Carl von Ossietzky Universität Oldenburg

# Applied Psychophysics I
# Applications in audio quality

## Spatial hearing sensations

Stephan Töpken, 27.11.2024

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# Applied Psychophysics I – Lecture schedule

| Week | Date | Topic |
|---|---|---|
| 1 | 16.10.24 | Introduction |
| 2 | 23.10.24 | Auditory physiology and selected auditory models |
| 3 | 30.10.24 | Suprathreshold scaling methods |
| 4 | 06.11.24 | Loudness perception, loudness models and audio metering |
| 5 | 13.11.24 | Selected sensations, sound attributes and measurement of timbre |
| 6 | 20.11.24 | Chocolate results Presentation topics |
| 7 | 27.11.24 | Spatial hearing sensations |
| 8 | 04.12.24 | Audio quality assessment methods and model approaches |
| 9 | 11.12.24 | Calibration of listening setups |
| 10 | 18.12.24 | Ethics and data protection |
| | | Winter break |
| 11 | 08.01.25 | Student presentations |
| 12 | 15.01.25 | Student presentations |
| 13 | 22.01.25 | Student presentations |
| 14 | 29.01.25 | Student presentations |

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# Spatial hearing sensations

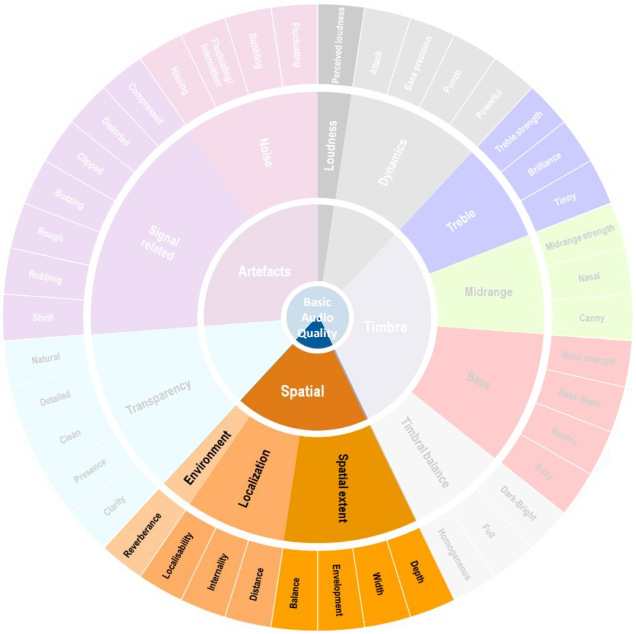
– Basic Definitions

– Binaural cues

– Sensitivity to binaural cues

– Localization

– Selected spatial sensations in closed rooms



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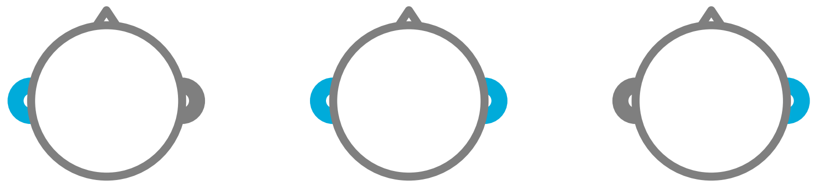
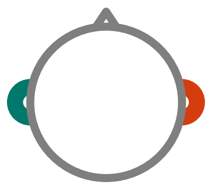
# Basic definitions

Monaural hearing



Binaural hearing



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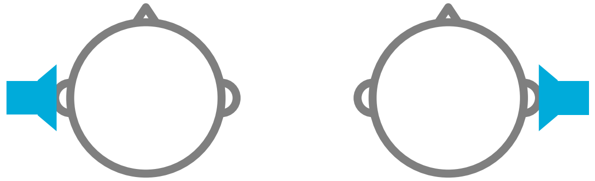
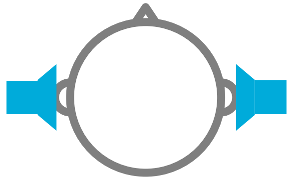
# Basic definitions

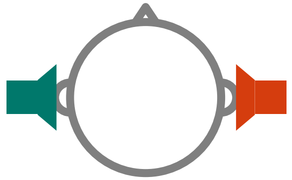
Monotic presentation



Diotic presentation



Dichotic presentation



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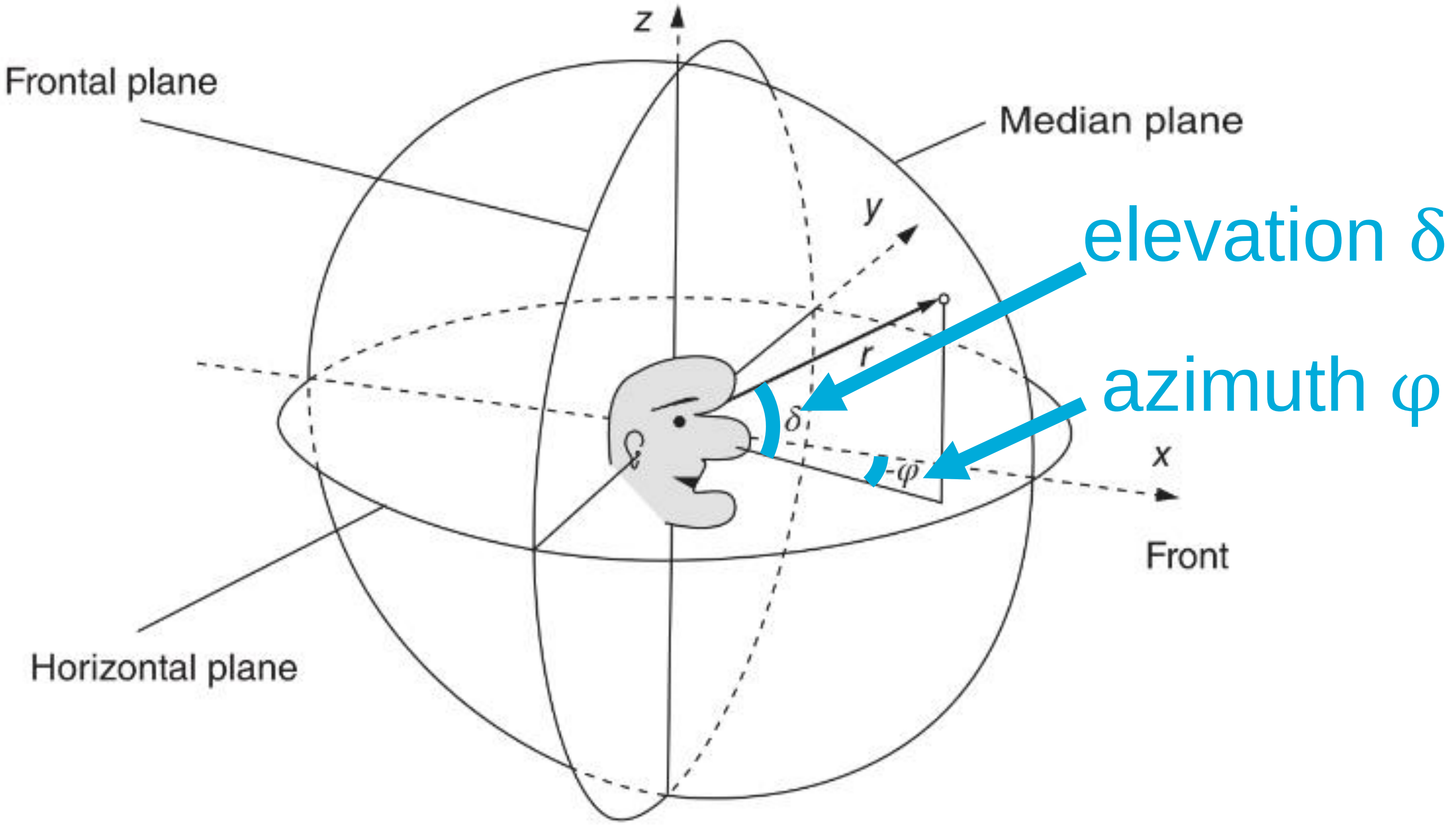
# Head centered coordinate system for spatial hearing

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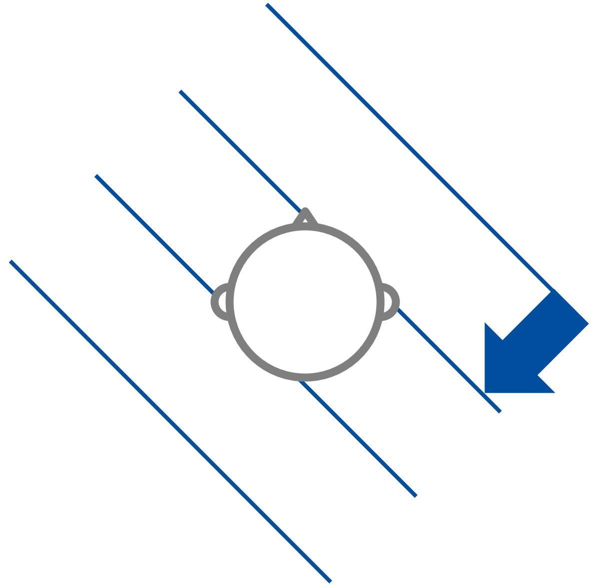
# Physical wave phenomena

Diffraction around the head

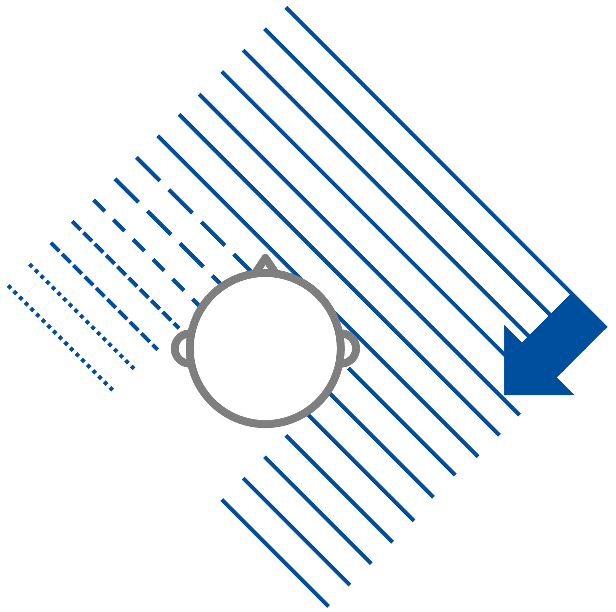
when wave length larger than head



Transition
f≈1…2 kHz
λ≈0.17…0.34 m

Head shadow and level reduction

when wave length smaller than head



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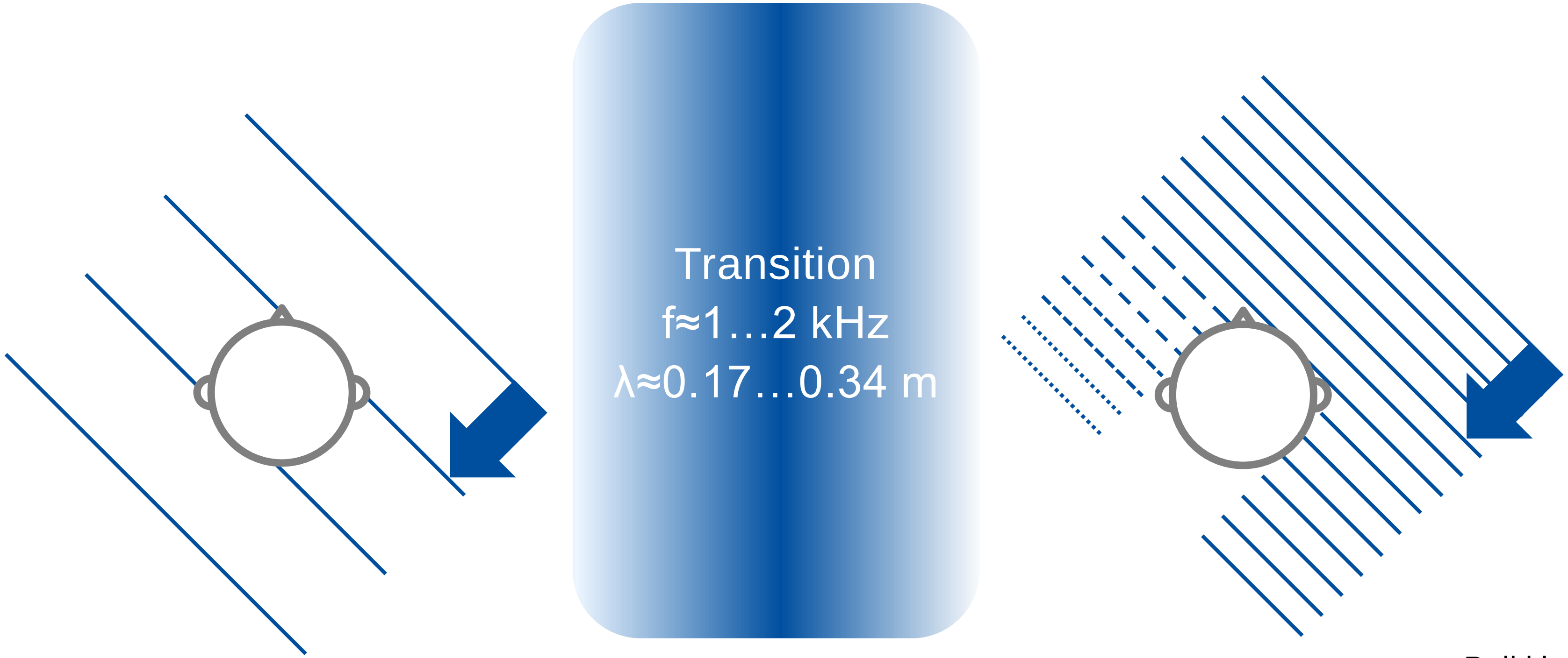
# Available binaural cues

ITDs:Interaural Time Difference

ILD: Interaural Level Differences

IPD: Interaural Phase Delay

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# Influence of the head

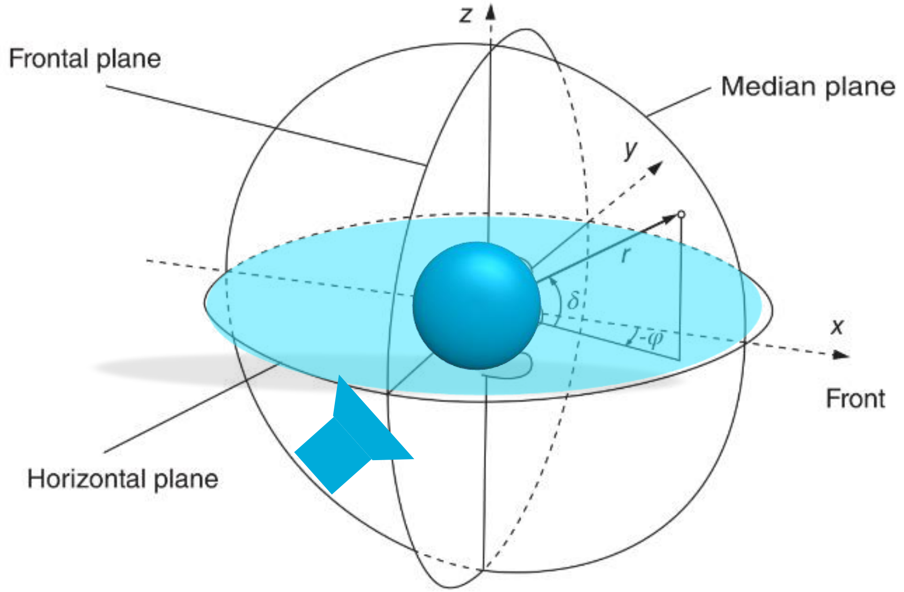
Level at left ear compared to no sphere present as a function of source incidence angle

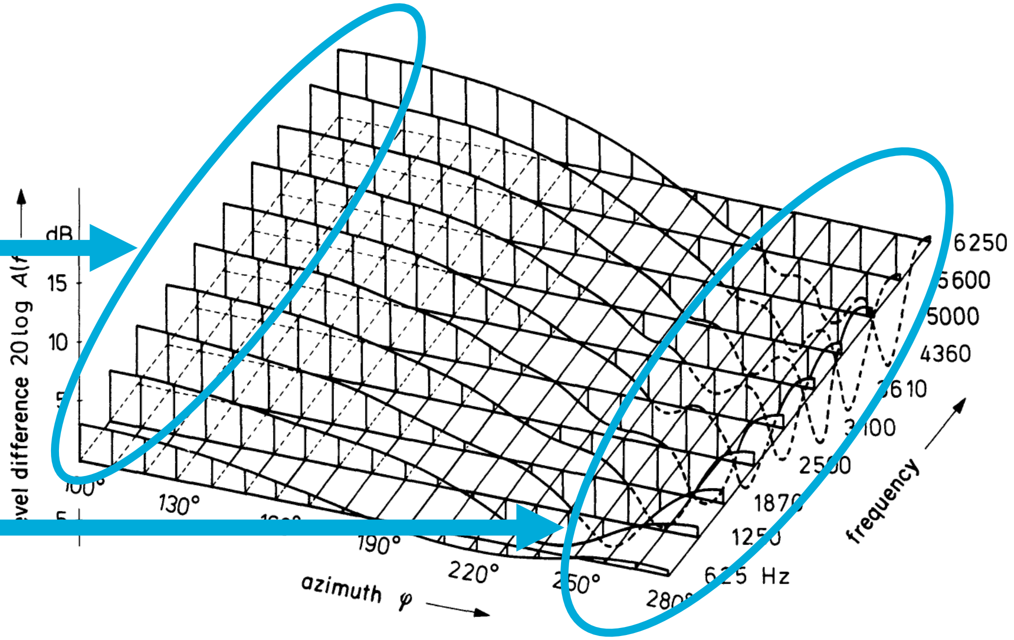
Ear at azimuth φ=100°, elevation δ=0° (middle of head)

Sphere 17.5 cm diameter

Amplification for waves directly facing the ear

Complex diffraction pattern at opposite side

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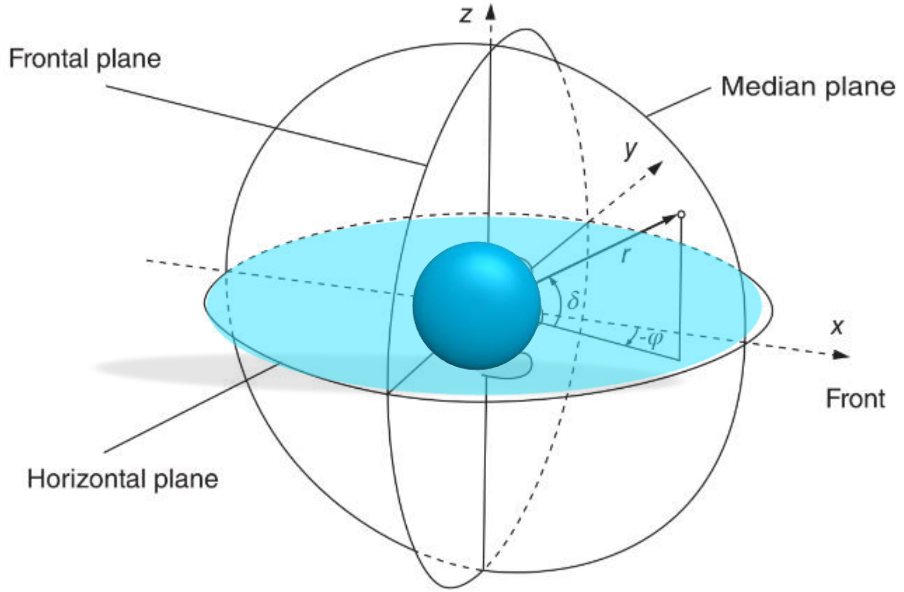
# Interaural level differences (ILDs)

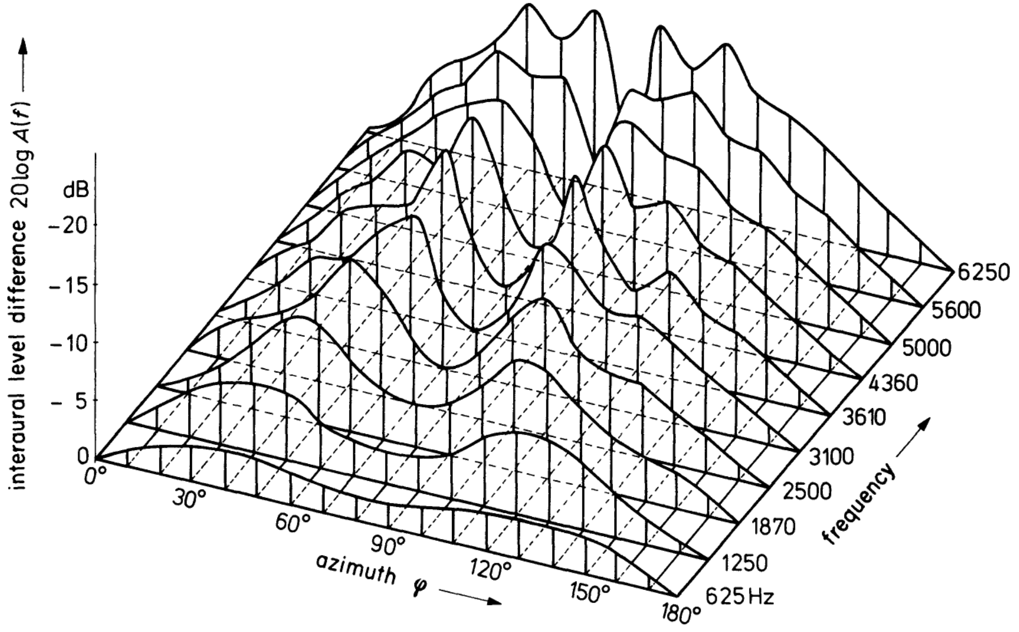



Interaural Level Difference (ILD) as a function of source incidence angle

Small dependence of ILD on azimuth at low frequencies.

At high frequencies stronger dependence.

ILD increases with azimuths up to about 45°.

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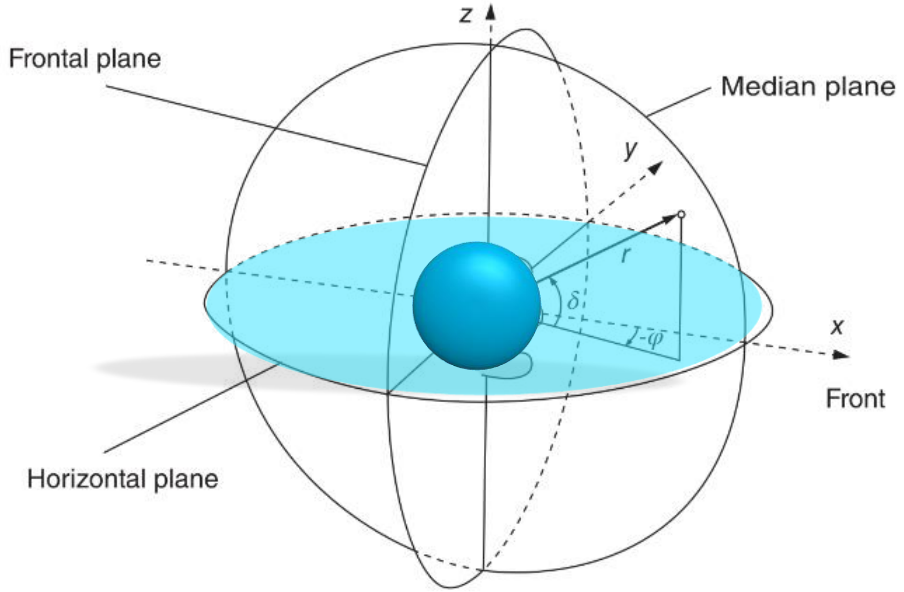
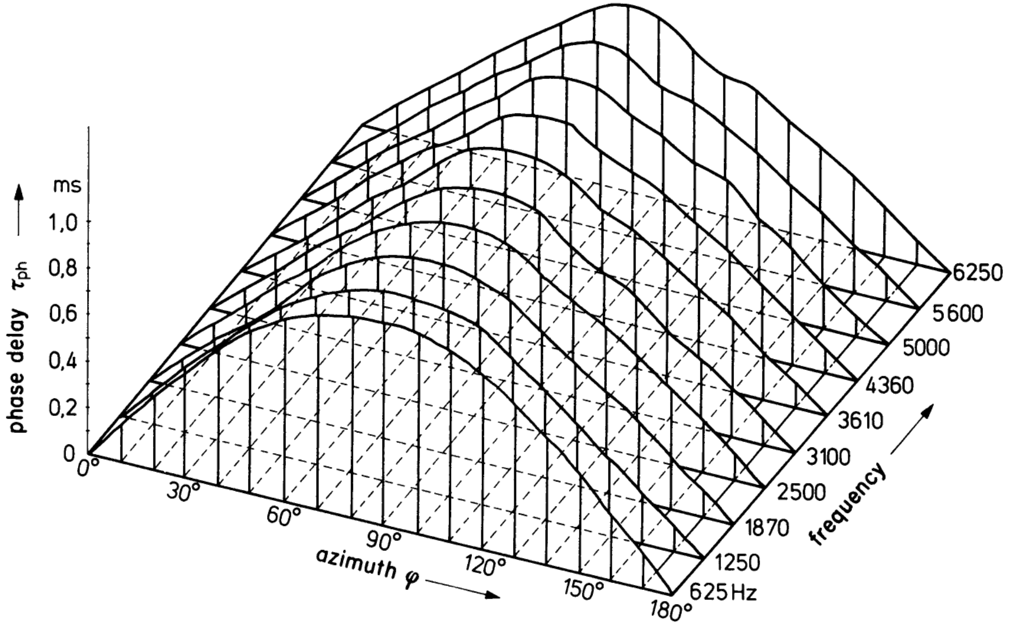
# Interaural phase delay (IPDs)




Interaural Phase Delay (IPD) in ms as a function of source incidence angle

Nearly uniform dependence of azimuth on IPD independent of frequency.

Note that at 5 kHz,
a phase delay of 1 ms corresponds to 5 periods of a sinusoid:
One cannot infer direction of sound from phase then.

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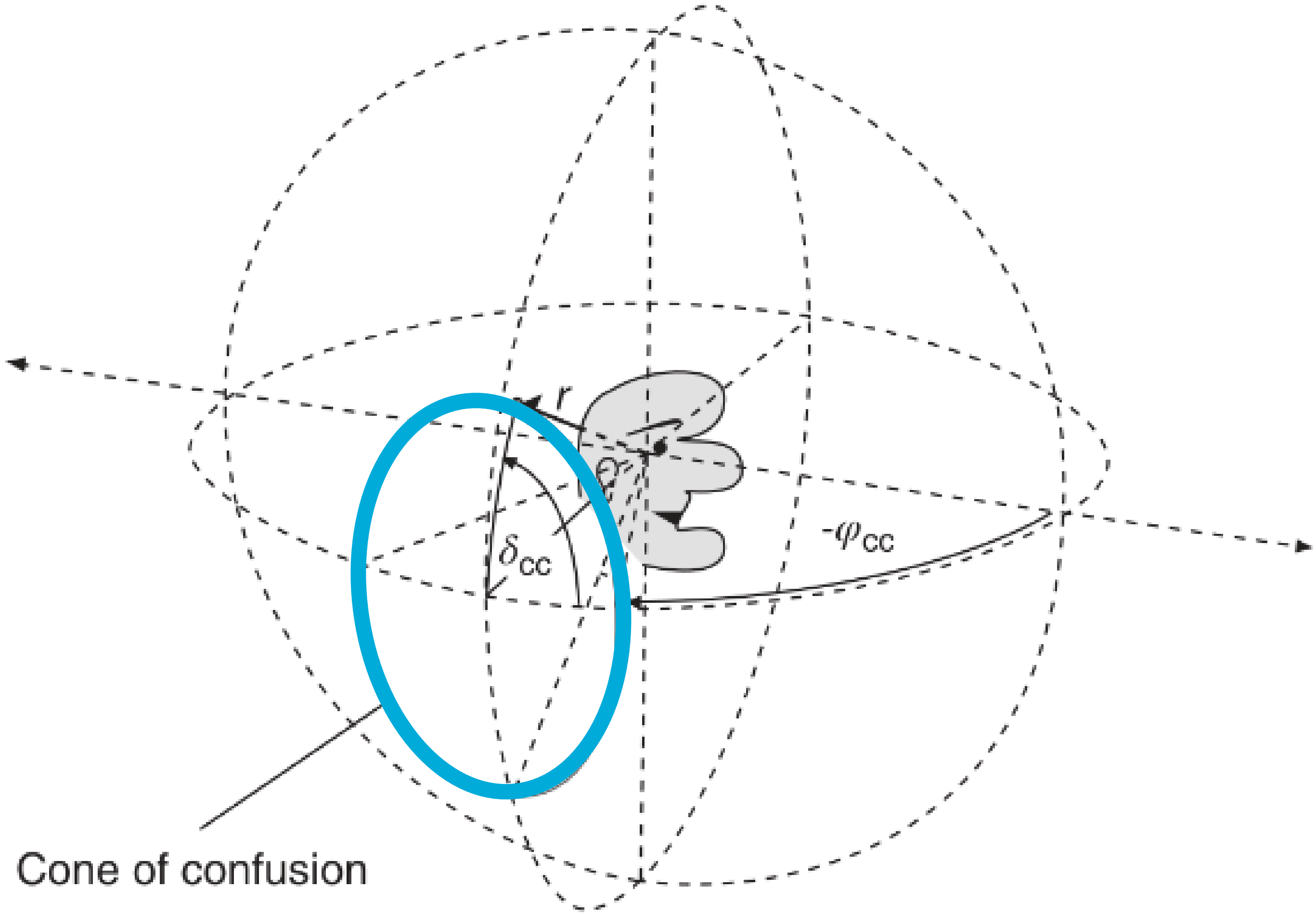
# Cone of confusion: ITDs and ILDs are constant

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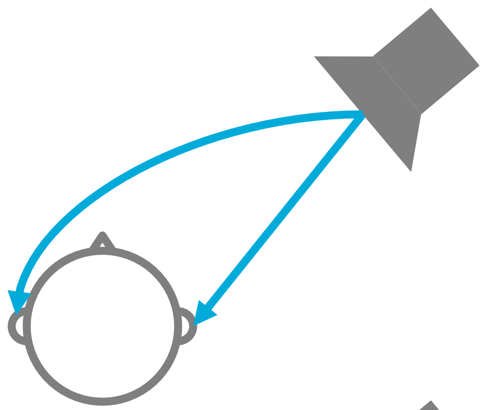
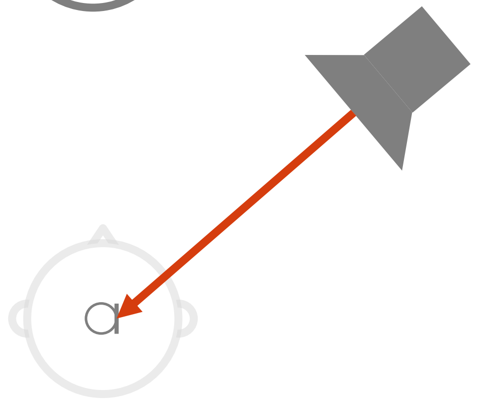
# Head related transfer functions (HRTFs)

$$H_R(\varphi, \delta, f) = \frac{H_R(\varphi, \delta, f)}{H_{ref}(f)}$$



$$H_L(\varphi, \delta, f) = \frac{H_L(\varphi, \delta, f)}{H_{Ref}(f)}$$



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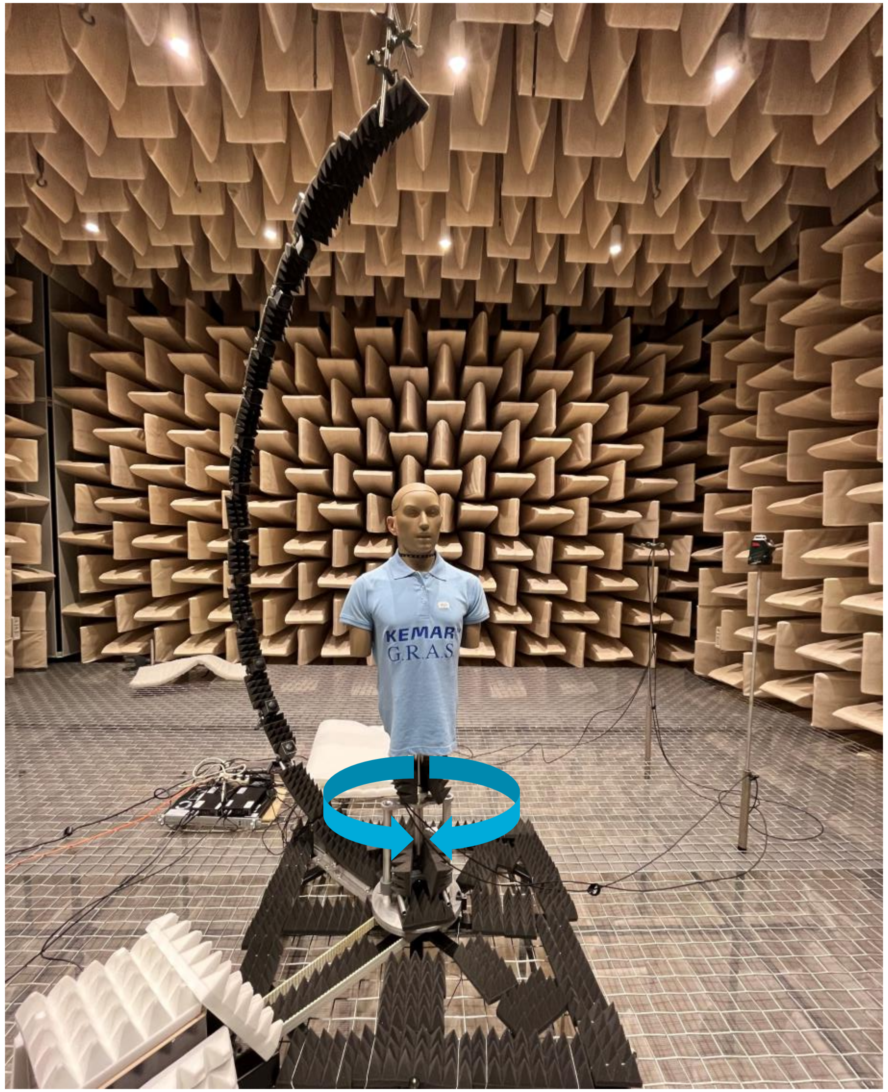
# Measurement of head related transfer functions (HRTFs) here: for an artificial head



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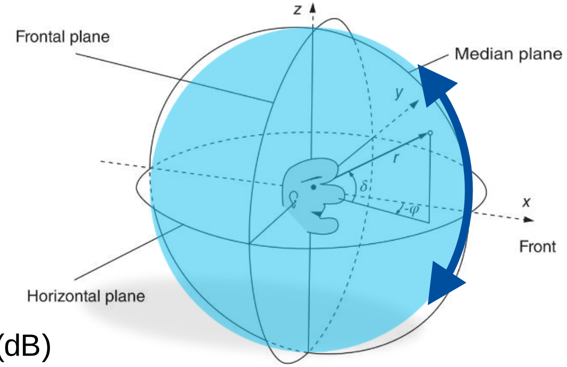
# Head related transfer functions (HRTFs)

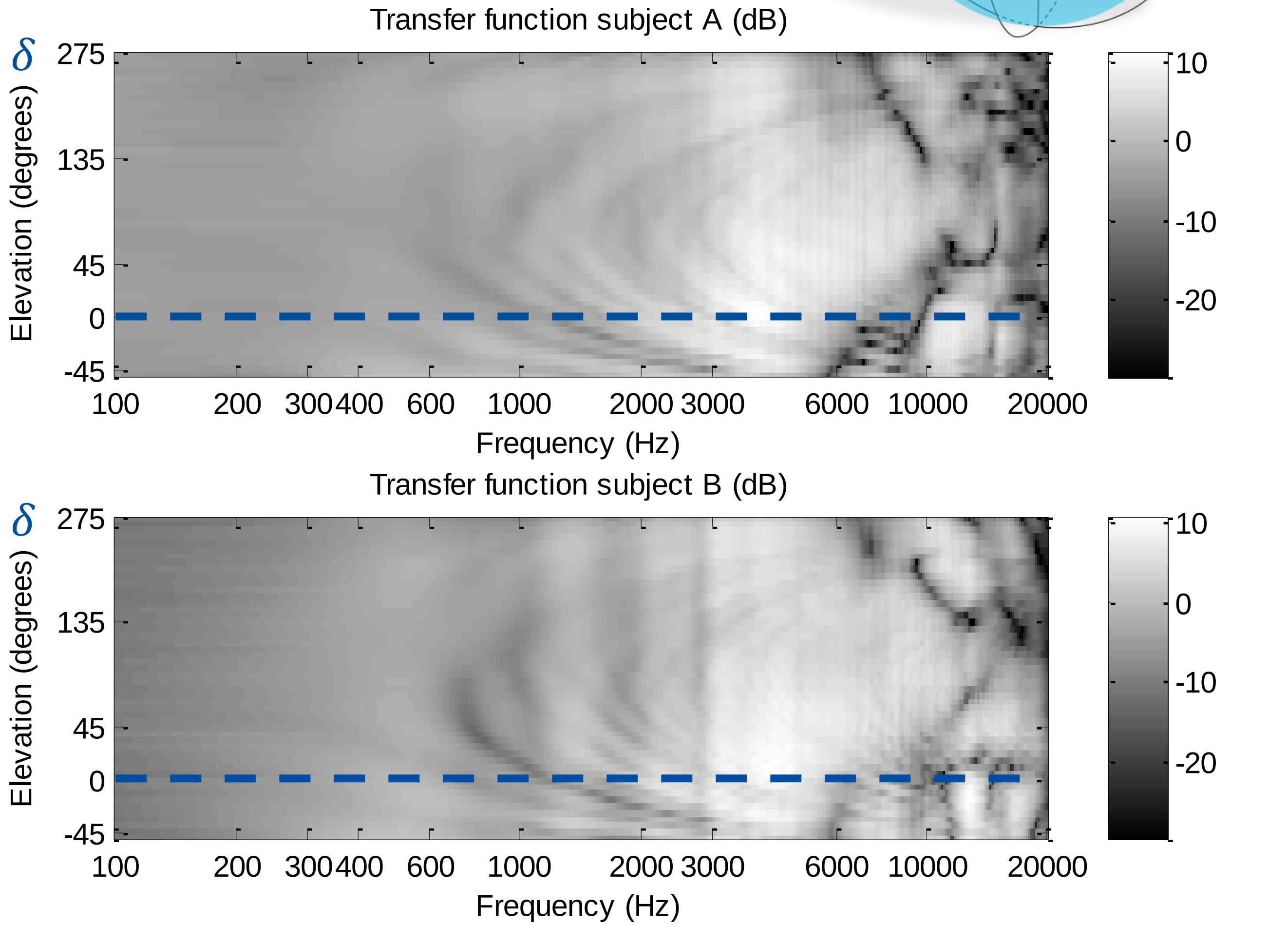



HRTF on right ear as a function of elevation:

$$20 \cdot log_{10}|H_R(\varphi = 0, \delta, f)|$$

HRTF reveals a strong dependence on elevation above 6 kHz

Position valleys depends on elevation



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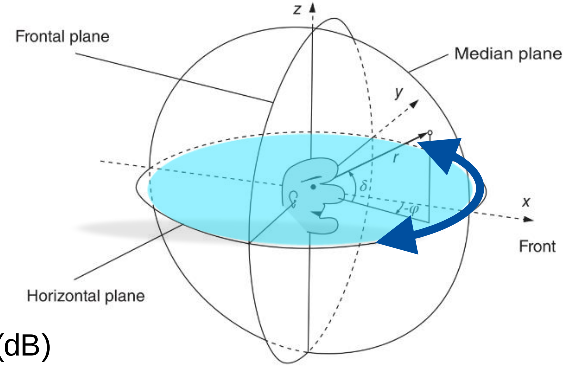
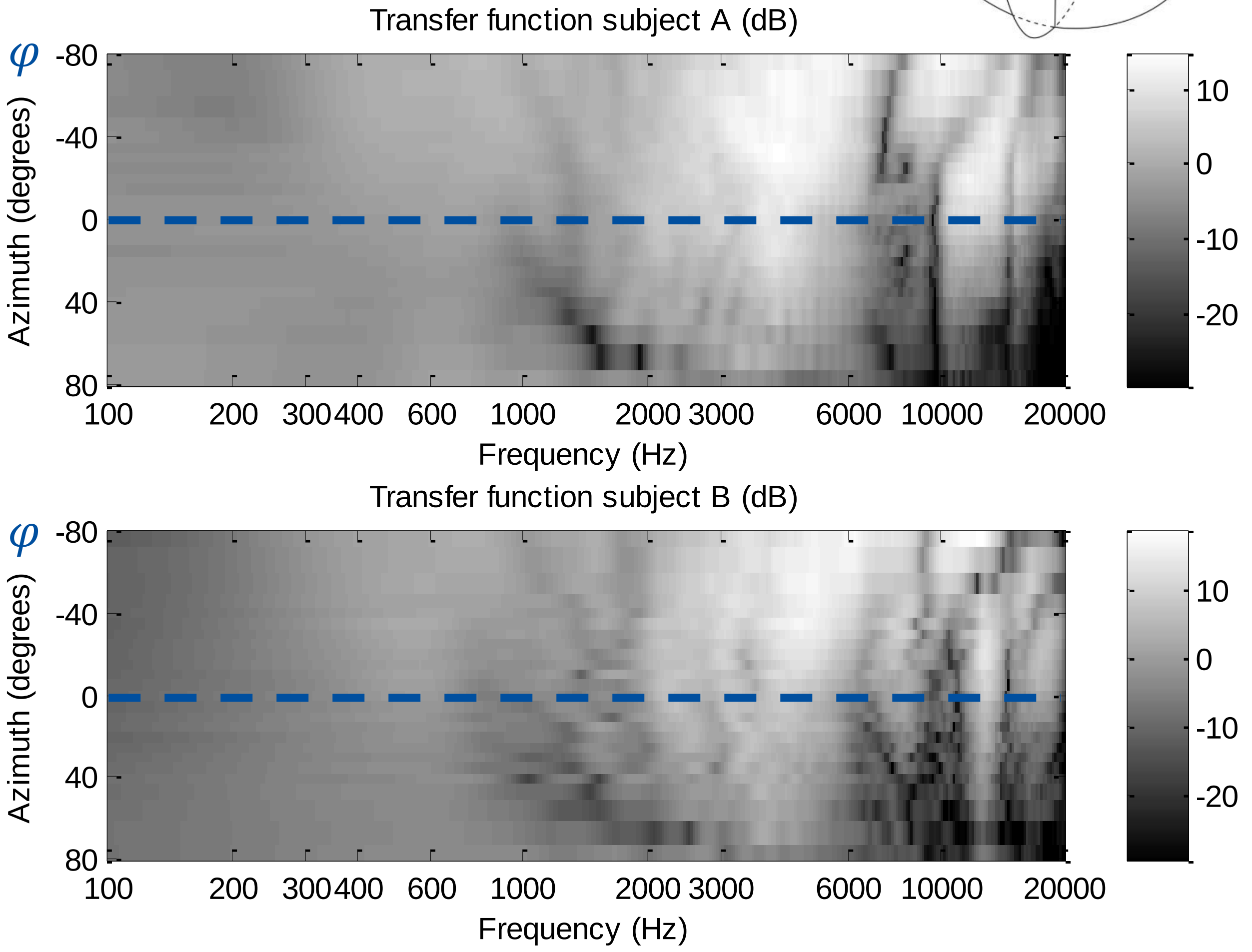
# Head related transfer functions (HRTFs)




HRTF on right ear as a function of azimuth:

$$20 \cdot log_{10}|H_R(\varphi, \delta = 0, f)|$$




HRTF reveals a strong dependence on azimuth above 6 kHz

Position valleys mostly independent of azimuth

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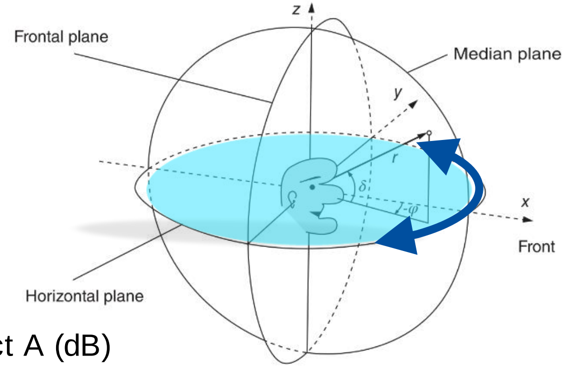
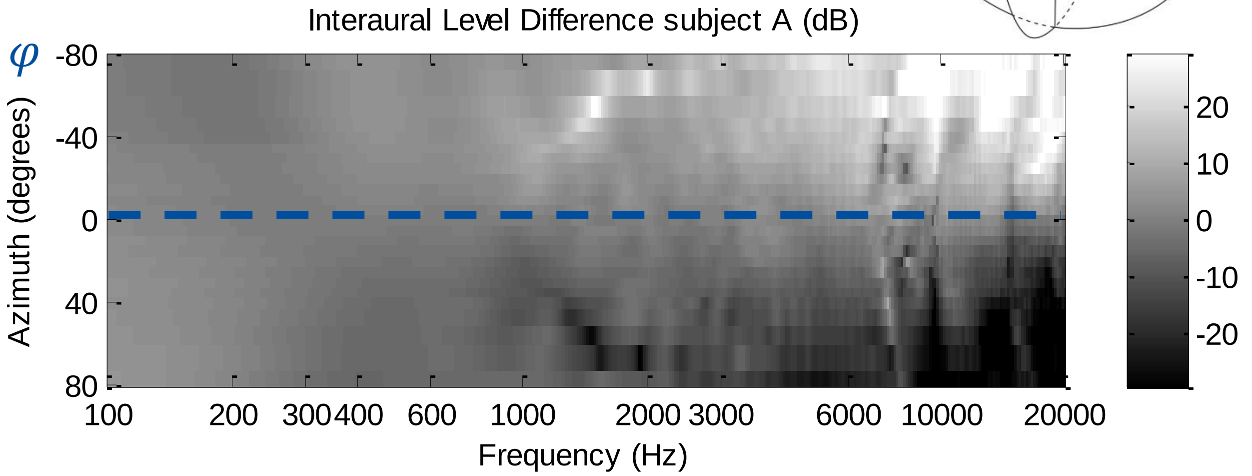
# Interaural level differences (ILDs)

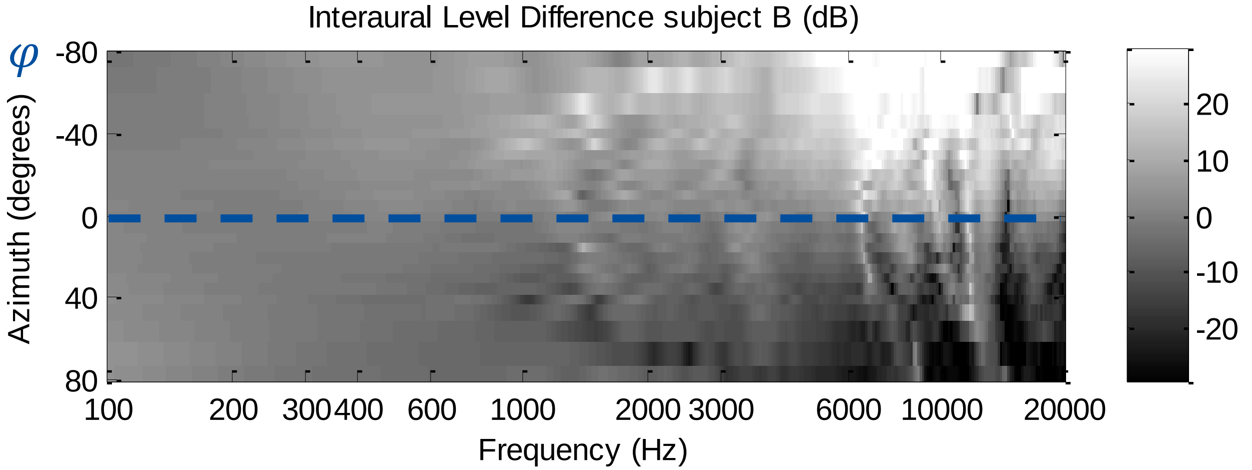



Interaural Level Difference
as a function of azimuth:

$$20 \cdot log_{10} \frac{|H_R(\varphi, \delta = 0, f)|}{|H_L(\varphi, \delta = 0, f)|}$$

ILD depends strongly on azimuth above 6 kHz



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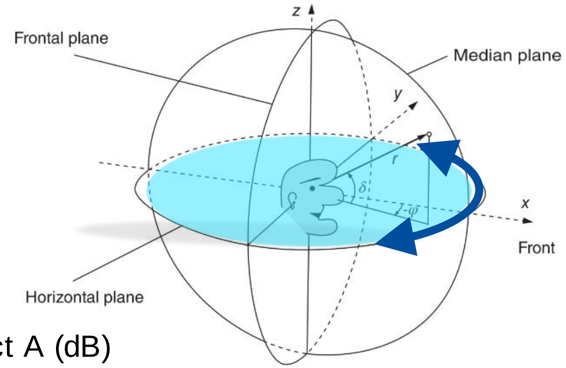
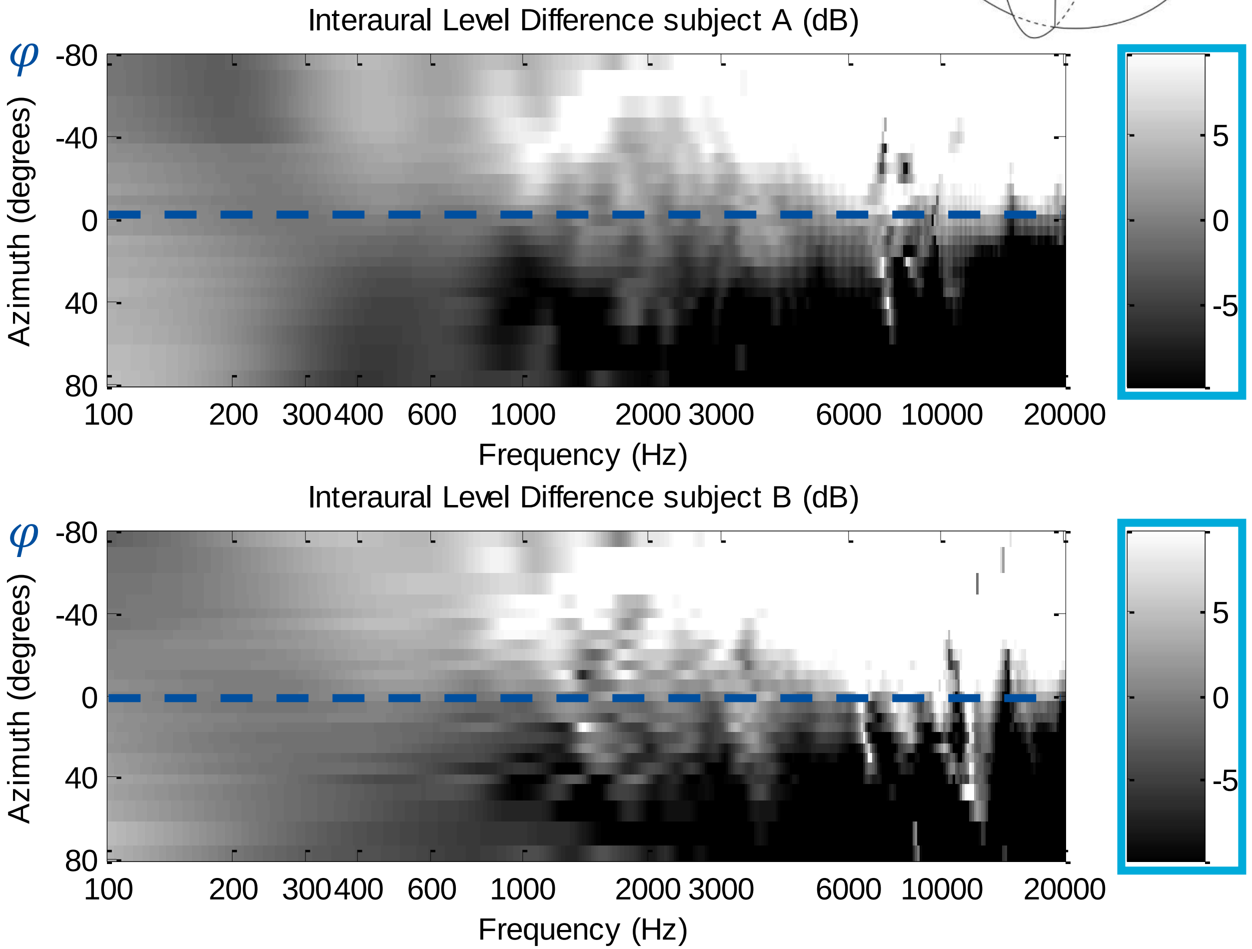
# Interaural level differences (ILDs)



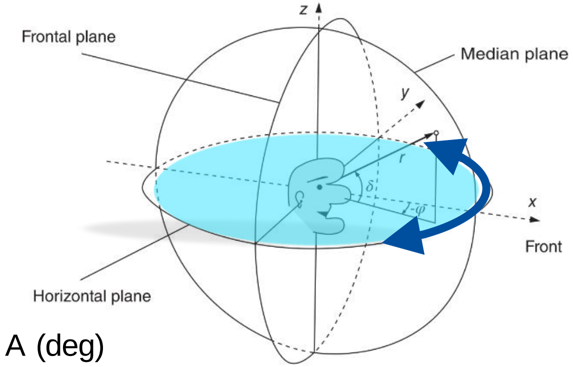

Interaural Level Difference
as a function of azimuth:

$$20 \cdot log_{10} \frac{|H_R(\varphi, \delta = 0, f)|}{|H_L(\varphi, \delta = 0, f)|}$$

ILD already depends on
azimuth above about 600 Hz



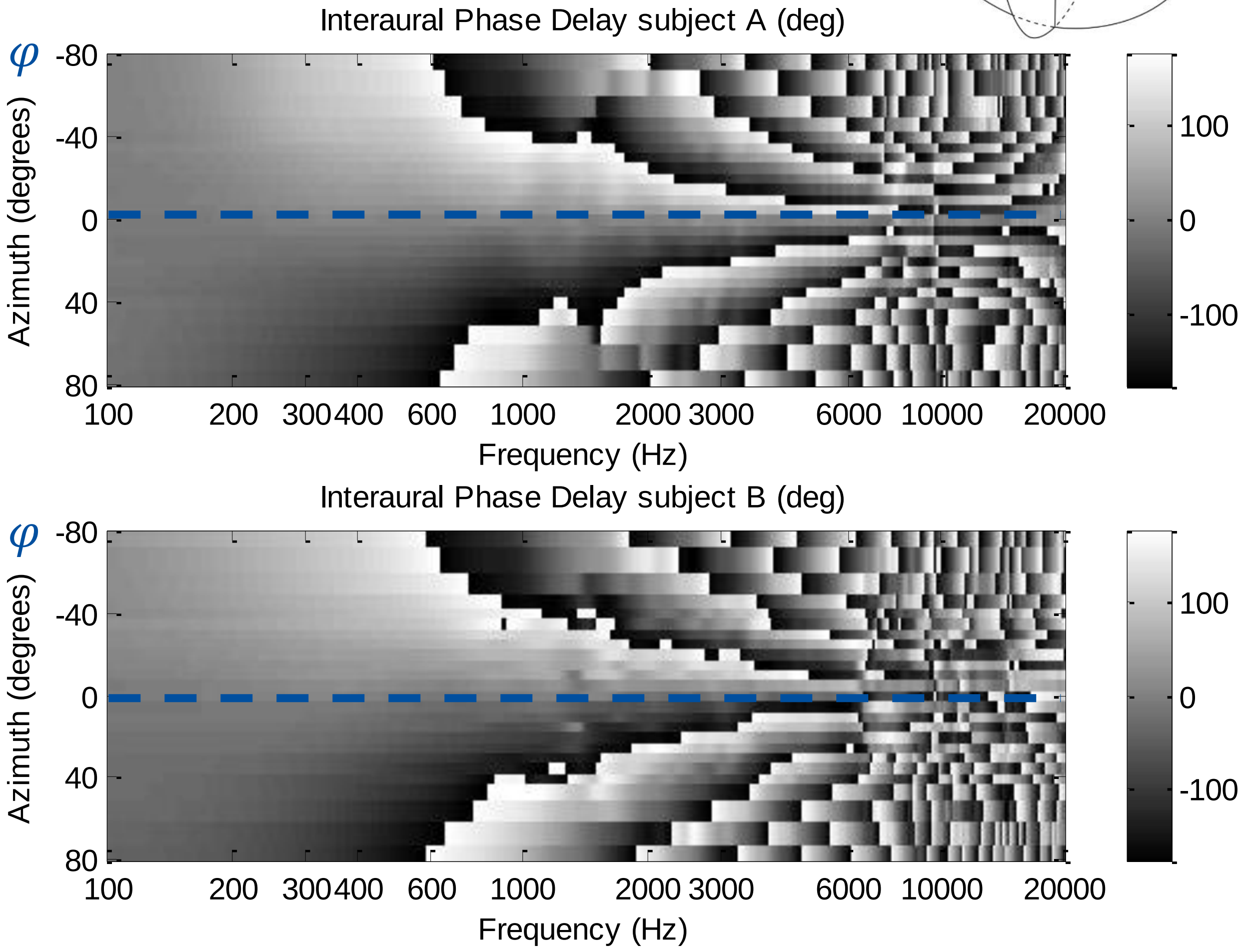
# Interaural phase delays (IPDs)




Interaural Phase Delay as a function of azimuth:

$$arg\frac{|H_R(\varphi,\delta=0,f)|}{|H_L(\varphi,\delta=0,f)|}$$

IPD is unambiguous up to about 600 Hz



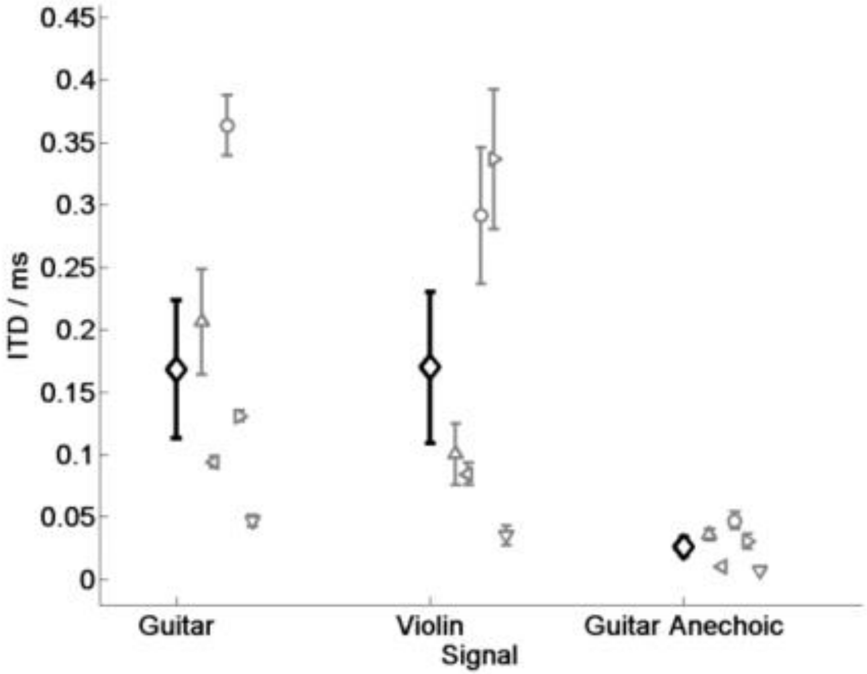
# Humans sensitivity for Interaural time differencs (ITDs)

- up to frequencies of about 1.5 kHz for sinusoids
- Envelope ITDs at high frequencies
- Perceived as lateral shift

- JNDs of about 20 µs at 500 Hz

≈1 sample at fs=44100 Hz

| Signal | | Threshold in [illegible]seconds | Number of listeners | Judgments per point per listener |
|---|---|---|---|---|
| Noise | [illegible] | [illegible] | 10 | 160 |
| | [illegible] | [illegible] | [illegible] | 80 |
| | [illegible] | [illegible] | 9 | 160 |
| | [illegible] | [illegible] | 8 | 80 |
| | 2400–[illegible] cps | 44 | 10 | 80 |
| | 3056–3344 cps[b] | 62 | 10 | 80 |
| Clicks (1 millisecond duration) | Single | 28 | 10 | 120 |
| | Repeated, 30 clicks in a 2 second burst | 11 | 13 | 160 |
| Tones | 90 cps | 75 | 10 | 10 |
| | 125 cps | 56 | 9 | 80 |
| | 250 cps | 27 | 9 | 80 |
| | 500 cps | 17 | 9 | 80 |
| | 1000 cps | 11 | 9 | 80 |
| | 1300 cps | 24 | 10 | 10 |
| | 1500 cps | ... | 10 | 10 |
| | 1800 cps | ... | 10 | 10 |
| | 3200 cps | ... | 10 | 80 |




Klumpp1956
Klockgether 2013

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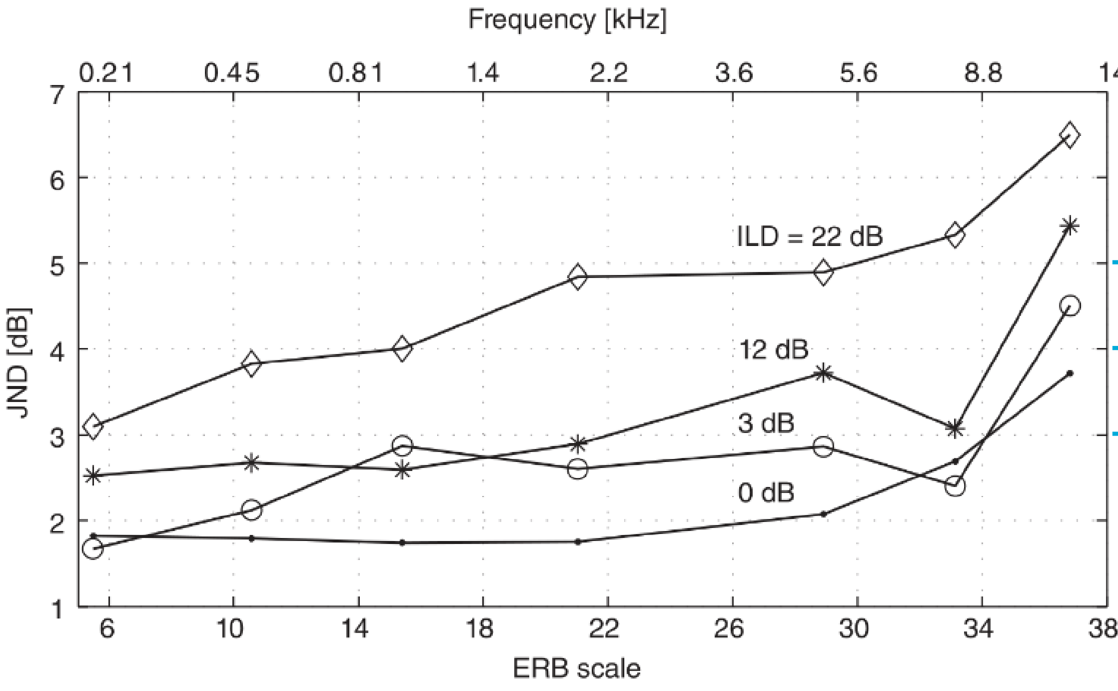
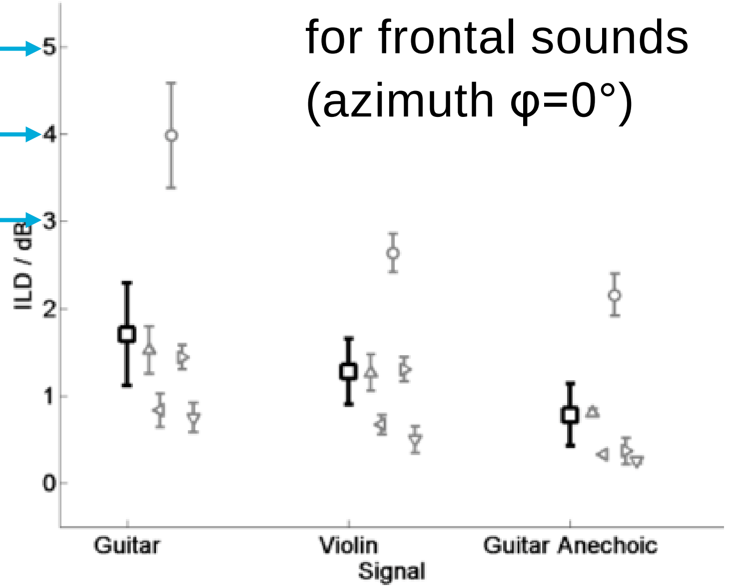
# Humans sensitivity for Interaural level differences (ILDs)

- JNDs of about 1-2 dB across all frequencies for ILDs = 0 dB
- Perceived as lateral shift




for frontal sounds (azimuth φ=0°)

Pulkki, 2015 (adapted from Weiping)
Klockgether 2013

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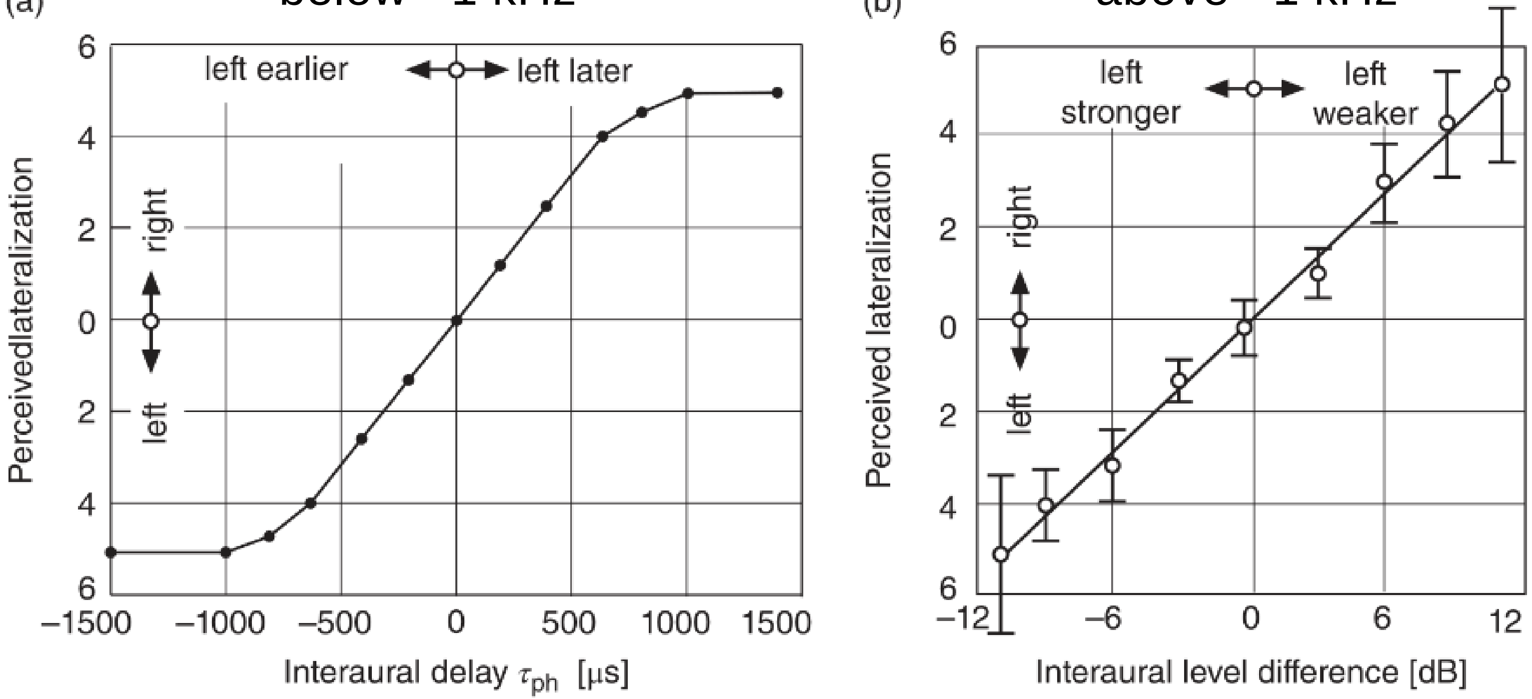
# Perceived lateralization as a function of ITDs and ILDs

below ~1 kHz                above ~1 kHz




Maximum lateralization for

τ ≈ 700 μs

ILD ≈ 12 dB

Pulkki, 2015 (adapted from Sayers)

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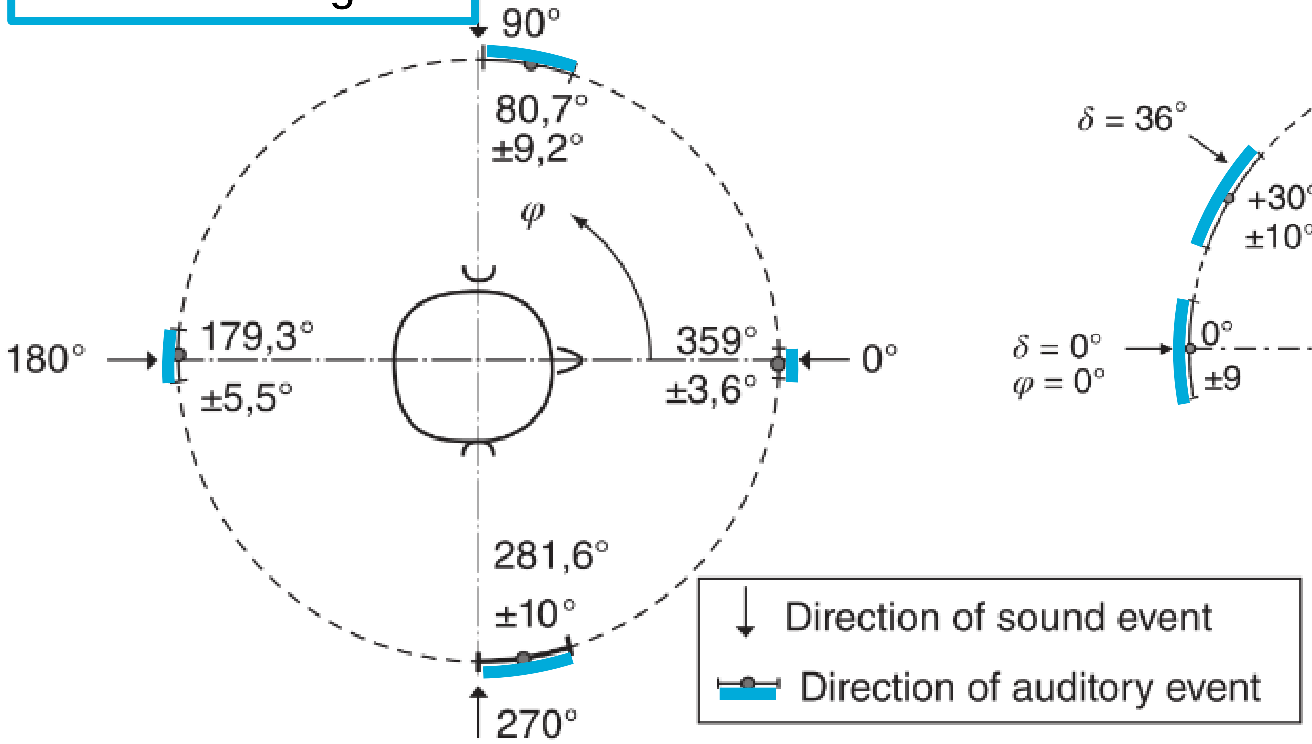
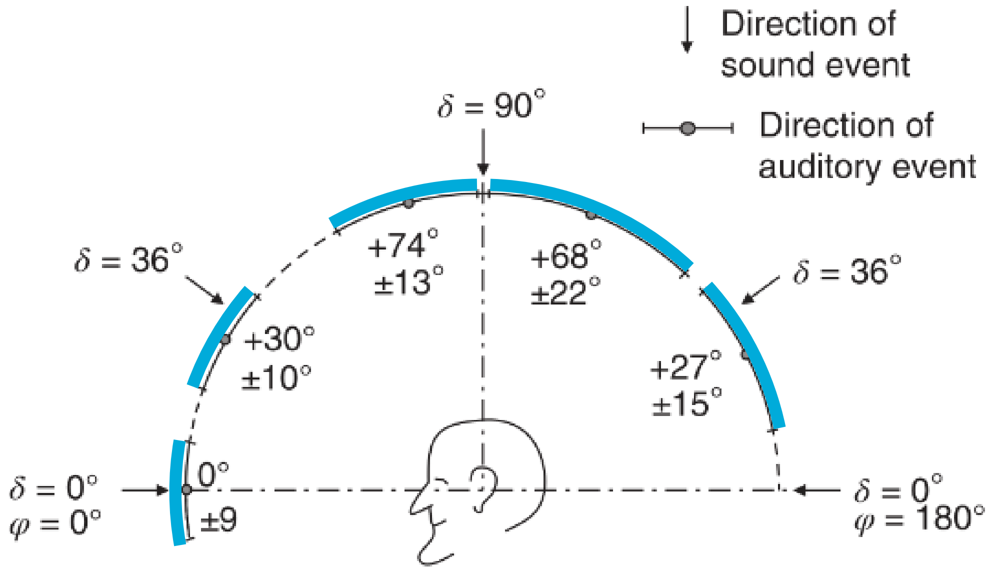
# Localization accuracy in azimuth an elevation

White noise signals




Speech signals

Pulkki, 2015 (adapted from Blauert / Damaske and Wagner)

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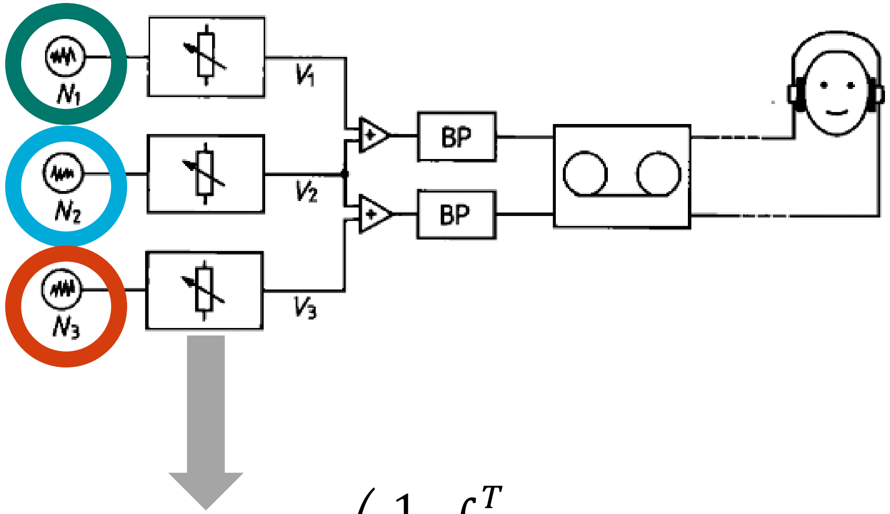
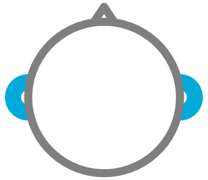
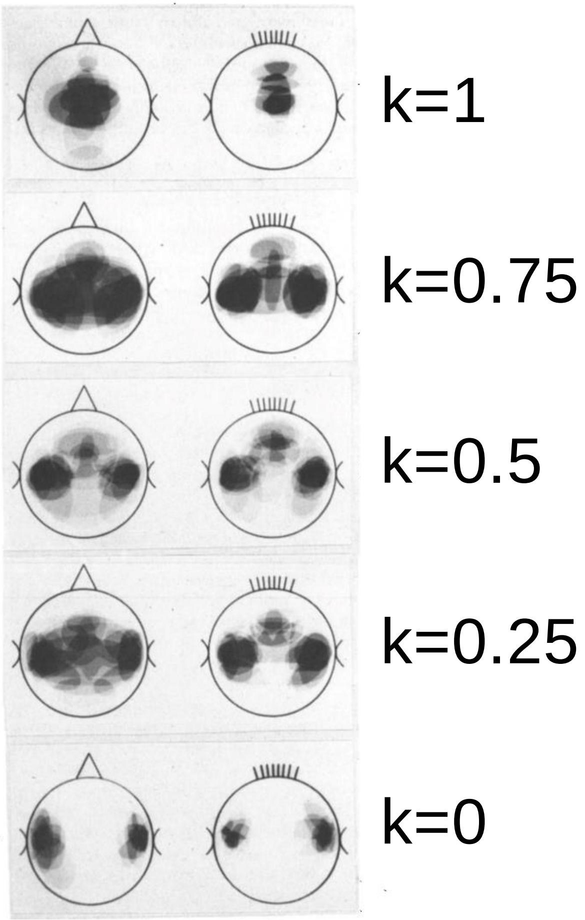
# Interaural coherence / cross correlation (IACC) and lateralisation

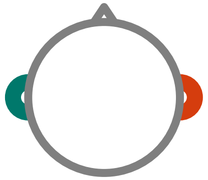



$$IACC(\tau) = \lim_{T\to\infty}\left(\frac{1}{2T}\int_{-T}^{T} l(t+\tau)r(t)dt \,/ l_{rms}r_{rms}\right)$$

$$k = \max|IACC|$$





Blauert 1986

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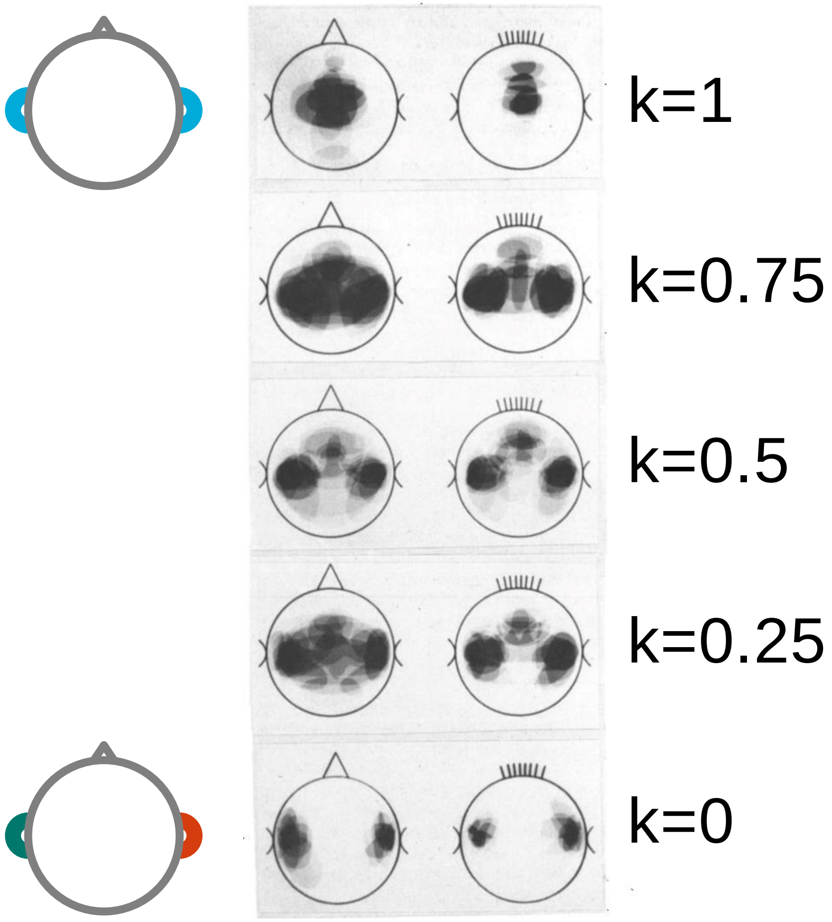
# Humans sensitivity for IACC

– k ≈ 1: JNDs of about 2 %

– k ≈ 0: JNDs of about 30 %

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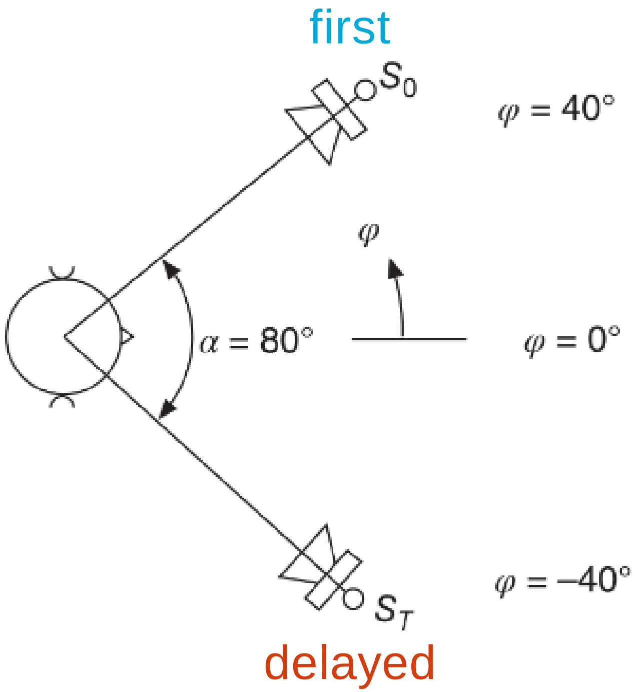
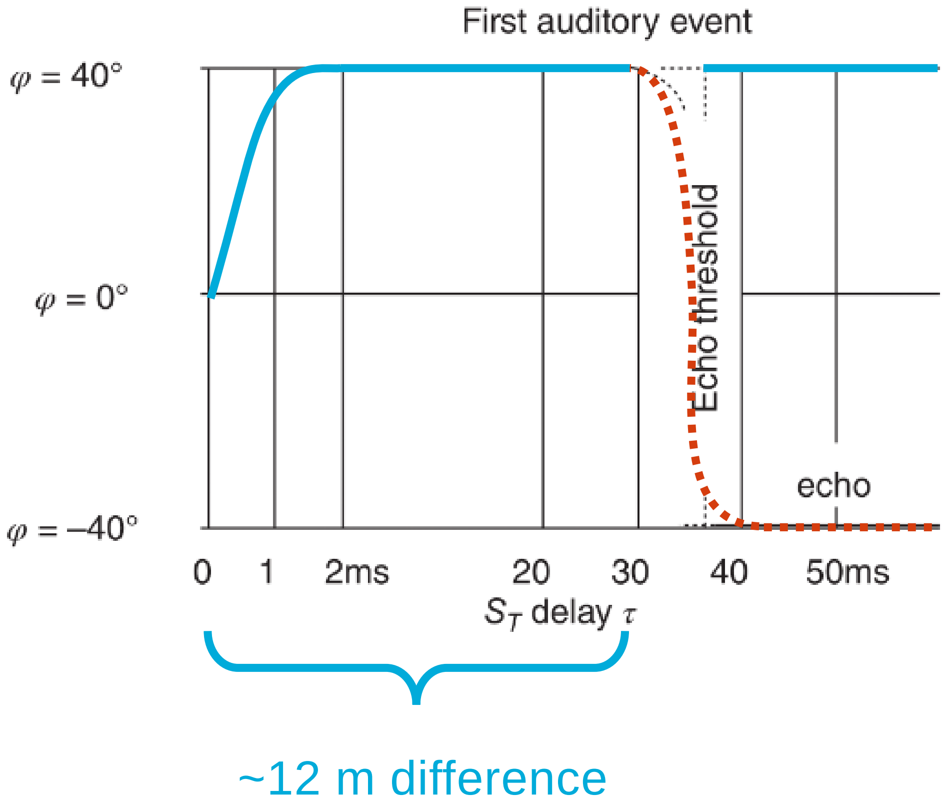
# Perception first lateral reflections




$L_{delayed} = L_{first}$




Pulkki, 2015
(adapted from Blauert)

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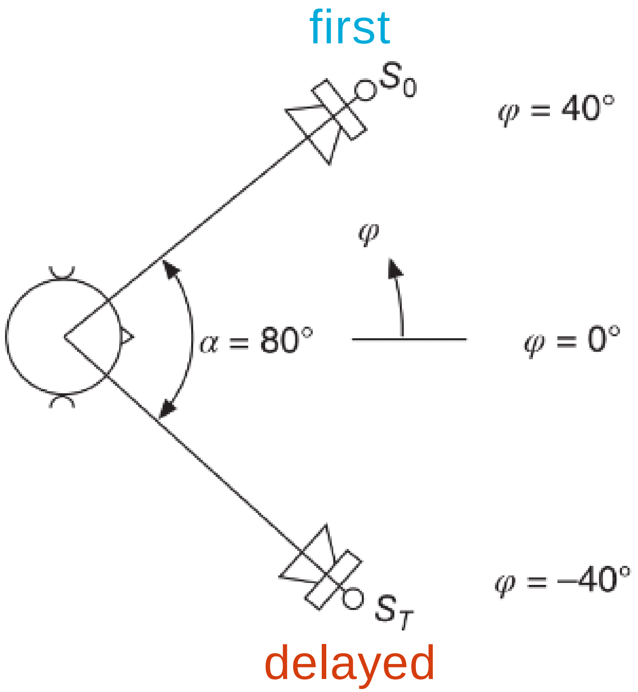
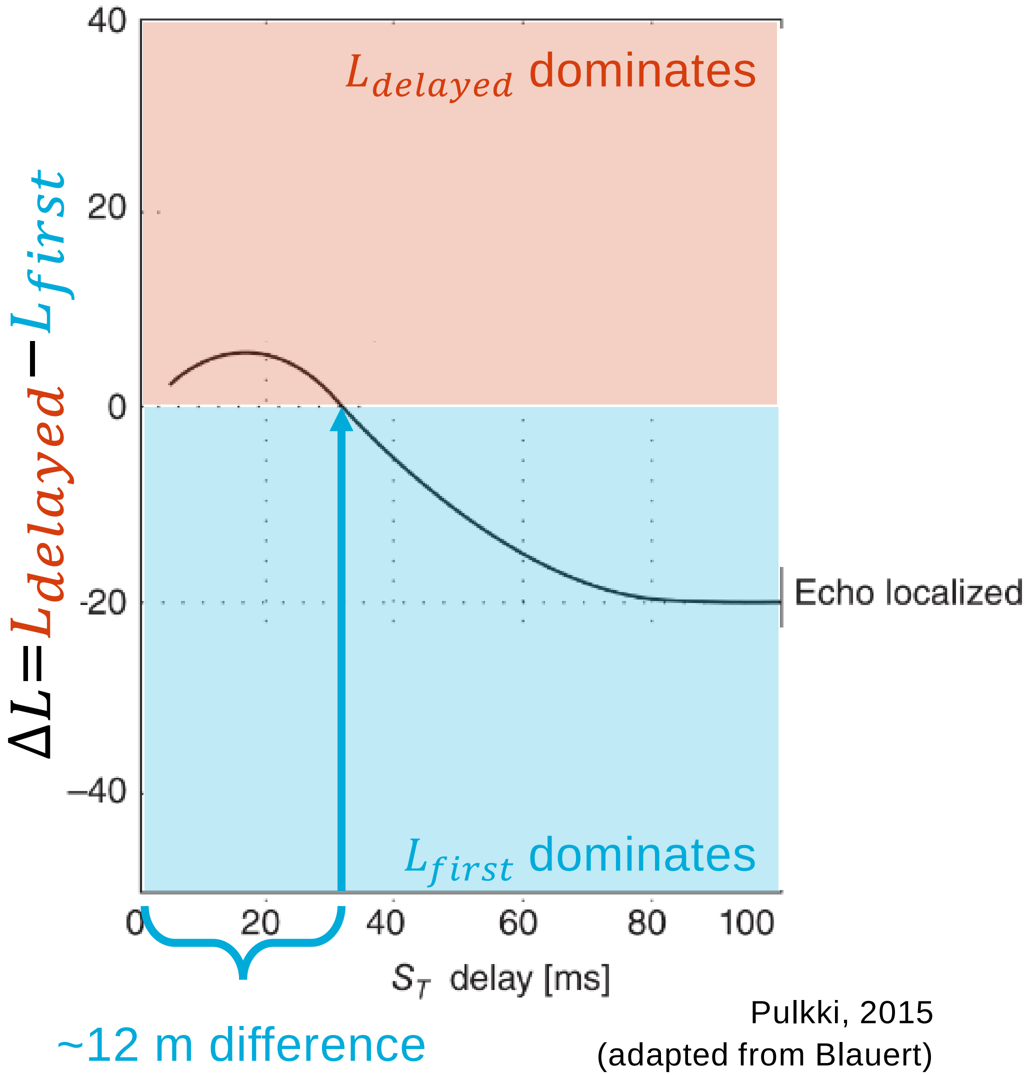
# Perception first lateral reflections




Pulkki, 2015
(adapted from Blauert)

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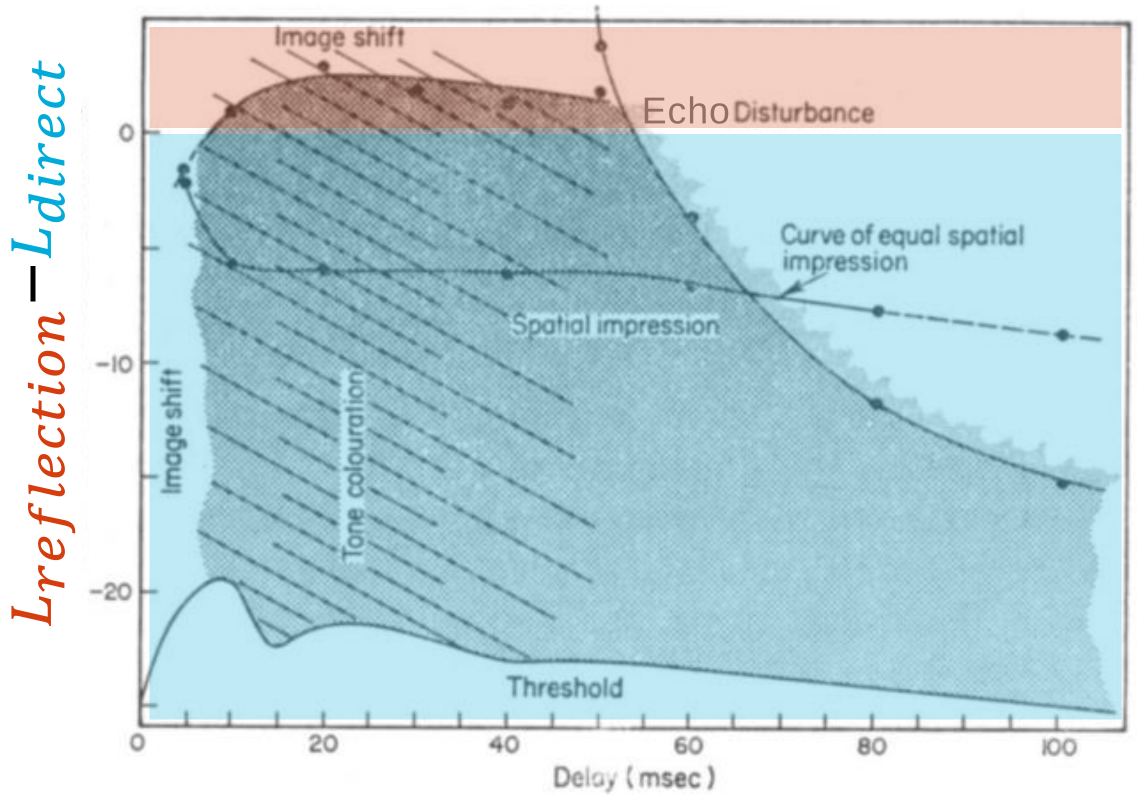
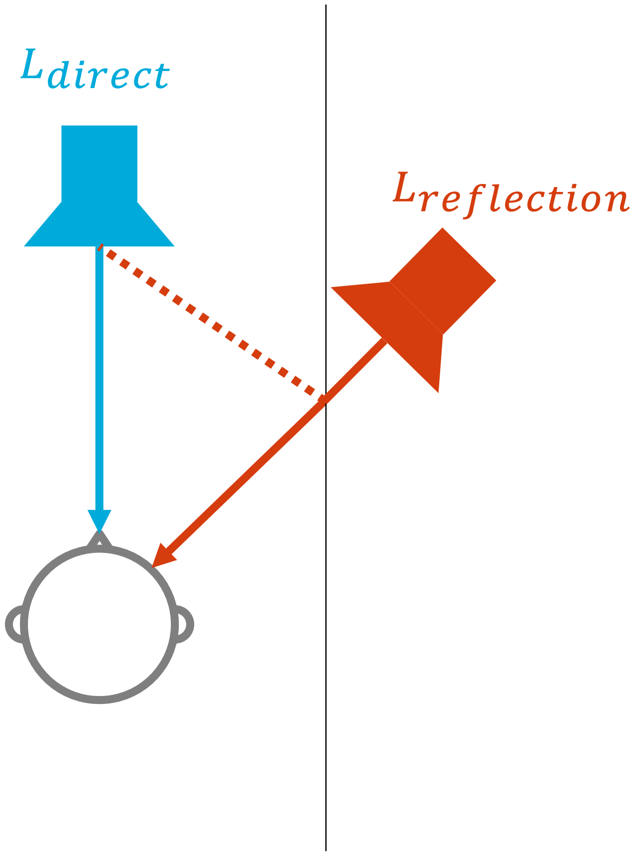
# Perception first lateral reflections




Barron 1971

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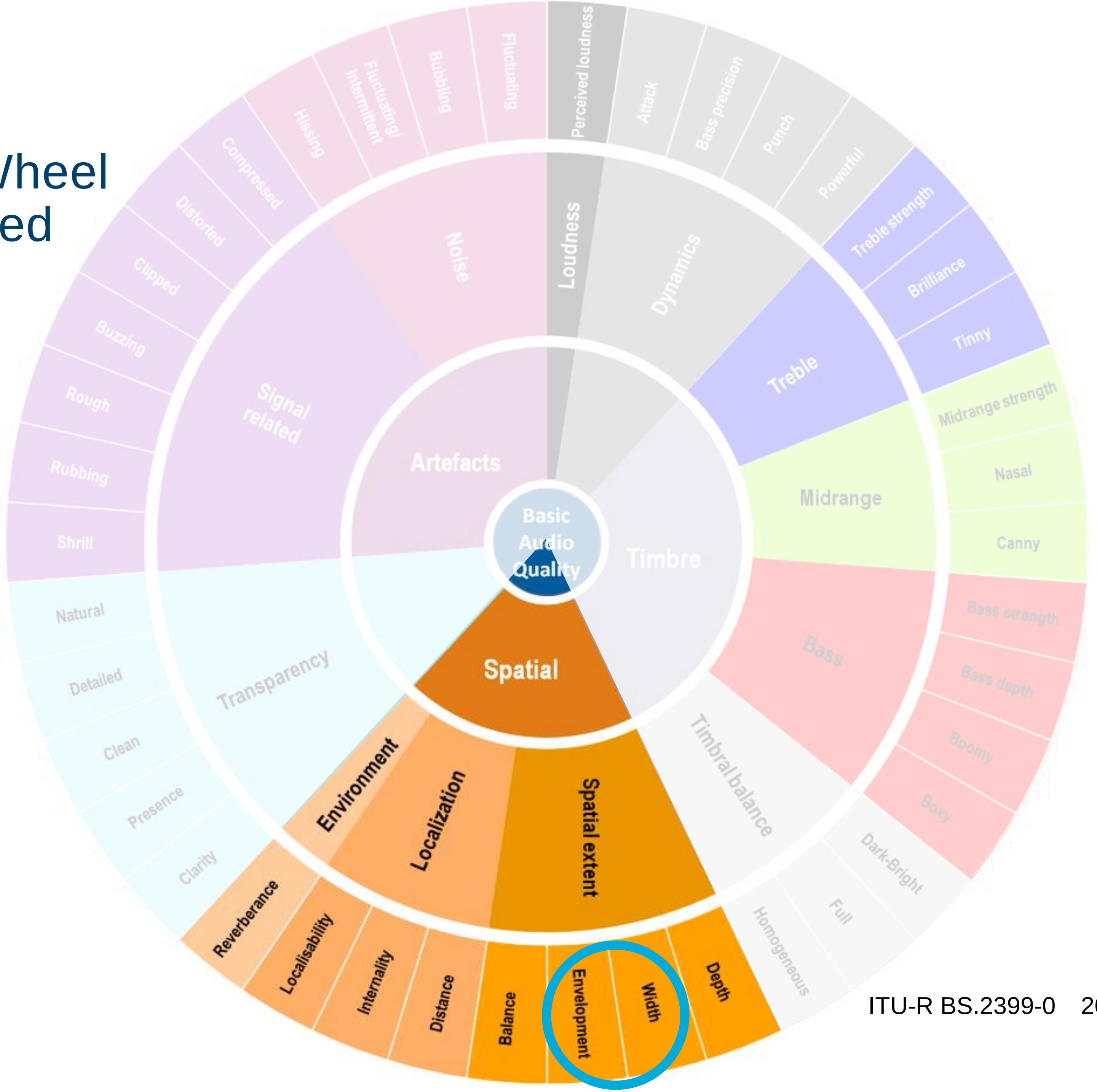
# The Audio Wheel for reproduced sound




ITU-R BS.2399-0 2017

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# Spatial Audio Quality Inventory (SAQI, Lindau 2014)

Acta Acustica united with Acustica
Vol. 100 (2014)



Table I. Spatial Audio Quality Inventory (SAQI) - English version.
*sound examples may be downloaded from http://dx.doi.org/10.14279/depositonce-1

| Quality | Circumscription | Scale End Label |
|---|---|---|
| Difference | Existence of a noticeable difference. | none – very large |
| **Timbre** | | |
| Tone color | Timbral impression which is determined by the ratio of high to low fre- | darker – brighter |
| **Geometry** | | |
| Horizontal direction | Direction of a sound source in the horizontal plane. | shifted anticlockwise – shifted clockwise (up to 180°) |
| Vertical direction | Direction of a sound source in the vertical plane. | shifted down – shifted up (up to 180°) |
| Front-back position | Refers to the position of a sound source before or behind the listener only. Impression of a position difference of a sound source caused by 'reflecting' its position on the frontal plane going through the listener. | dichotomous scale: not confused/confused |
| Distance | Perceived distance of a sound source. | closer – more distant |
| Depth | Perceived extent of a sound source in radial direction. | less deep – deeper |
| Width | Perceived extent of a sound source in horizontal direction. | less wide – wider |
| Height | Perceived extent of a sound source in vertical direction. | less high – higher |
| Externalization | Describes the distinctness with which a sound source is perceived within or outside the head regardless of their distance. Terminologically often enclosed between the phenomena of in-head localization and out-of-head localization. Examples: Poorly/not externalized = perceived position of sound sources at diotic sound presentation via headphones, good/strongly externalized = perceived position of a natural source in reverberant environment and when allowing for movements of the listener. | more internalized – more externalized |
| **Room** | | |
| Level of reverberation | Perception of a strong reverberant sound field, caused by a high ratio of reflected to direct sound energy. Leads to the impression of high diffusivity in case of stationary excitation (in the sense of a low D/R-ratio). Example: The perceived intensity of reverberation differs significantly between rather small and very large spaces, such as living rooms and churches. | less – more |
| Duration of reverberation | Duration of the reverberant decay. Well audible at the end of signals. | shorter – longer |
| Envelopment (by reverberation) | Sensation of being spatially surrounded by the reverberation. With more pronounced envelopment of reverberation, it is increasingly difficult to assign a specific position, a limited extension or a preferred direction to the reverberation. Impressions of either low or high reverberation envelopment arise with either diotic or dichotic (i.e., uncorrelated) presentation of reverberant audio material. | less pronounced – more pronounced |

# Room Acoustic Quality Inventory (RAQI, Weinzierl 2018)

TABLE II. Three possible solutions of the CFA yielding four, six, and nine factors as sub-dimensions of room acoustical impression. The corresponding questionnaires would contain 14, 20, and 29 items, which are given with corresponding poles. Weights (*W*) and intercepts (*I*) should be used to measure factors and for structural equation analysis (see Sec. IV). Four additional items with high re-test reliability, which could not be assigned to one of the factors, are given below.

| Solutions | Factors | Items | Poles | W | I |
|---|---|---|---|---|---|
| 9-factor RAQI / 6-factor RAQI / 4-factor RAQI | Quality | Liking | I like it – I don't like it | 1.0 | 2 |
| | | Room acoustic suitability | suitable – not suitable | 1.0 | 56 |
| | | Ease of listening | difficult – effortless | 0.9 | 10 |
| | | Global balance | balanced – unbalanced | 0.8 | 4 |
| | Strength | Size | small – large | 1.0 | 57 |
| | | Loudness | soft – loud | 0.7 | 64 |
| | | Width | small – large | 0.8 | 57 |
| | Reverberance | Duration of reverberation | short – long | 1.0 | 47 |
| | | Reverberance | dry – reverberant | 1.0 | 54 |
| | | Strength of reverberation | weak – strong | 1.0 | 51 |
| | | Envelopment by reverberation | weak – strong | 0.7 | 48 |
| | Brilliance | Brilliance | not brilliant – very brilliant | 1.0 | 48 |
| | | Tone Color bright/dark | bright – dark | -0.8 | -7 |
| | | Treble range characteristic | attenuated – emphasized | 0.7 | 3 |
| | Irregular decay | Flutter Echo | none – very strong | 1.0 | 26 |
| | | Echo | none – very strong | 0.7 | 40 |
| | | Irregularity in sound decay | none – very strong | 0.9 | 32 |
| | Coloration | Boominess | not boomy – very boomy | 1.0 | 37 |
| | | Roughness | not rough – very rough | 0.7 | 31 |
| | | Comb filter coloration | none – very strong | 0.8 | 34 |
| | Clarity | Temporal clarity | clear – blurred | 1.0 | 10 |
| | | Spatial transparency | blurred – transparent | 1.0 | 1 |
| | | Precision of localization | precise – diffuse | -0.8 | -6 |
| | Liveliness | Liveliness | dead – lively | 1.0 | 11 |
| | | Spatial presence | low – high | 1.0 | 63 |
| | | Dynamic range | small – large | 0.9 | 50 |
| | Intimacy | Intimacy | remote – intimate | 1.0 | -3 |
| | | Distance | close – distant | -0.8 | 51 |
| | | Warmth | cool – warm | 0.5 | 3 |
| Single items | | Metallic tone color | not metallic – very metallic | | |
| | | Openness | open – constricted | | |
| | | Attack | soft – crisp | | |
| | | Richness of sound | low – high | | |

classifications compared to an *a priori* probability of 3.2% for most rooms (2.1% for the ten rooms not suitable for orchestra play). Hence, the factors are able to reliably discriminate between different rooms, even if the factor scores alone are, of course, not able to identify a specific room.

**E. Primary research data**

All primary research data of the current study are available as a digital publication (Ackermann *et al.*, 2018) includes 3D mod...

performance venues for music and speech. In a first step, a vocabulary of 50 attributes was generated by an expert focus group, including scholars as well as room acoustical consultants. Even if some of the attributes turned out to be unsuitable in the following stimulus-based evaluation, the item battery itself can be considered as an attempt to standardize the mostly inconsistent terminology to assess the qualities of performance venues for music and ...

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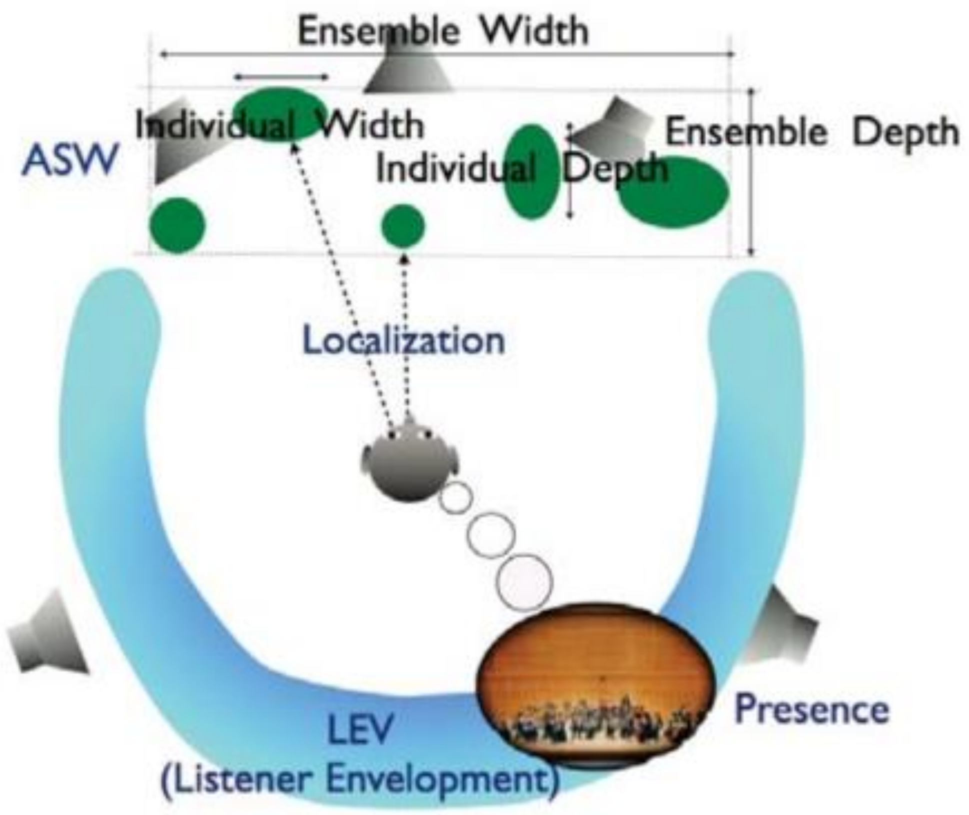
# Important spatial attributes for audio/music in enclosed rooms

Apparent Source Width (ASW)




Listener Envelopement (LEV)

Kamekawa 2013

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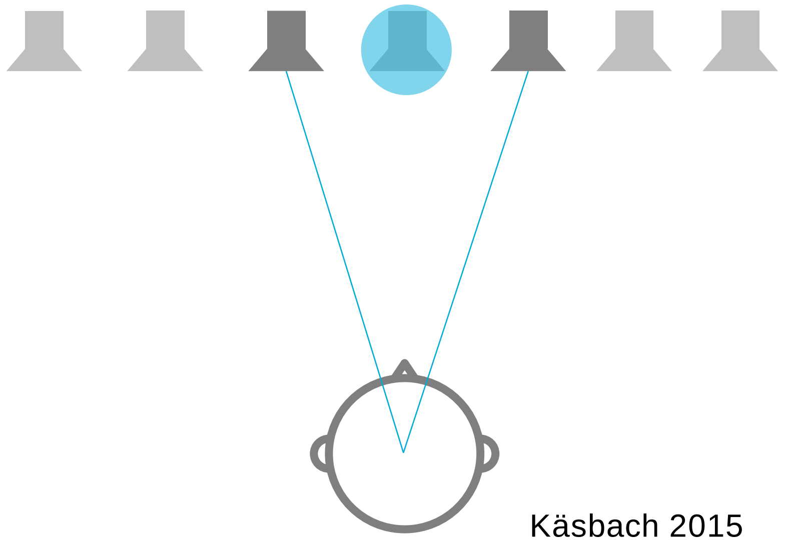
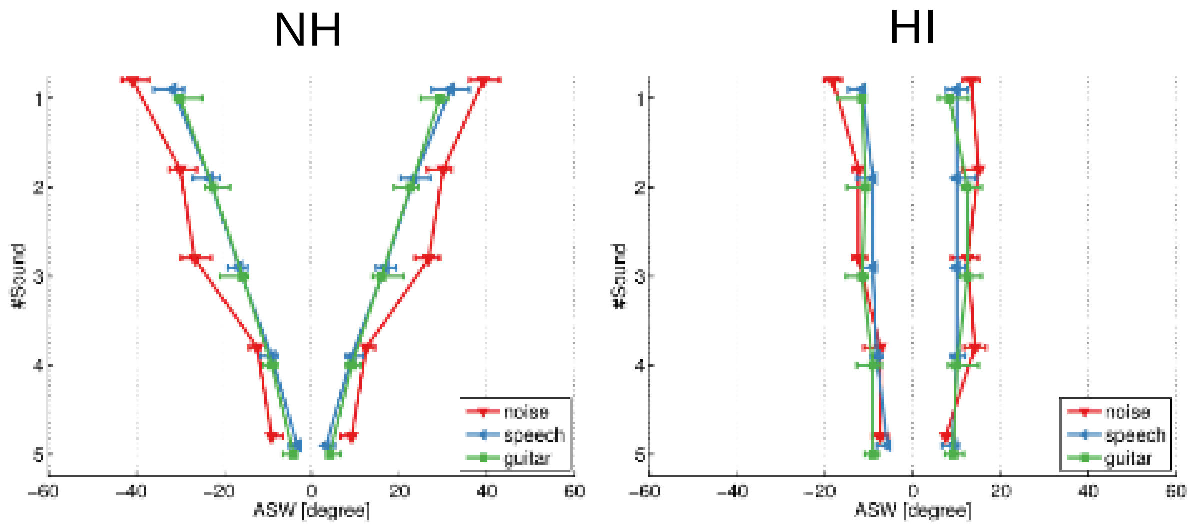
# ASW in normal hearing (NH), hearing impaired (HI)

| Sound | Parameters | | | $IACC_{E3}$ | | |
|---|---|---|---|---|---|---|
| | LS ang. [°] | dist. [m] | Φ [°] | noise | speech | guitar |
| #1 | ±42.5 | 2,29 | 30 | 0.49 | 0.43 | 0.61 |
| #2 | ±30 | 1,95 | 40 | 0.47 | 0.53 | 0.54 |
| #3 | ±30 | 1,95 | 20 | 0.62 | 0.67 | 0.63 |
| #4 | ±16 | 1.74 | 20 | 0.71 | 0.73 | 0.80 |
| #5 | ±0 | 1.69 | - | 0.82 | 0.85 | 0.80 |

Phantom sound source






Käsbach 2015

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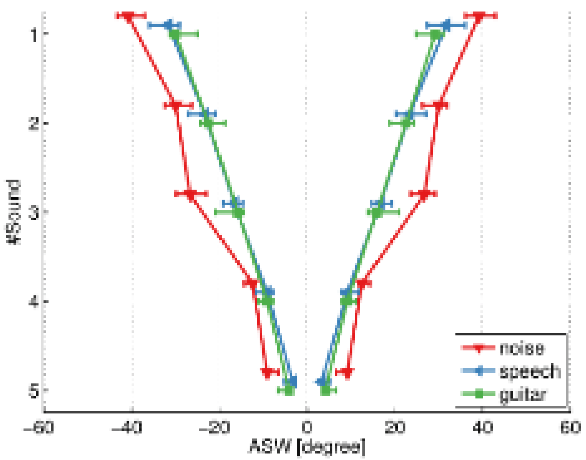
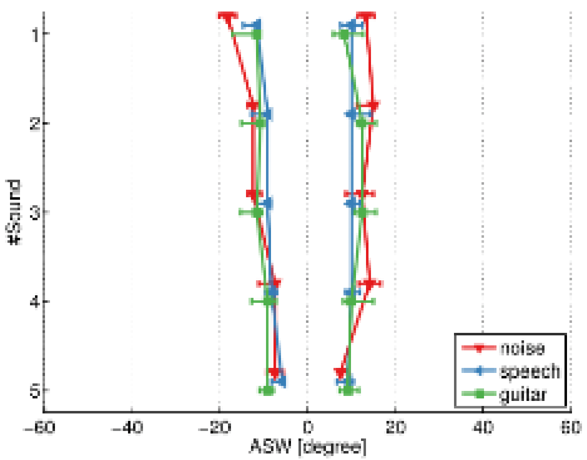
# ASW in normal hearing (NH), hearing impaired (HI) and aided listening

| Sound | Parameters | | | $IACC_{E3}$ | | |
|---|---|---|---|---|---|---|
| | LS ang. [°] | dist. [m] | $\Phi$ [°] | noise | speech | guitar |
| #1 | ±42.5 | 2,29 | 30 | 0.49 | 0.43 | 0.61 |
| #2 | ±30 | 1,95 | 40 | 0.47 | 0.53 | 0.54 |
| #3 | ±30 | 1,95 | 20 | 0.62 | 0.67 | 0.63 |
| #4 | ±16 | 1.74 | 20 | 0.71 | 0.73 | 0.80 |
| #5 | ±0 | 1.69 | - | 0.82 | 0.85 | 0.80 |

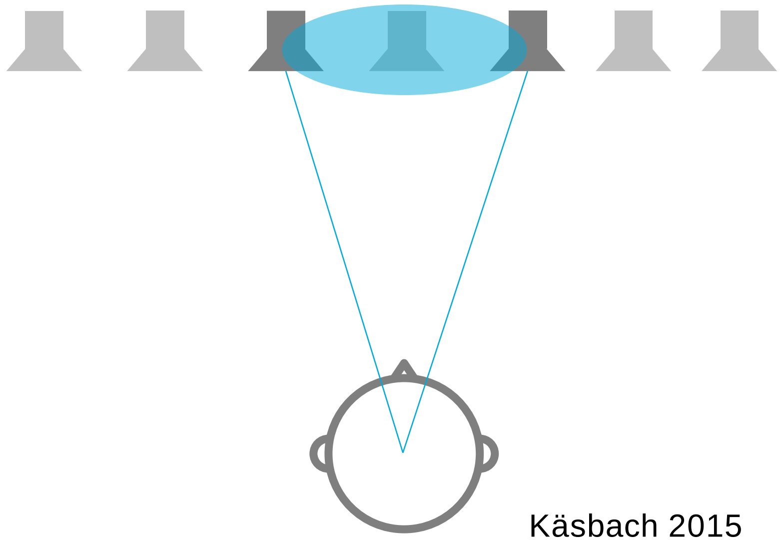
NH




HI




Phantom sound source



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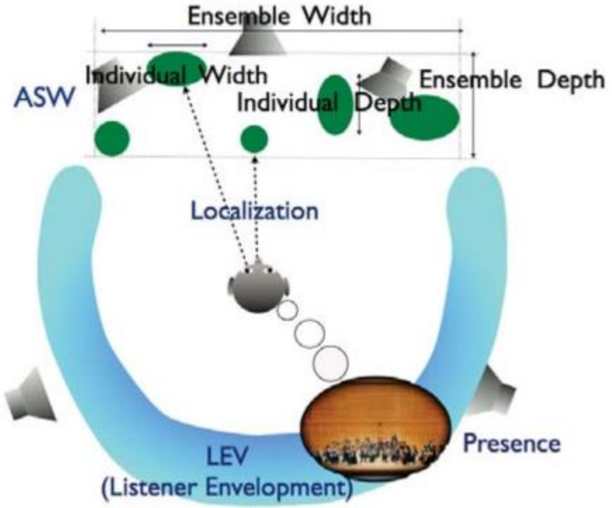
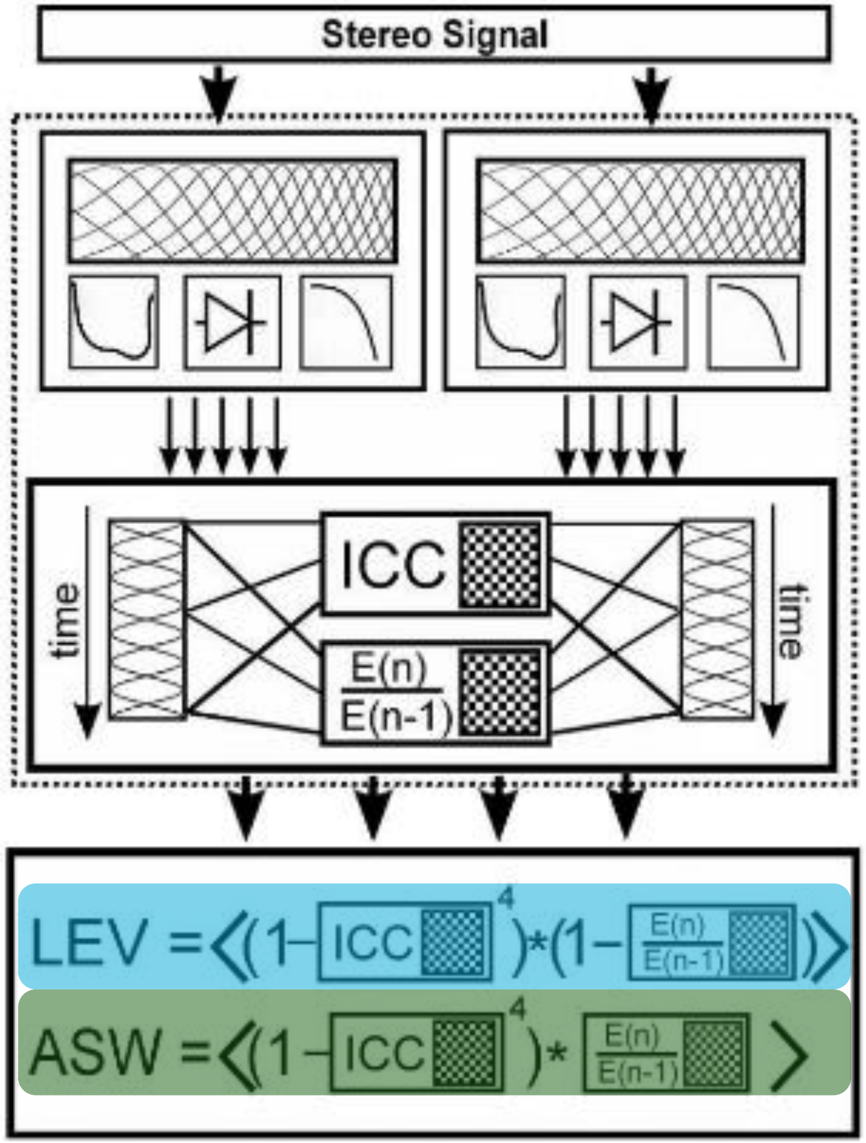
# Modelling LEV and ASW

**Apparent Source Width (ASW)**




**Listener Envelopement (LEV)**




Δt = 40 ms

Kamekawa 2013
Klockgether 2014

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# Energie based measures to characterize concert hall acoustics

– Subjective level of sound

Strength *G*

$$G = 10\,log_{10}\frac{\int_0^\infty p^2(t)dt}{\int_0^\infty p_A^2(t)dt}$$

$p_A$: level, 10 m away from omnidirectional source

– Perceived reverberance

Early decay time EDC(t)

$$EDC(t) = \int_t^\infty h^2(\tau)\,d\tau$$

– Perceived clarity of sound

– Clarity $C_{80}$ in dB

$$C_{80} = 10\,log_{10}\frac{\int_0^{80\,ms} p^2(t)dt}{\int_{80\,ms}^\infty p^2(t)dt}$$

Effects of e.g. IACC not reflected!

– Apparent source width

– Early lateral energy fraction $J_{LF}$

$$J_{LF} = 10\,log_{10}\frac{\int_{5\,ms}^{80\,ms} p_8^2(t)dt}{\int_{0\,ms}^{80\,ms} p^2(t)dt}$$

$p_8$: figure of eight mic

– Listener envelopement

– Late lateral sound level $L_J$

$$L_J = 10\,log_{10}\frac{\int_{80\,ms}^\infty p_8^2(t)dt}{\int_{0\,ms}^\infty p_A^2(t)dt}$$

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# General literature references

Blauert, J. (1996) Spatial hearing: The psychophysics of human sound localization (revised Edition). MIT Press, ISBN 978-0-262-26868-4
https://doi.org/10.7551/mitpress/6391.001.0001

Pulkki, V., Karjalainen, M. (2015) Communication acoustics : an introduction to speech, audio, and psychoacoustics. Wiley and Sons, ISBN 978-1-118-86654-2

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# Applied Psychophysics I – Lecture schedule

| Week | Date | Topic |
|---|---|---|
| 1 | 16.10.24 | Introduction |
| 2 | 23.10.24 | Auditory physiology and selected auditory models |
| 3 | 30.10.24 | Suprathreshold scaling methods |
| 4 | 06.11.24 | Loudness perception, loudness models and audio metering |
| 5 | 13.11.24 | Selected sensations, sound attributes and measurement of timbre |
| 6 | 20.11.24 | Chocolate results Presentation topics |
| 7 | 27.11.24 | Spatial hearing sensations |
| 8 | 04.12.24 | Audio quality assessment methods and model approaches |
| 9 | 11.12.24 | Calibration of listening setups |
| 10 | 18.12.24 | Ethics and data protection |
| | | Winter break |
| 11 | 08.01.25 | Student presentations |
| 12 | 15.01.25 | Student presentations |
| 13 | 22.01.25 | Student presentations |
| 14 | 29.01.25 | Student presentations |

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# Your comments and take-home messages

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# Papers for presentation

| | Date | Topic | Presenter | Date |
|---|---|---|---|---|
| 1 | Porysek et al. 2024 | Identifying Principal Attributes for Evaluating Audio Quality of Reproduction Systems With Spatially Dynamic Program Material | Pascal | |
| 2 | Marozeau 2007 | The effect of fundamental frequency on the brightness dimension of timbre | (Patrick) | |
| 3 | Jacobsen & Siedenburg 2024 | Exploring the relation between fundamental frequency and spectral envelope in the perception of musical instrument sounds | Patrick | |
| 4 | Culling et al. 2024 | Effect of ambisonic order on spatial release from masking | Annika | |
| 5 | Hots et al. 2024 | Spatial weights in loudness judgements | Konosuke | |
| 6 | Aker et al. 2024 | Some, but not all, cochlear implant users prefer music stimuli with congruent haptic stimulation | Florian | |
| 7 | Bürgel et al. 2024 | Enhanced salience of edge frequencies in auditory pattern recognition | | |
| 8 | JosephBenjamin & Siedenburg 2023 | Exploring level- and spectrum-based music mixing transforms for hearing-impaired listeners | Porsche Phufah? | |
| 9 | Szwarcberg & Lavandier 2024 | Third-octave analyses describing two perceptual dimensions of sound reproduction and the resulting overall perceived dissimilarity between loudspeakers or headphones | | |
| 10 | Madsen & Oxenham 2024 | Mistuning perception in music is asymmetric and relies on both beats and inharmonicity | | |

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# Papers for presentation

| | Date | Topic | Presenter | Date |
|---|---|---|---|---|
| 11 | Francombe 2017a,b | Evaluation of Spatial Audio Reproduction Methods<br>Part 1: Elicitation of Perceptual Differences / Part 2: Analysis of Listener Preference | | |
| 12 | Wilson 2016 | Perception of Audio Quality in Productions of Popular Music | Porsche | |
| 13 | JosephBenjamin & Siedenburg 2024 | Evaluating audio quality ratings and scene analysis performance of hearing-impaired listeners for multi-track music | Phufah | |
| 14 | Aker 2024b | Perceived auditory dynamic range is enhanced with wristbased tactile stimulation | | |
| 15 | | | | |
| 16 | | | | |
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| 19 | | | | |
| 20 | | | | |

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| | | Winter break |
| 11 | 08.01.25 | Student presentations Annika |
| 12 | 15.01.25 | Student presentations Patrick |
| | 22.01.25 | Student presentations |
| 14 | 29.01.25 | Student presentations |

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# Thank you for your attention!

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