Sound Localization

Binaural hearing, HRTF, and spatial perception

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[Course info]

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SOUND LOCALIZATION

Spatial Hearing in Audio Practice

Spatial hearing informs how we capture, shape, and evaluate sound scenes:

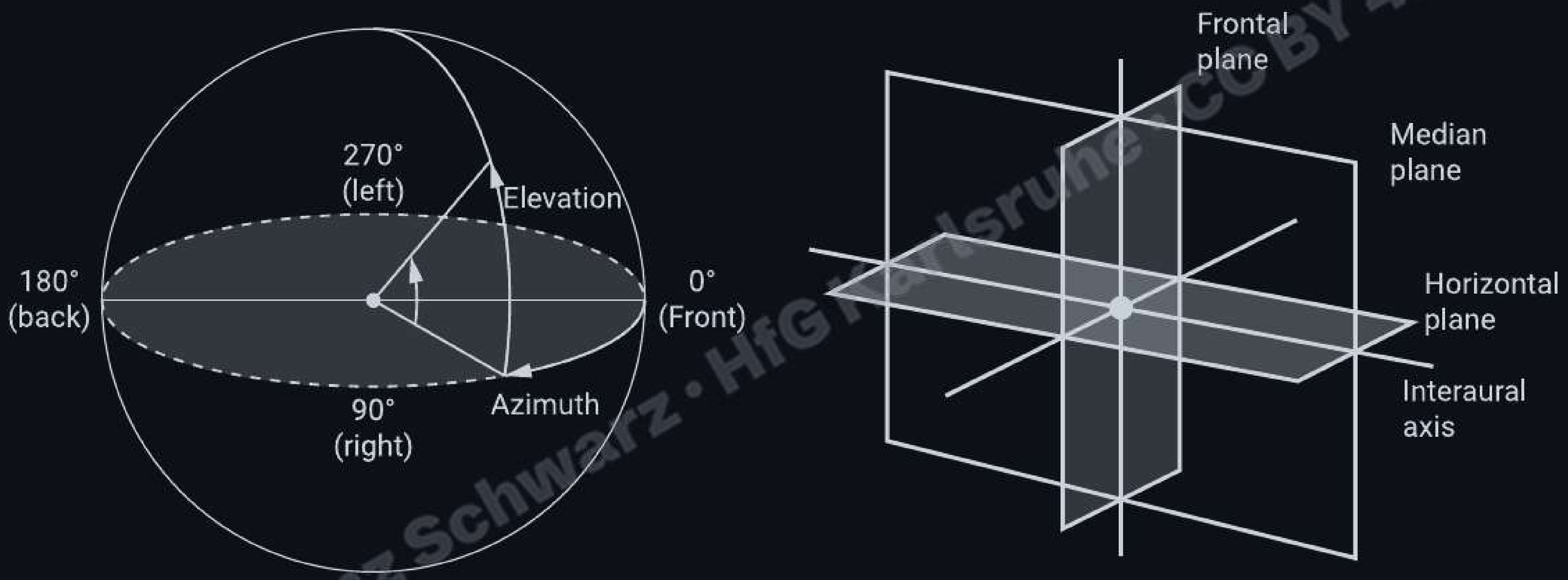
- Microphone technique and stereo array selection (localization cues, stereo width)
- Panning, depth, and spatial processing (level/time differences, reverberation cues)
- Immersive and binaural production workflows
- Assessment of monitoring and room acoustics (imaging, translation)

BINAURAL HEARING

Spatial references in binaural hearing

- Azimuth (horizontal angle)
- Elevation (vertical angle)
- Distance

Anatomical reference planes: frontal (front/back), horizontal (upper/lower), median (left/right)



Horizontal coordinate system (left) and anatomical planes (right)

Lateralization and localization

- Lateralization: Perceived left-right position of a sound presented over headphones, typically experienced inside the head.

▶ Lateralization (listen via headphones)

- Localization: Perception of a sound source at a specific position in external space, as with loudspeakers or real sound sources.

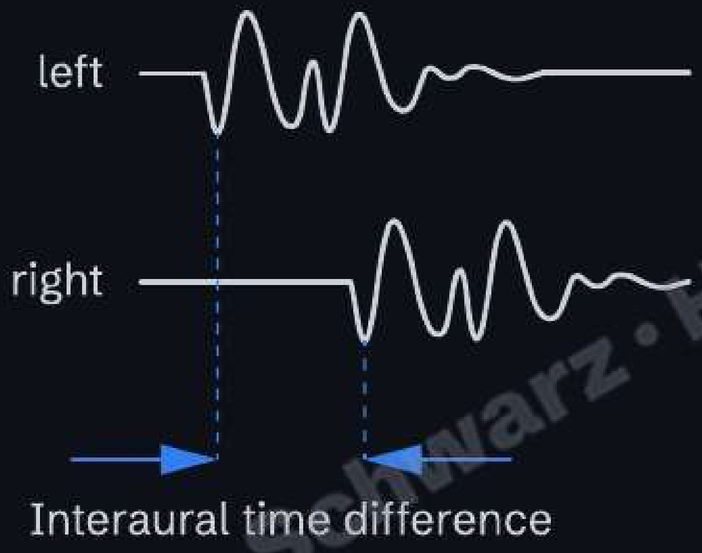
▶ Localization (listen via headphones)

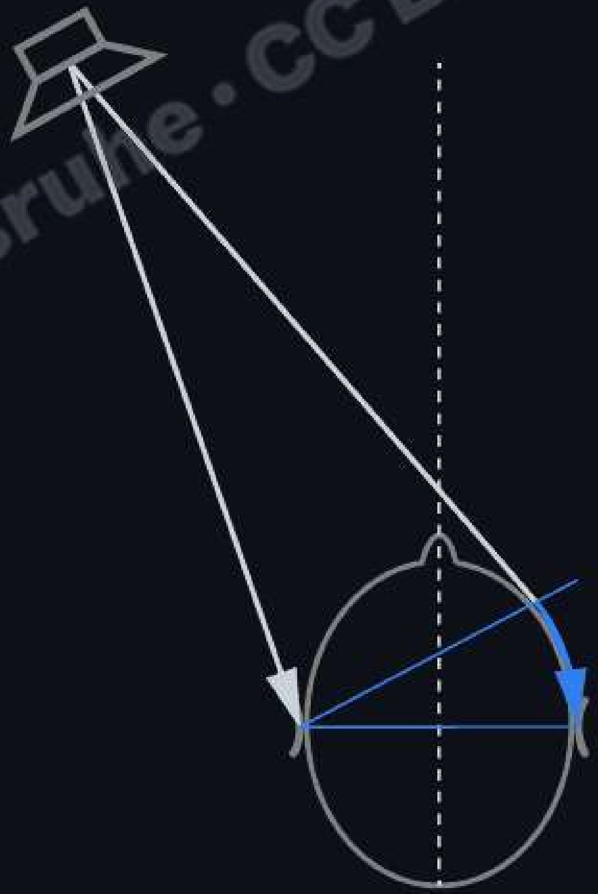
Binaural hearing and source localization

The first theory of lateral sound localization was proposed by Lord Rayleigh as "duplex theory." Later extended with Blauert's spectral cues.

- **Interaural Time Difference (ITD):**
  - Difference in arrival time between ears. Effective for low frequencies (<1500 Hz) because long wavelengths maintain phase coherence between ears.
- **Interaural Level Difference (ILD):**
  - Difference in sound intensity between ears. Effective for high frequencies (>1500 Hz) due to head shadow effect (short wavelengths are blocked by the head).
- **Spectral Cues:**
  - Additional information from how the head and pinnae filter sound (HRTF).

Interaural time difference (ITD)





Interaural time difference (ITD)

ITD helps localize low-frequency sounds.

For an ear distance of $\lambda \approx 22$ cm, the natural interaural time delay is approximately $\approx 660\mu s$

$$f = \frac{c}{\lambda} = \frac{343\frac{m}{s}}{0.22m} \approx 1500Hz$$

- Phase delays at low frequencies (if wavelength is greater than half the distance between the ears $< 800Hz$)

▶ ITD noise bursts (listen via headphones)

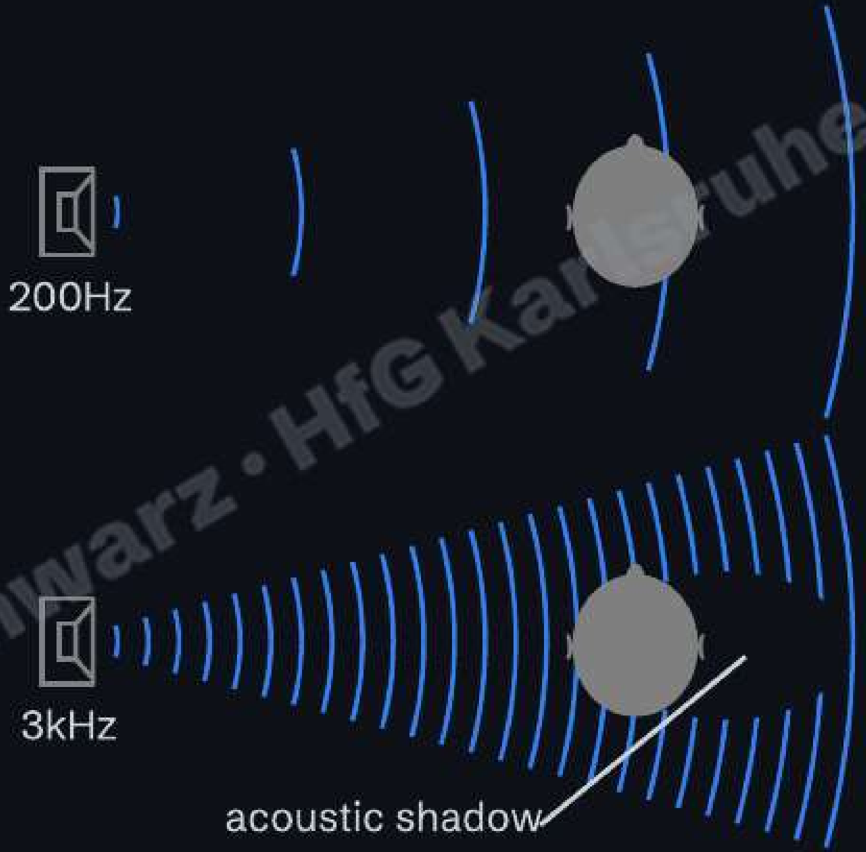
Interaural level difference (ILD)

Interaural Level Difference (ILD), also known as Interaural Intensity Difference (IID), plays a key role in the localization of high-frequency sounds.

- Low frequencies bend around the head with minimal attenuation
- High frequencies are significantly attenuated due to the head shadow effect
- Level differences increase above ~1600 Hz

▶ ILD noise bursts (listen via headphones)

Interaural level difference (ILD)



ITD and ILD

Localization accuracy:

- 1° for sources in front
- 15° for sources to the sides

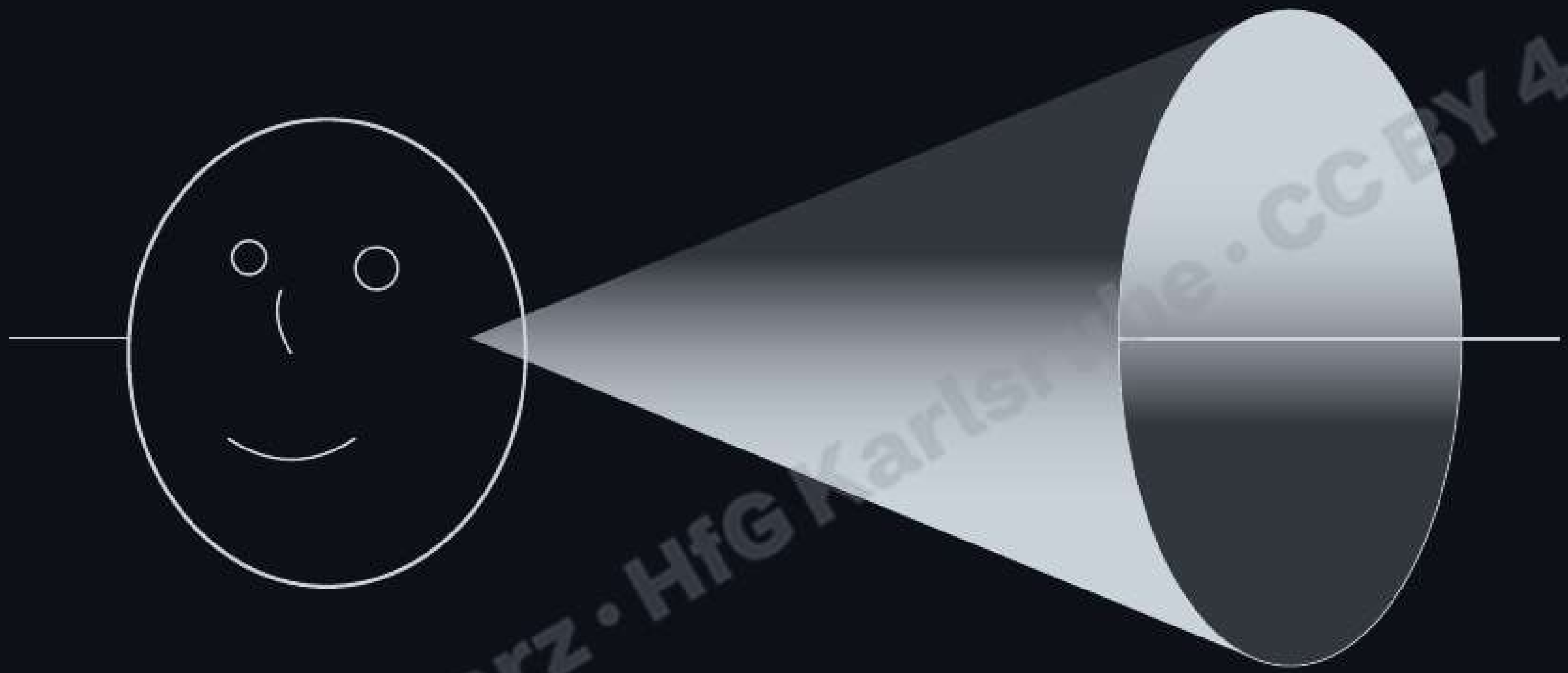
Frequency ranges:

- ITD dominant for $f < 800$ Hz
- Both contribute between 1000-1500 Hz
- ILD dominant for $f > 1600$ Hz
- No localization below 80 Hz

White noise at -90° azimuth: maximum ITD of 0.63 ms

Cone of confusion

- **Front-back ambiguity:** Cannot discriminate between sounds originating from the front or rear.
- **No elevation cues:** ITD and ILD do not provide information about vertical localization (elevation).



A region in space where sound sources produce identical ITDs and ILDs, making localization ambiguous.

Resolving ambiguity

- **Tilting the head:** Introduces new timing and level information to help resolve the location of the sound source.
- **Spectral cues:** The filtering effects of the pinnae and torso shape the sound spectrum, helping to distinguish elevation and front-back positioning.

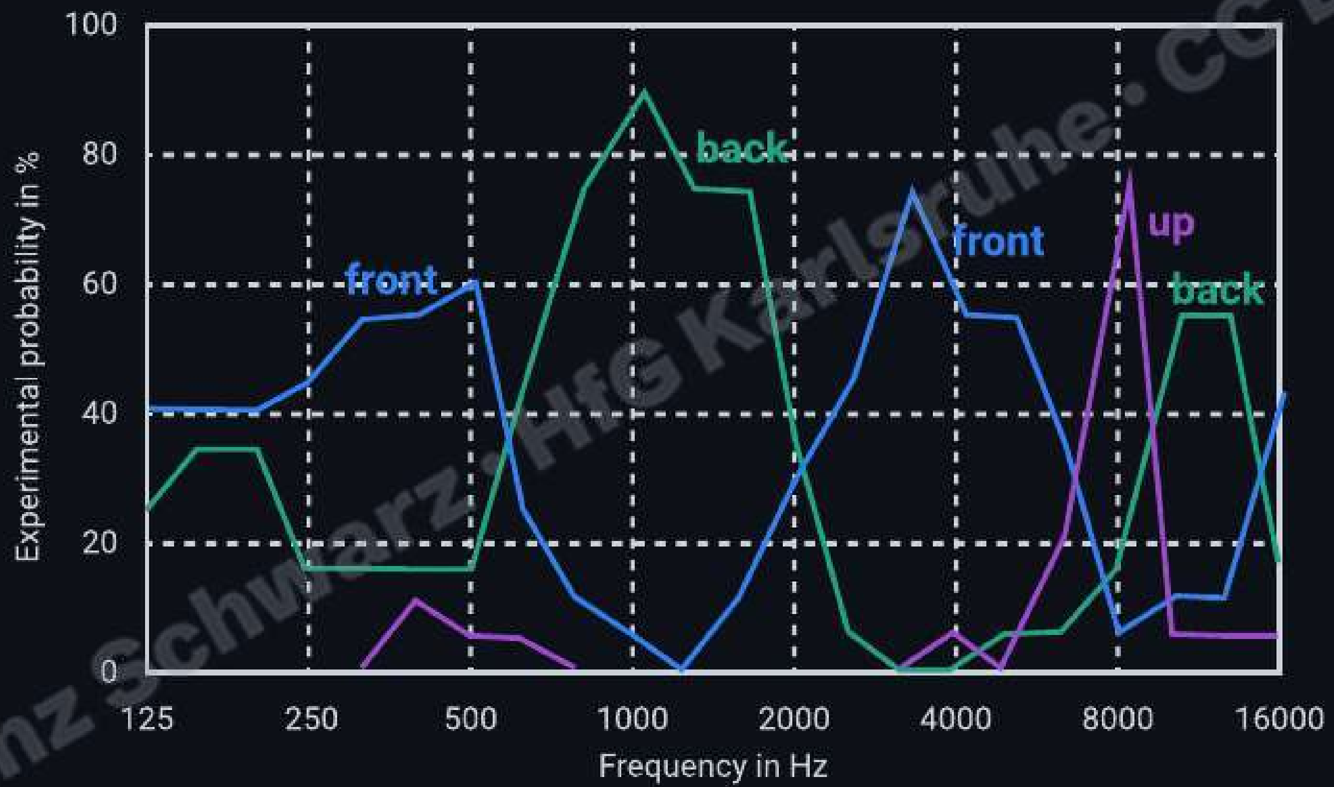
SPECTRAL CUES

Spectral cues

The outer ear, auricle (pinna), and ear canal act as a resonator system, shaping sound based on its direction of incidence.

- Frequency-dependent filtering provides spatial information, aiding in sound localization.
- Encodes vertical and front-back localization cues (median plane), primarily through frequency bands affected by the pinna.

Directional bands (after J. Blauert)



▶ Pink noise back and front ear level and above (listen via headphones)

Head related transfer function (HRTF)

HRTF describes how spatial audio cues are encoded in the sound reaching the ears, allowing for sound source localization.

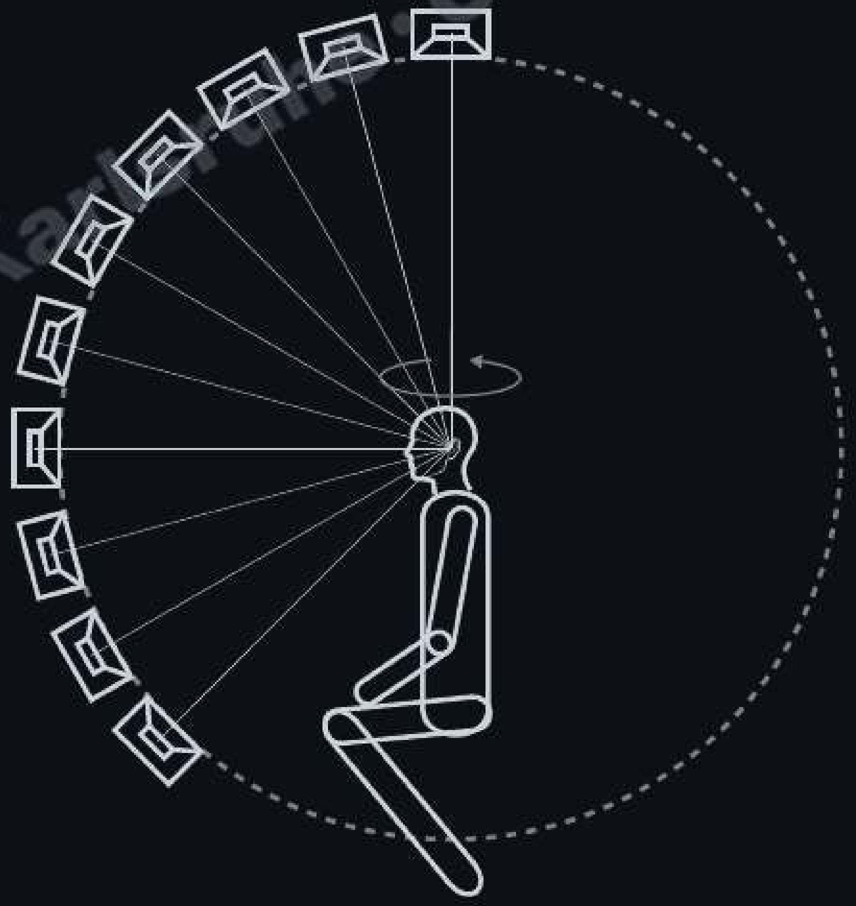
The torso, head, and pinna act as direction-dependent filters, introducing frequency-specific alterations to the sound.

→ *This effect can be mathematically represented as a transfer function.*

▶ Clicks rotating 360° up - down (listen via headphones)

HRTF measurement

HRTFs are measured at small angular increments in an anechoic chamber, with interpolation used to estimate unmeasured positions.



Applications of HRTF

- 3D audio rendering
- VR & AR
- Binaural recording

→ *The auditory system adapts to a modified head-related transfer function over time.*

Franssen effect

The Franssen effect demonstrates how the auditory system localizes sound based on attack transients rather than sustained energy.

A tone begins in one speaker with a sharp onset, then continues from the opposite speaker. Despite the energy source switching sides, the perceived location remains anchored to the initial onset.

Note: This demonstration requires stereo speakers with sufficient separation. It will not work with headphones.

▶ Play Franssen effect

Franssen effect

Auditory distance perception

The auditory system has limited ability to determine distance, relying on:

- **Initial Time Delay Gap (ITDG):** Time between direct sound and first reflection
- **Direct-to-reverberant ratio:** Closer sources have more direct sound
- **Reverberation density:** More diffuse reflections indicate greater distance
- **High-frequency absorption:** Distant sounds lose high-frequency content
- **Loudness:** Closer sources perceived as louder
- **Motion parallax:** Closer sources shift position faster for moving listeners

▶ Distance close - far

STEREOPHONIC REPRODUCTION

Stereophonic Sound

When two channels are played through separate speakers, listeners perceive a soundstage extending between those speakers.

- **Summing localization:** Brain combines signals from both speakers to create phantom sound sources
- **Phantom center:** Virtual sound source perceived between the speakers

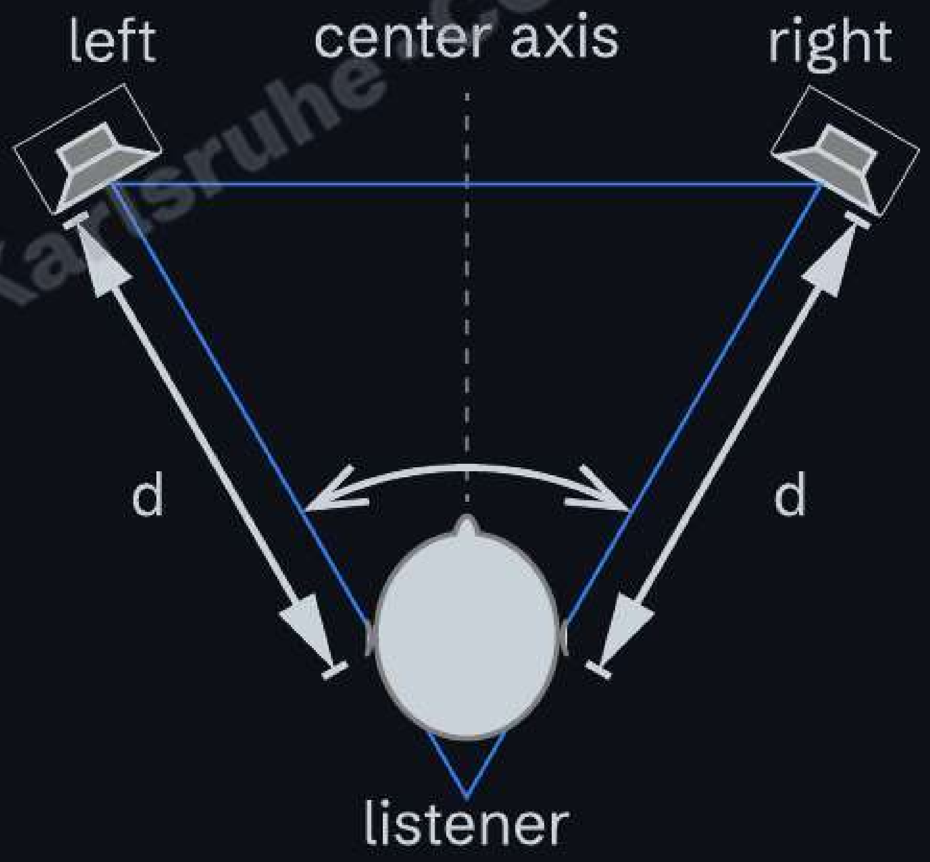
Creates an illusion of multi-directional spatial perspective.

Artificial stereo and phantom center

The recommended placement forms an equilateral triangle: each speaker and the listener at equal distances:

- Sweet spot or reference listening position

▶ Panning from left to right



Dual-mono signal

Mono source material played back through two stereo channels with identical signals on both the left and right channels.

- Identical waveform in both L and R channels
- Creates phantom center image when played through speakers
- Perceived as center image in headphones (lateralization)
- Common in broadcast, mono recordings, and centered mix elements

Summing localization

Two speakers create a phantom sound source between them by manipulating the same binaural cues the brain uses for natural localization:

- **Amplitude panning** (ILD)
- **Time delay** (ITD)

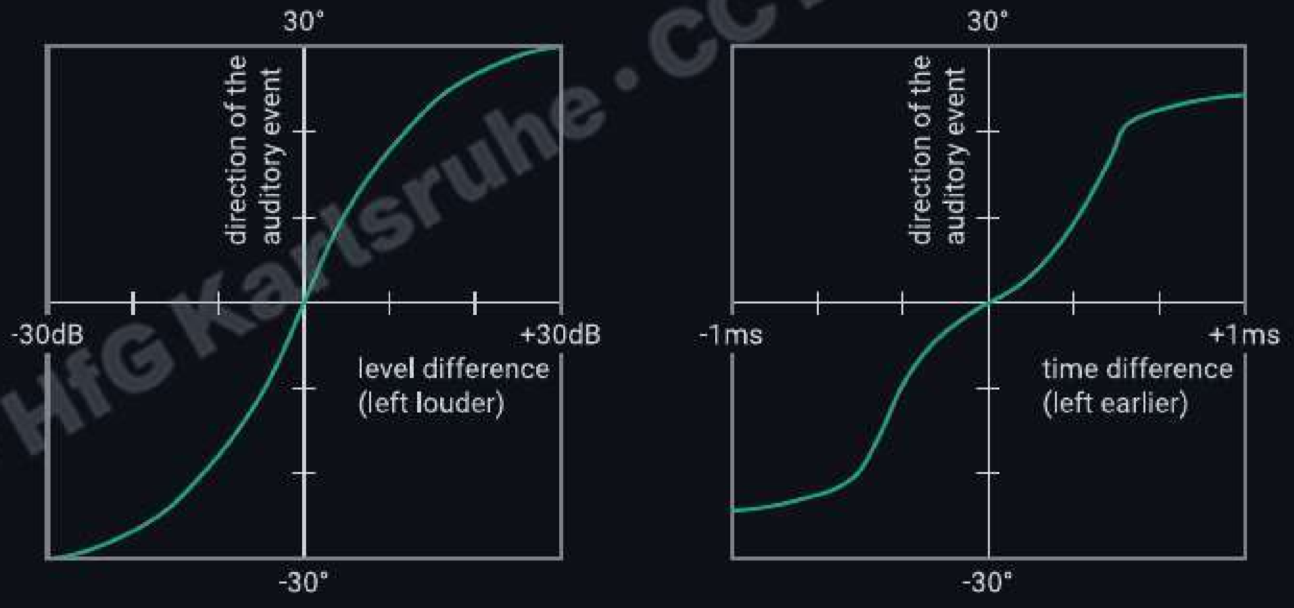


Diagram: perceived source location (Wendt, 1963)

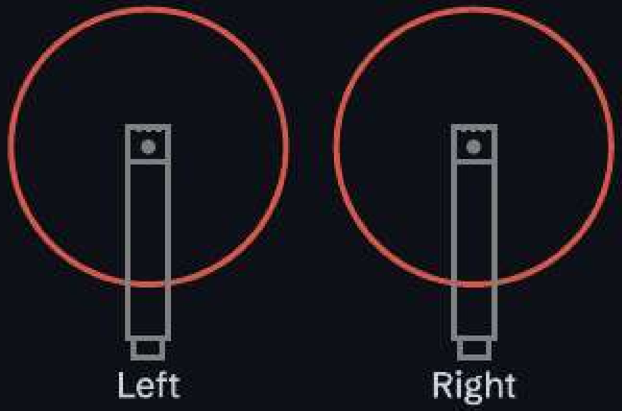
Stereo recording

ITD and ILD are used in common stereo recording practices:

Stereo recording techniques:

- Coincident pair (X-Y): Accurate localization
- Spaced pair (A-B): Wide stereo image

XY: level differences



A-B: time-of-arrival stereo

Summary: sound localization

- ITD (time differences) for low frequencies
- ILD (level differences) for high frequencies

Ambiguity (Cone of confusion) resolved through head movement and spectral cues (HRTF) for elevation and front-back.

Applications:

- Stereo reproduction relies on phantom imaging
- HRTF measurements enable binaural 3D audio

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