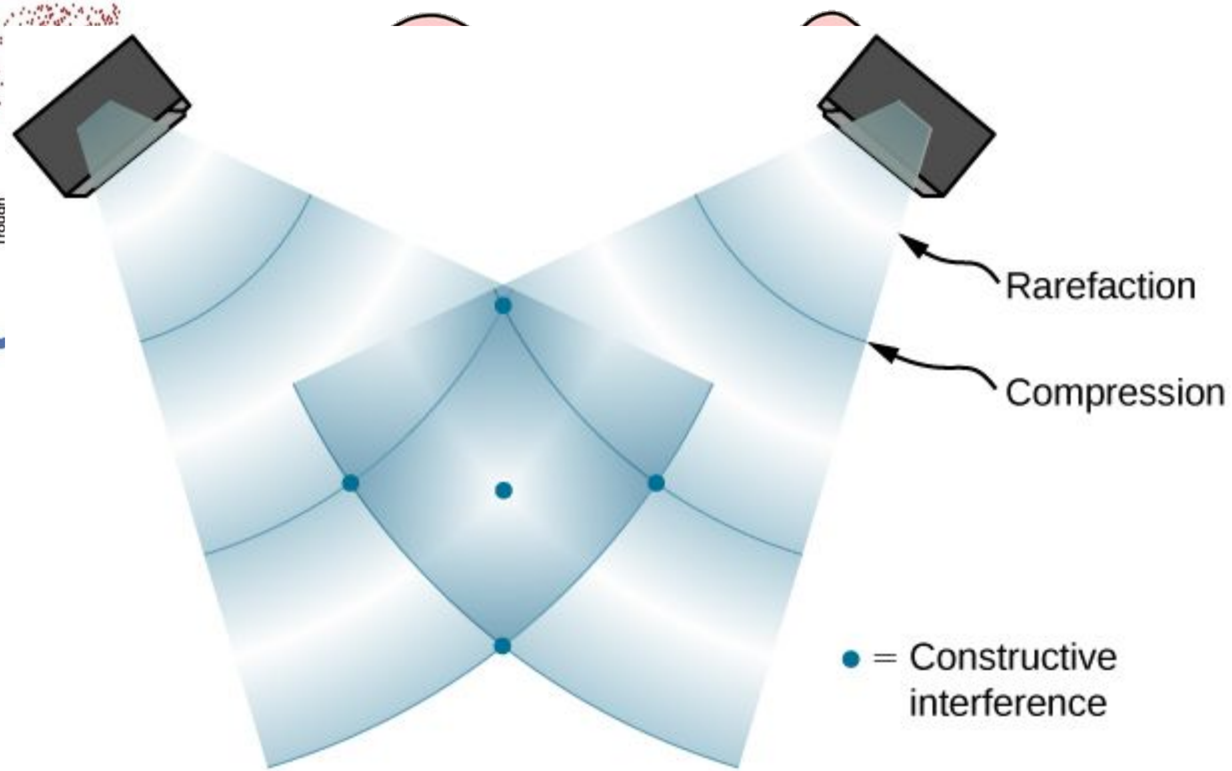
$$A = K\frac{V}{T}$$

Example: Restaurant 2 with a reverberation time of 2 sec is 3 dB louder than Restaurant 1.

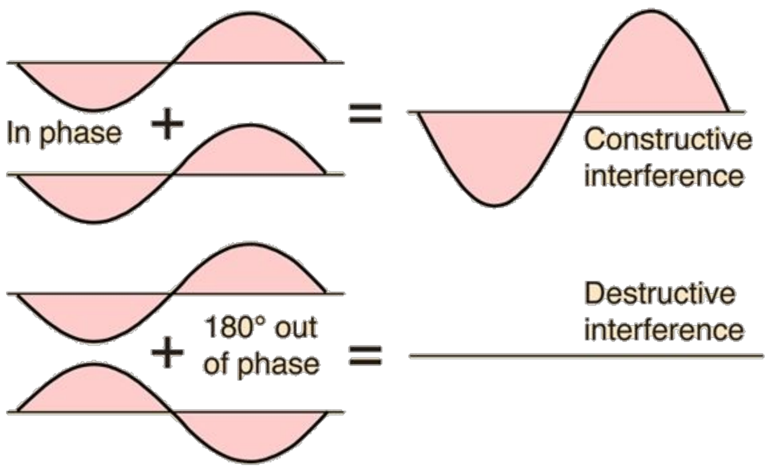
$$L_{p2} - L_{p1} = 10\log\left[\frac{T_2}{T_1}\right]$$

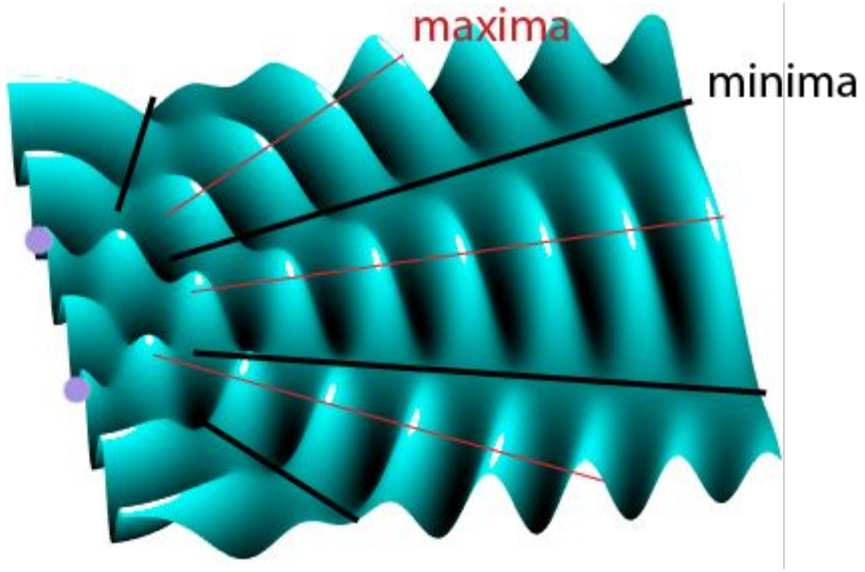
Constructive and destructive interference





Constructive and destructive interference





link

Appendix

Schalldruckpegel L_p	
• Einheit: [dbSPL] • P_0: Hörschwelle $2\cdot10^{-5}$Pa (20µPa) bei 1 kHz • Q: Bündelungsgrad 1...n (1=Kugel, 2=halbkugel, etc.) • A: Äquivalente Absorptionsfläche (Sabinesche Gleichung nach A)	$L_p = 20\cdot\log\left(\frac{p}{p_0}\right)$ $p = p_0\cdot 10^{\frac{L_P}{20}}$

Addition kohärenter Schalldrücke	
• p: Pascal [Pa] • L_{ptot}: Total aller Pegel in [dB] • P_0: Hörschwelle $2\cdot10^{-5}$Pa (20µPa) bei 1 kHz • max. +6dB (2 gleichlaute Pegel)	$p_{tot} = p_1 + p_2 + p_3 + \dots$ $L_{p\ tot} = 20\log\left(\frac{p_1 + p_2 + p_3 + \dots}{p_0}\right)$

Appendix

Schalleistungspegel L_w • Einheit: [dB] • unabhängig vom Ort der Quelle bzw. des Empfängers • W_0: Referenzleistung 10^{-12} [W/m²]	$L_W = 10 \cdot \log\left(\frac{W}{W_0}\right)$ $W = W_0 \cdot 10^{\frac{L_W}{10}}$
Addition nicht kohärenter Schalldrücke • p: Pascal [Pa] • L_{ptot}: Total aller Pegel in [dB] • P_0: Hörschwelle $2 \cdot 10^{-5}$Pa (20µPa) bei 1 kHz • $L_{peinzel}$: mehrere gleichlaute nicht korrelierende Quellen in [dB] • n: Anzahl gleichlauter Systeme • max. +3dB (2 gleichlaute Pegel)	$p_{tot} = \sqrt{p_1^2 + p_2^2 + p_3^2 + \ldots}$ $L_{ptot} = 20 \cdot \log\left(\frac{\sqrt{p_1^2 + p_2^2 + p_3^2 + \ldots}}{p_0}\right)$ $L_{ptot} = 10 \log\left(10^{\frac{L_{p1}}{10}} + 10^{\frac{L_{p2}}{10}} + \ldots\right)$ $L_{peinzel} = 10 \log\left(\frac{10^{\frac{L_{ptot}}{10}}}{n}\right)$

Appendix

Punktquelle	
Punktquelle • L_2: Pegel in [dB] 2. Messort • L_1: Pegel in [dB] 1. Messort • r_2: Distanz in [m] 2. Messort • r_1: Distanz in [m] 1. Messort	$L_2 = L_1 - 20\log\left(\frac{r_2}{r_1}\right)$ $r_2 = r_1 \cdot 10^{\left(\frac{L_2 - L_1}{-20}\right)}$
Linienquelle • Einheit: [dB] • L_2: Pegel 2. Messort, • L_1: Pegel 1. Messort • r_2: Distanz 2. Messort • r_1: Distanz 1. Messort • c: Ausbreitungsgeschwindigkeit • f: Frequenz • r_c: Kritischer Abstand (Linienquelle zu Punktquelle, z.B. bei Line Arrray) • h: Höhe des Line Arrays	$L_2 = L_1 - 10\log\left(\frac{r_2}{r_1}\right)$ $r_c = \frac{h^2 \cdot f}{2 \cdot c}$

Appendix

Nachhallzeit, grosse Räume	
• Sabinesche Formel • Zeit in der nach Abschalten einer Schallquelle die Schallenergie auf den Millionsten Teil, bzw der Schalldruck um 60 dB gesunken ist • nur für grosse, schwach bedämpfte Räume • V: Raumvolumen [m³] • A: Schallabsorptionsfläche [m²] • T: Nachhallzeit [s] • K: Koefizient 0.163 $\left(\frac{m}{s}\right)^{-1}$, $\frac{s}{m}$	$T = \frac{K \cdot V}{A}$ $A = \frac{K \cdot V}{T}$ $V = \frac{A \cdot T}{K}$

Appendix

Nachhallzeit, kleine Räume	
• Für kurze Nachhallzeiten • V: Raumvolumen [m³] • A: **Gesamtoberfläche** des Raumes mit Einrichtung [m²] • T: Nachhallzeit [s] • α_m: Mittlerer Absorptionsgrad • K: Koefizient 0.163 $\left(\frac{m}{s}\right)^{-1}$, $\frac{s}{m}$	$T = 0.163 \dfrac{V}{-A \cdot \ln(1-\alpha_m)}$

Appendix

Hallradius	
• r_H: Hallradius m • A: Schallabsorptionsfläche [m^2] • V: Raumnettovolumen • T: RT_{60} Nachhallzeit in [s] • Q: Leistungsbündelungsgrad	$r_H = 0.141\sqrt{A}$ $r_H = 0.057\sqrt{\frac{V}{T}\cdot Q}$

Wrap up and Feedback