Architectural Acoustics

Human Perception

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Agenda

- 15:45 - 16:00 The auditory system - Anatomy and Physiology
  Extra-aural sound perception
- 16:00 - 16:30 Dimensions in human hearing
    - Frequency range
    - Dynamic range
    - Location
    - Temporal resolution
    - Information
    - Temporal resolution
    - Age related hearing loss
- 16:45 - 17:30
- 17:45 - 18:15 Exercise 1
- 18:15 - 18:30 Exercise 2

Sound propagation in air and other media

Speed of sound in air: c = 343 m/s (@ standard atmospheric conditions)

Wave propagation velocity in water 1500 m/s.

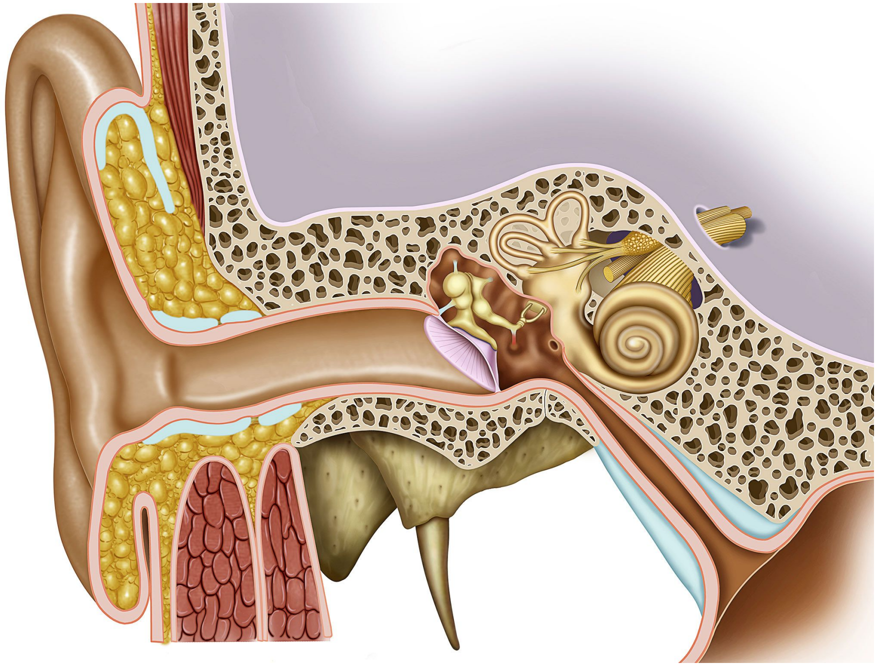
Wave propagation velocity in steel 5790 - 5940 m/s

Wave speed vs particle speed. (Exercise done outdoors: Circle, diameter, touch neighbour, stop time vs. Runner.)

Wave propagation in traffic jams (waves move backwards):
Phantom Traffic Jams

Wave propagation and particle propagation:
Sound Propagation - Animation | Auditory Neuroscience

Anatomy and physiology - outer and middle ear

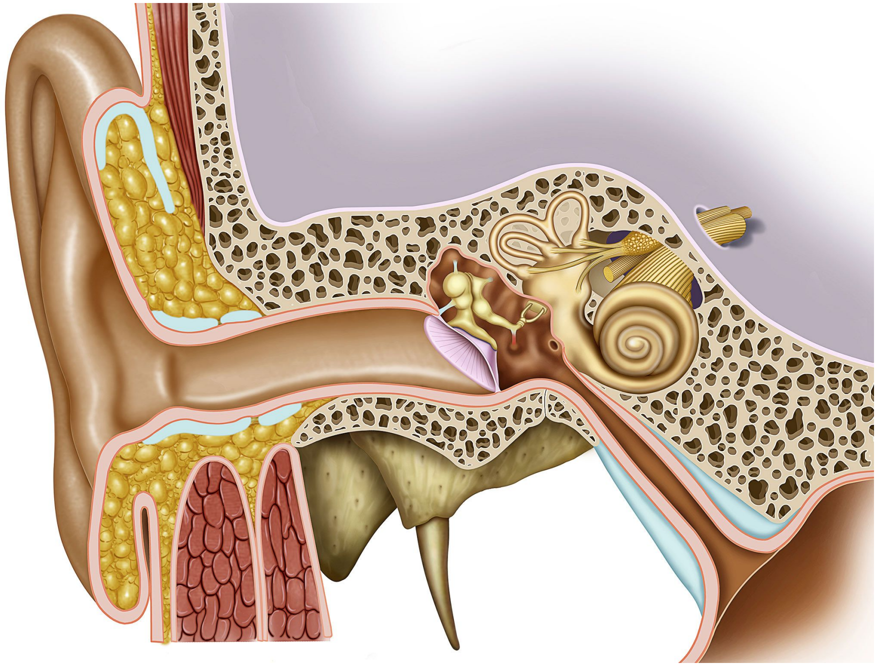


Main parts of the ear:

Sound waves pass through the auricle and the ear canal to reach the eardrum, causing it to vibrate (**outer ear**). This membrane vibration is transmitted through a lever system (in the air filled **middle ear**) to fluid-filled the **inner ear**.

The lever system of the auditory ossicles (hammer-anvil-stirrup system) does not have an absolute defined pivot point but is fixed by bands with a certain elasticity. Over time, deposits (otosclerosis) accumulate on the auditory ossicles in many people, increasing the mass and reducing the system's mobility. This leads to decreased hearing ability, especially at high frequencies.

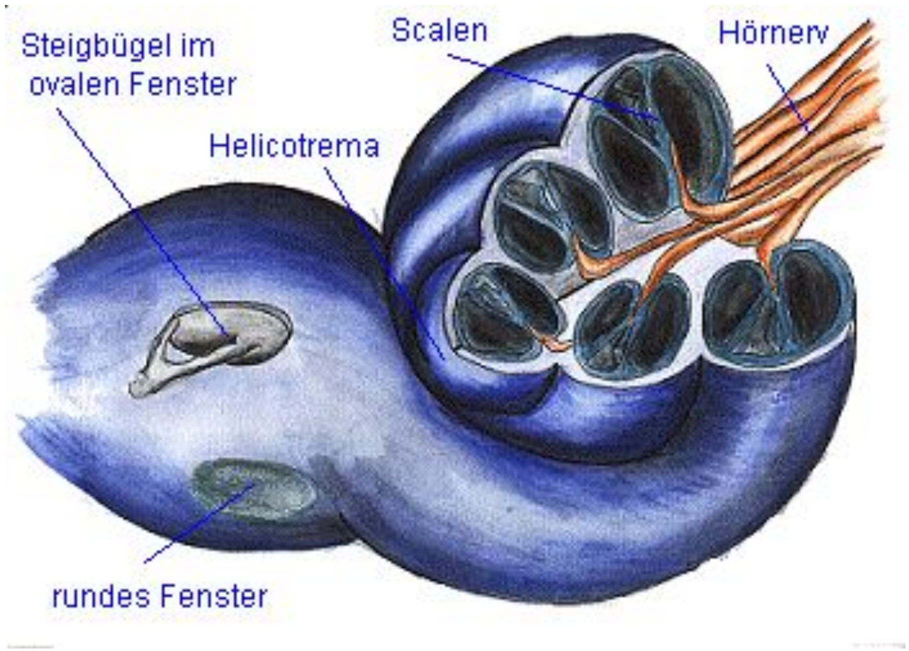
Anatomy and physiology - outer and middle ear



The transmission properties of the hammer-anvil-stirrup system can be altered by adjusting the tension of the suspension system by the middle ear muscles and can protect the hearing from overload. They contract reflexively at high sound intensities, reducing hearing sensitivity by up to 30 dB.

However, this reflex has a certain response time and may fail as protection if the intensity increase is very rapid, as is the case with sudden loud noises. (Traumas from explosions.)

Anatomy and physiology - outer and middle ear

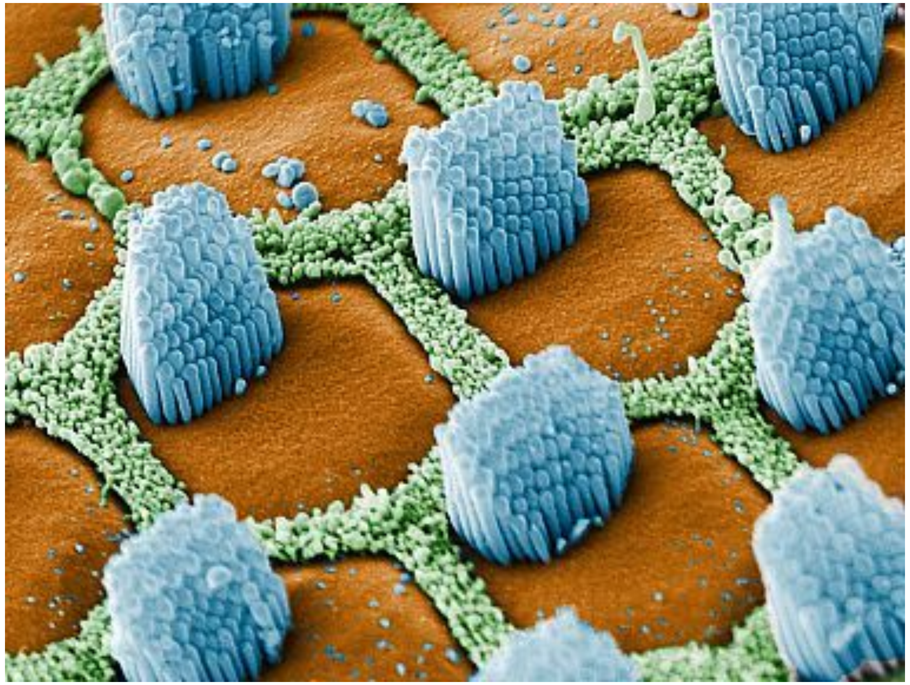


In the inner ear, the sound vibration, now as fluid sound, travels through the **cochlea**. This cavity in the bone material has the shape of a snail's shell with a largest diameter of approximately 7 mm and harbours the **basiliar membrane with the sensitive nerve cells**.

The higher the sound intensity, the more impulses are generated per unit of time on a nerve fiber. However, tone pitch perception is different. The traveling waves in the fluid have their maximum amplitude at a distance from the oval window that increases with wavelength. Each location on the basilar membrane prefers a specific range of frequencies. This means that pitch information is spatially separated onto separate nerve pathways.

https://auditoryneuroscience.com/index.php/ear/bm4_tocata_fugue

Anatomy and physiology - outer and middle ear



Strong sound intensities increase the oxygen demand in the hair cells. If the exposure lasts too long, insufficient oxygen can be supplied, resulting in damage or death of individual cells. This can lead to zones of reduced sensitivity on the basilar membrane, resulting in frequency-selective hearing impairment (acoustic trauma, noise-induced hearing loss).

A similar process occurs as a part of aging and can lead to deafness. This type of hearing impairment cannot be surgically improved. However, it is now possible to directly stimulate the auditory nerve with implanted microelectronic devices, restoring rudimentary hearing (cochlear implant).

Dimensions of the human auditory 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.

Amplitude dimension, static properties

- The **dB scale** is used to measure the (physical) loudness of a certain sound by determining the sound pressure level.
- The **Phon scale** is used to measure the perceived loudness of a particular sound.

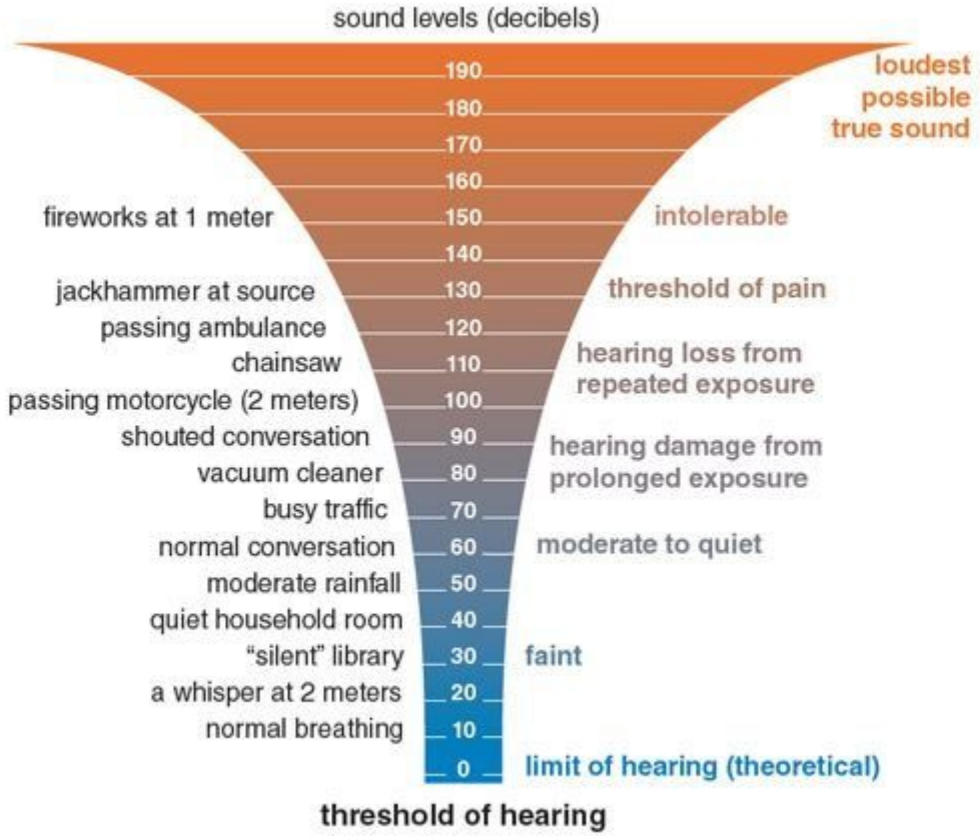


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Table of sound levels L and corresponding sound pressure and sound intensity

Examples	Sound Pressure Level L_p dBSPL	Sound Pressure p $N/m^2 = Pa$	Sound Intensity I W/m^2
Jet aircraft, 50 m away	140	200	100
Threshold of pain	130	63.2	10
Threshold of discomfort	120	20	1
Chainsaw, 1m distance	110	6.3	0.1
Disco, 1 m from speaker	100	2	0.01
Diesel truck, 10 m away	90	0.63	0.001
Kerbside of busy road, 5 m	80	0.2	0.0001
Vacuum cleaner, distance 1 m	70	0.063	0.00001
Conversational speech, 1m	60	0.02	0.000001
Average home	50	0.0063	0.0000001
Quiet library	40	0.002	0.00000001
Quiet bedroom at night	30	0.00063	0.000000001
Background in TV studio	20	0.0002	0.0000000001
Rustling leaf	10	0.000063	0.00000000001
Threshold of hearing	0	0.00002	0.000000000001

Amplitude dimension, dynamic changes

Perception of loudness changes

[dB: What is a decibel?]

Change in loudness	Perception
0 … 1 dB	Not audible
2 .. 4 dB	Barely audible
5 … 10 dB	Clearly audible
> 10 dB	Convincing change

Wake-up threshold by emergent sounds

The necessary level increase to wake a person from sleep varies but typically requires a sound level about **10 to 15 dB louder than the background noise**. Emergence is the ability of a sound to stand out from background noise and be noticed, which is crucial for waking someone up. A sharp onset of the sound is required.

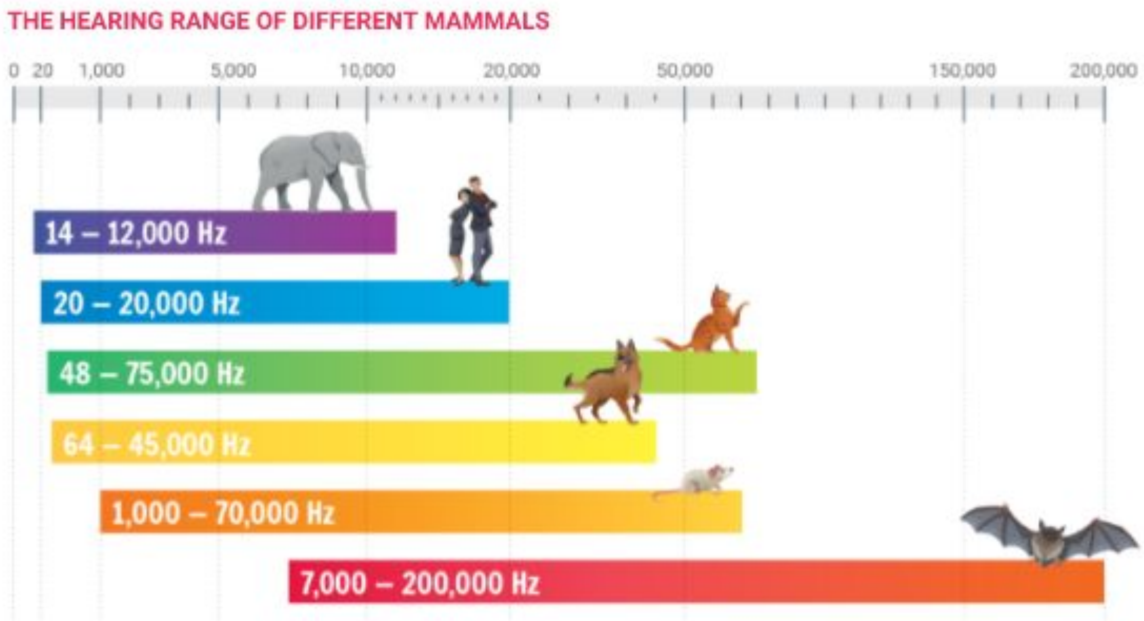
Spectral dimension

Different species hear different frequency ranges.

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

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

This is where the Fletcher Munson curves (equal loudness curves) come into play.



Experiment: Demo with gliding tone.

https://www.animations.physics.unsw.edu.au/jw/sound-pitch-loudness-timbre.htm

Spectral and amplitude dimensions

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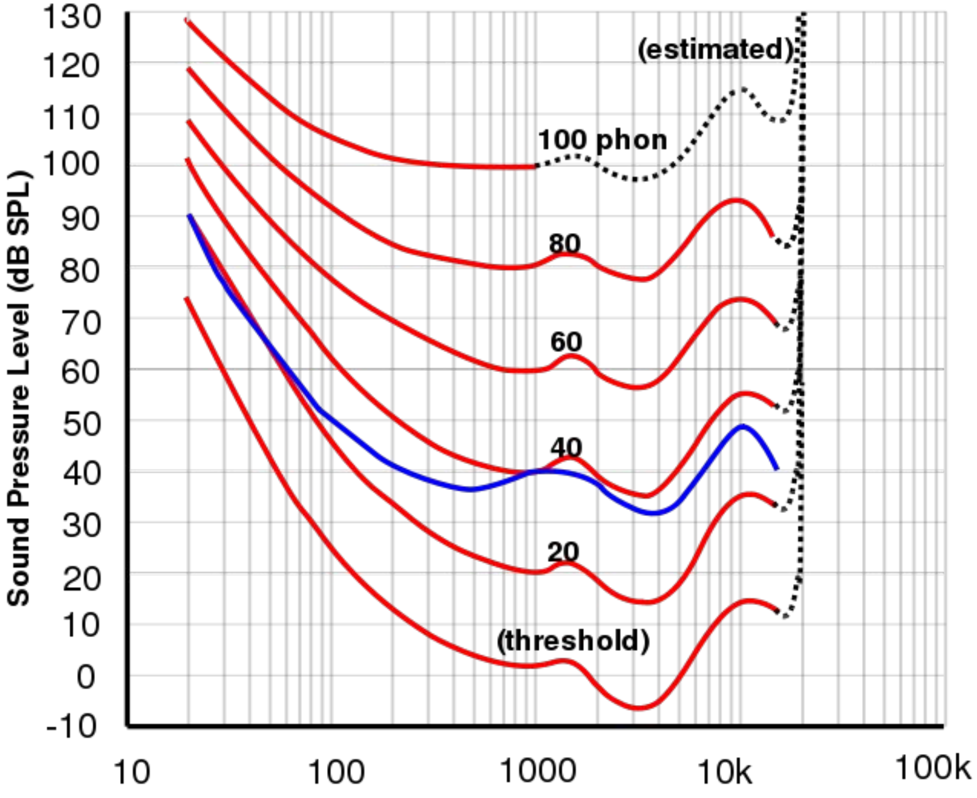

Equal-loudness contours (red) (from ISO 226:2003 revision)
Original ISO standard shown (blue) for 40-phons

Experiment: Demo with gliding tone / audacity.

Demo: A visualization with a real time spectrum and a spectrogram is shown.

Spectral and amplitude dimensions

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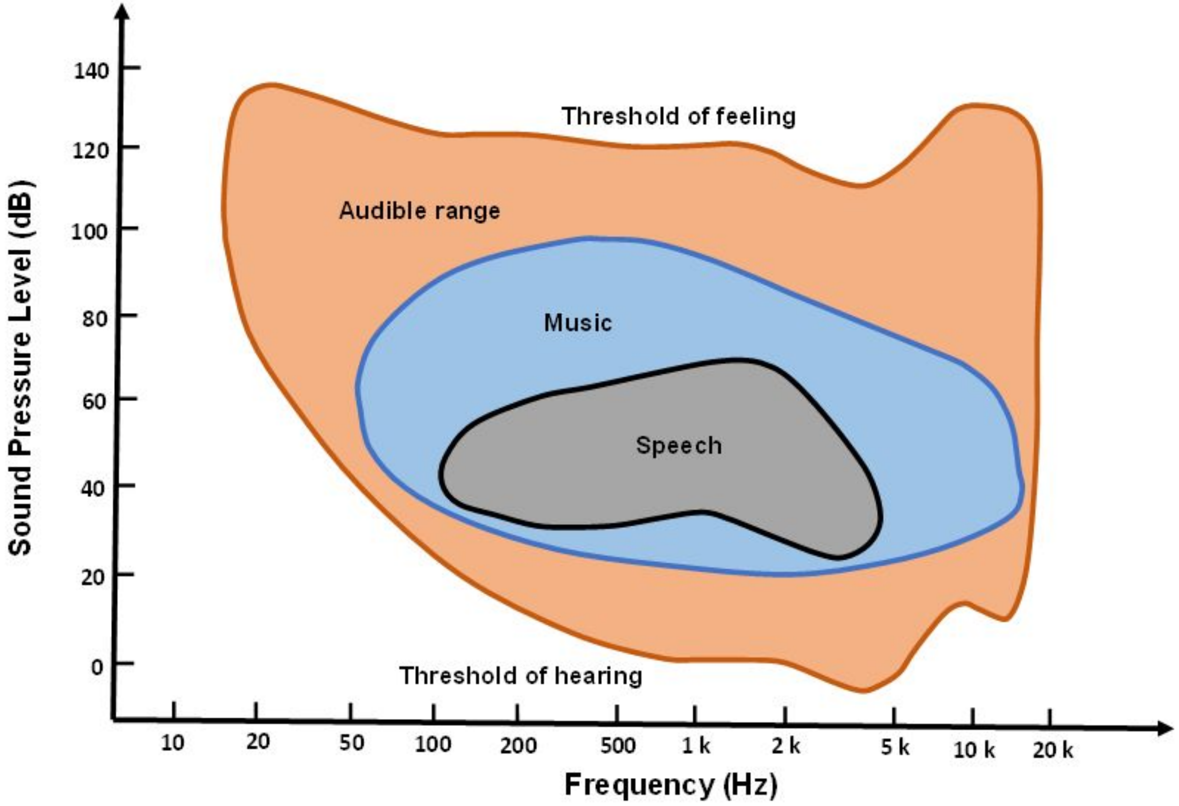


Experiment:	Demo with gliding tone / audacity.
Demo:	A visualization with a real time spectrum and a spectrogram is shown.

Temporal dimension and resolution

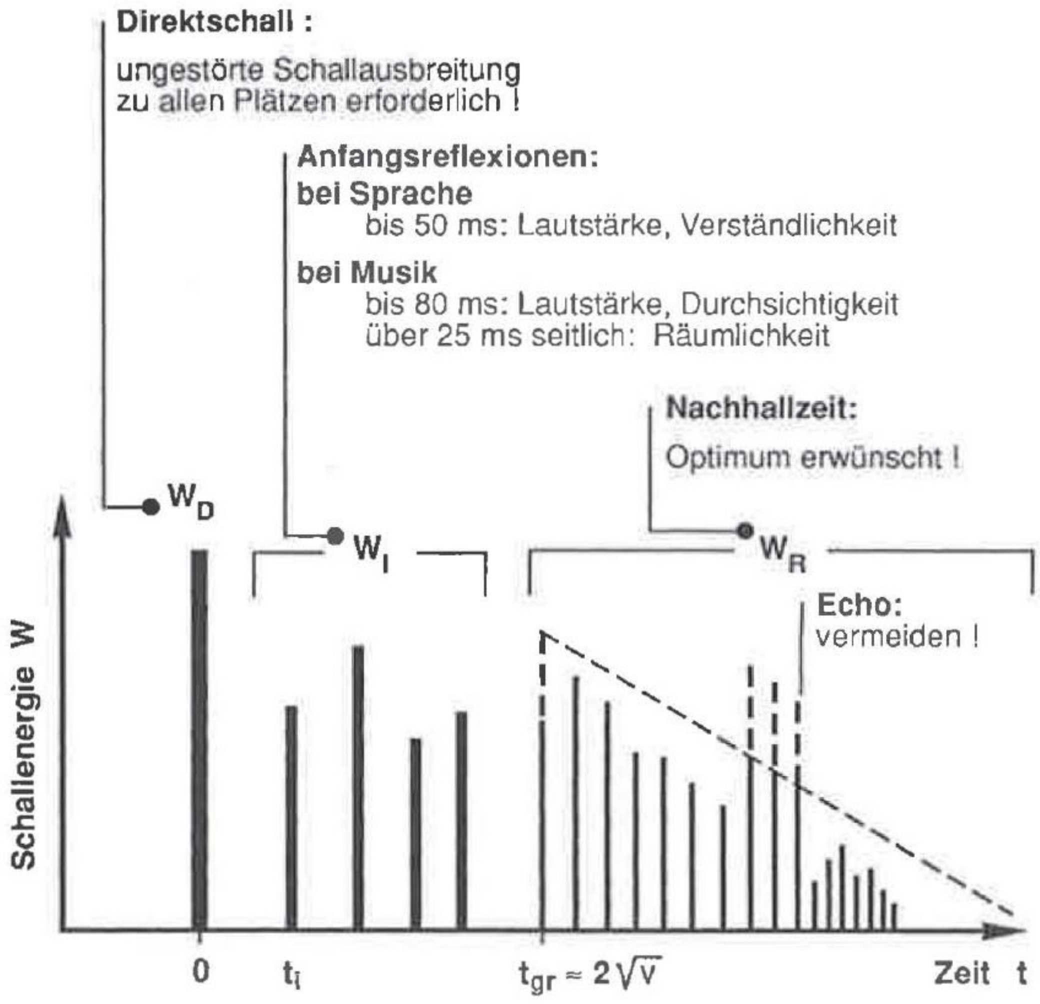
Experiment: Play a mono(-phonic) signal over two loudspeakers and locate it.

- Precedence effect and sum localization
- Haas effect and sum localization
- Echo audibility with clicks and spoken word.
    - Early reflections
    - Late reflections
    - Reverb

Temporal resolution and speech intelligibility / music quality

Experiment: Play a mono(-phonic) signal over two loudspeakers and locate it.

- The echo audibility has a very big effect on room acoustic design.
  Some reflections are wanted, some are not!



Temporal resolution and speech intelligibility

The precedence effect, for spoken word also known as the Haas effect, is a psychoacoustic phenomenon where the human auditory system prioritizes the perception of the first-arriving sound (the "direct sound") over later-arriving reflections (the "preceding echoes"), especially when they arrive within a certain time window, allowing listeners to perceive sound as coming from its initial location.

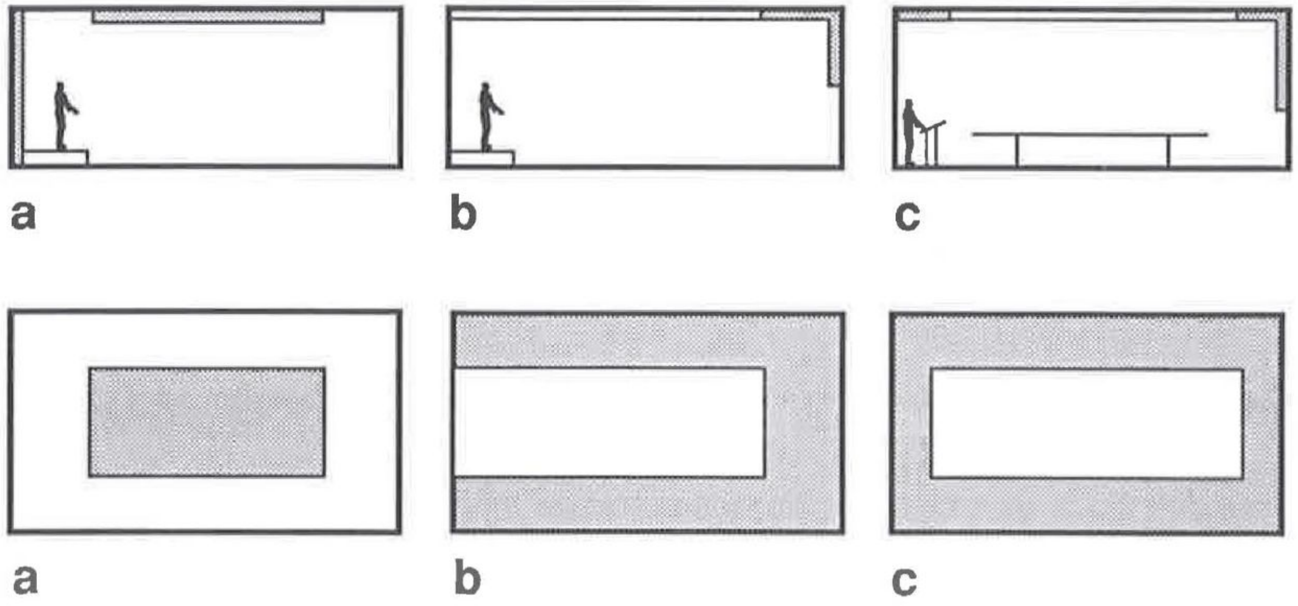


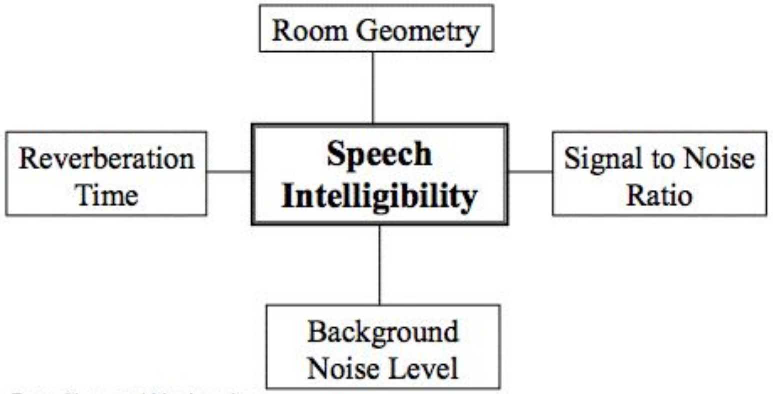
Bild 4.83 Unzweckmäßige und zweckmäßige Verteilung von breitbandigen Schallabsorbern [630]
oben: Längsschnitt; unten: Deckenansicht
a) unzweckmäßig: nützliche Reflexionsflächen werden unwirksam gemacht
b) c) zweckmäßig: nützliche Reflexionsflächen bleiben erhalten

Temporal resolution and speech intelligibility

Experiment: Play a mono(-phonic) signal over two loudspeakers and locate it.

- The echo audibility has a very big effect on room acoustic design.
  Some reflections are wanted, some are not!

Assessment model of class-room acoustics criteria for enhancing speech intelligibility and learning quality



From Airey and Mackenzie

Text analogy

The following is a list of Farmer's markets to be held in the surrounding areas

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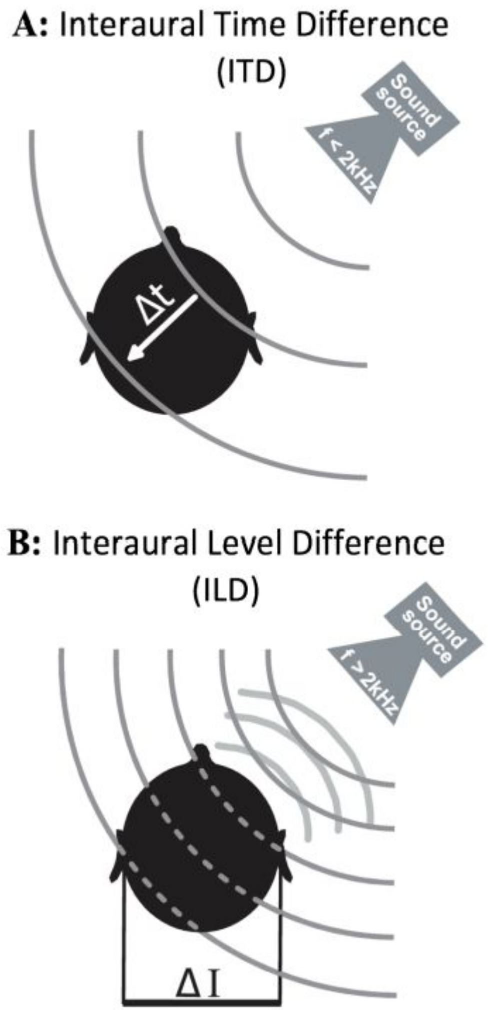
Spatial dimension, binaural localization

Binaural Hearing: Humans have two ears located on opposite sides of the head, which allows for binaural hearing. Each ear receives a slightly different version of a sound event in terms of timing and intensity. The brain processes these differences to determine the azimuth of the sound source.

Interaural Time Difference (ITD): ITD is the difference in the time it takes for a sound to reach each ear. When a sound source is located to one side of the listener, it arrives at the closer ear slightly earlier than the farther ear. The brain processes this time delay to determine the azimuth of the source.

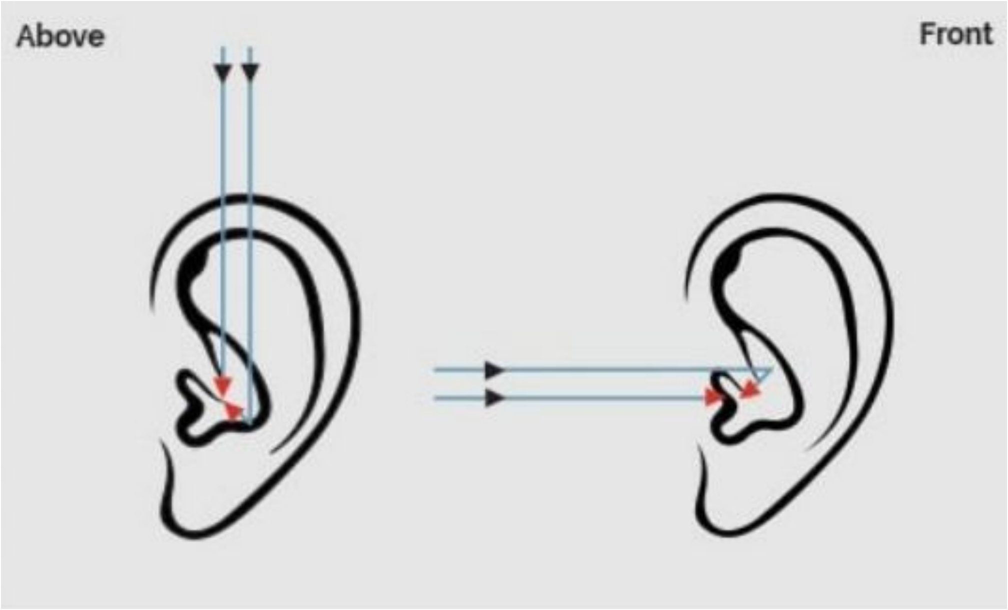
Interaural Level Difference (ILD): ILD refers to the difference in sound intensity or volume between the two ears. When a sound source is off-center, the closer ear receives a slightly louder sound than the farther ear. The brain uses this intensity difference to help determine the azimuth of the source.

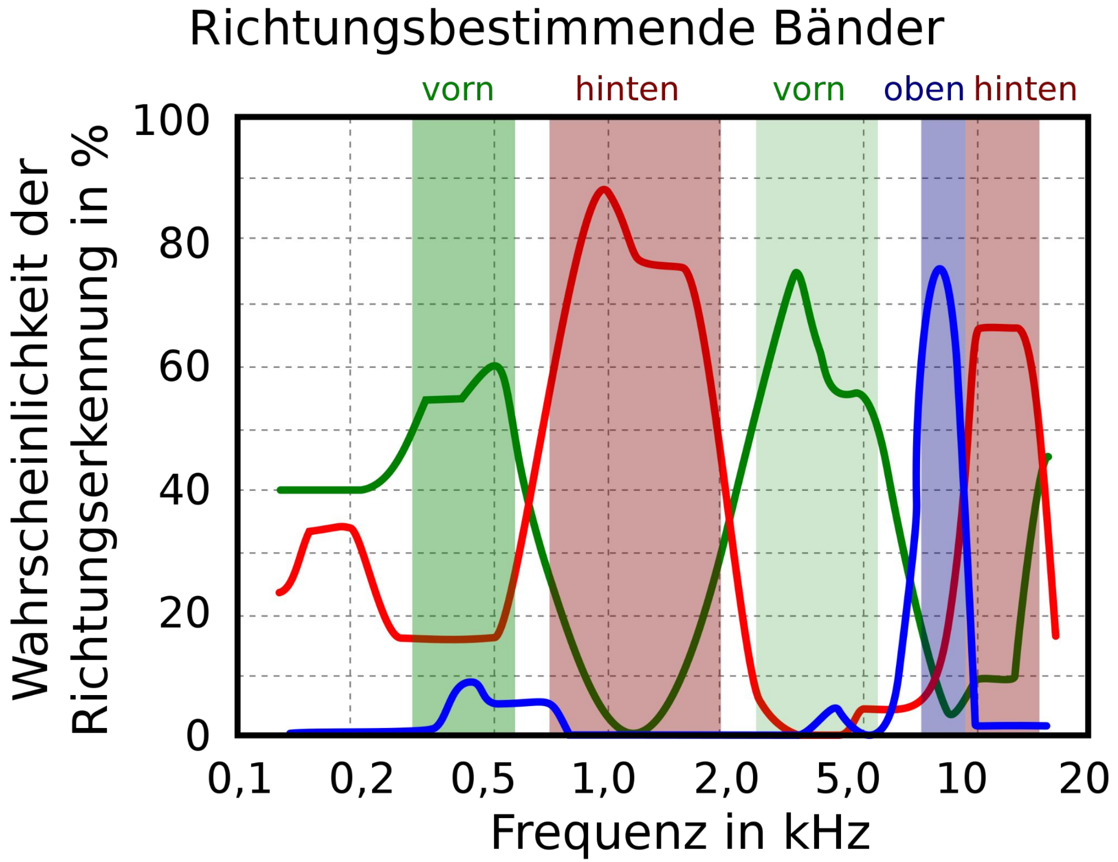
https://auditoryneuroscience.com/index.php/spatial-hearing/time-intensity-trading



Spatial dimension, binaural localization

Spatial localization in the saggital plane (front-to-back dimension) primarily relies on spectral cues related to **head-related transfer functions (HRTFs)**. These spectral cues help us perceive whether a sound source is in front, above of or behind us.





Informational dimension

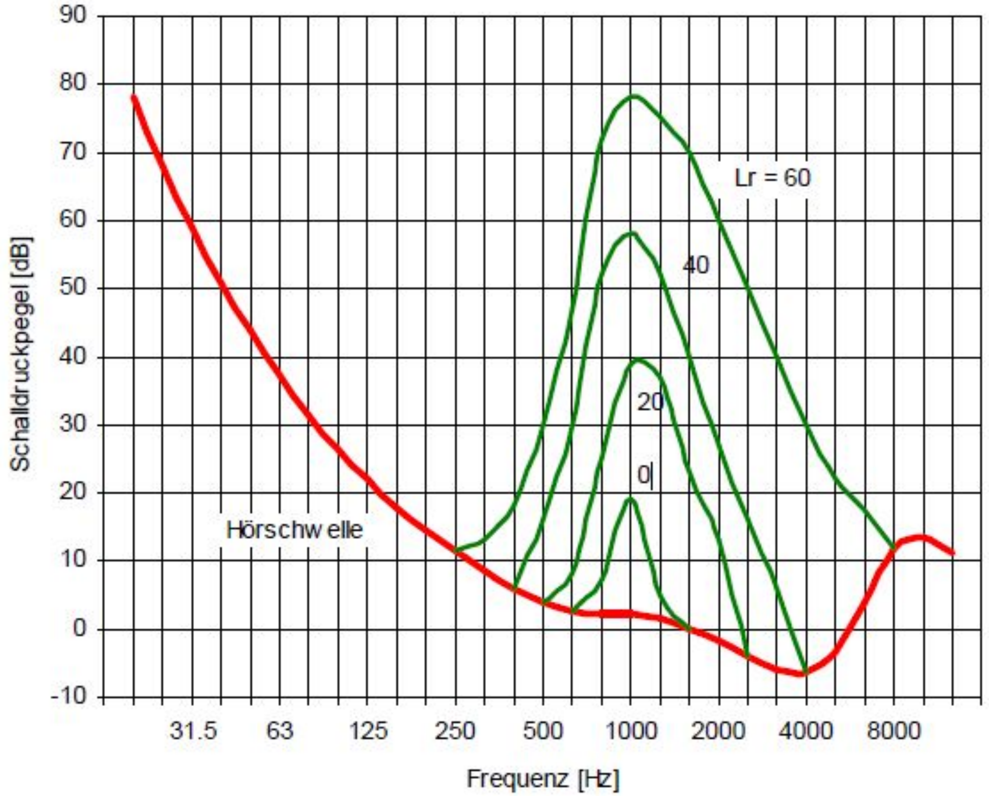
A couple of numerical psychoacoustic measurement units exist: Loudness, sharpness, roughness, fluctuation length. These can be calculated from audio signal measurements (recordings).

A quick and statistically not representative survey:

- What songs (or music genres...) interfere with your concentration when you are learning/reading/writing?
- What songs (or music genres...) interfere with your concentration when you are doing sports?
- For both use cases: Are these the same songs?

Psychoacoustics: Noise masking effect

The psychoacoustic noise masking effect is the principle of using background sounds or white noise to reduce the perception of distracting noises in modern offices, enhancing focus and productivity by masking unwanted sounds with more tolerable ones.



Demonstration: What can you hear?

https://auditoryneuroscience.com/scene-analysis/continuity-illusion

https://auditoryneuroscience.com/scene_analysis/masking_tone_noise

Further readings and ressources

- Adelman-Larsen, Niels Werner. *Rock and Pop Venues, Acoustic and Architectural Design.* 2nd ed., Springer Verlag Berin Heidelberg, 2021. (ISBN 978-3-030-62319-7)
  Chapter 2 provides inputs about the terms, language and concepts of Auditorium Acoustics.
- Fasold, Wolfgang; Veres, Eva. *Schallschutz und Raumakustik in der Praxis*. 2nd ed., Huss-Medien, 2003. (ISBN: 3345008017)
  A must have, although no longer in stock.
- https://auditoryneuroscience.com/index.php/
  Contains a lot of interesting demos to play with.
- https://www.animations.physics.unsw.edu.au/jw/sound-pitch-loudness-timbre.htm
- https://en.wikipedia.org/wiki/Head-related_transfer_function

Wrap up and Feedback