Aalto University
School of Electrical Engineering

Tutorial 26
Applications of Binaural Psychoacoustics in Audio — Designing Spatial Audio Techniques for Human Listeners

Ville Pulkki

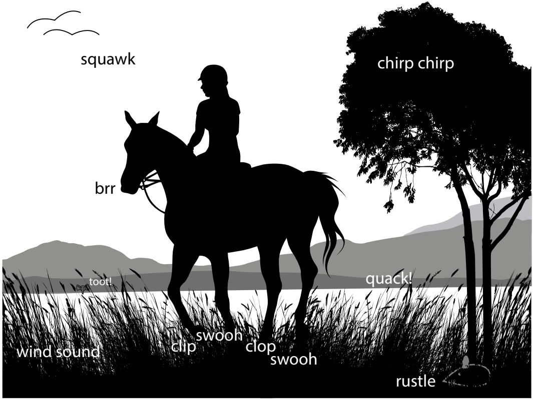
Department of Signal Processing and Acoustics
Aalto University, Finland

Background literature

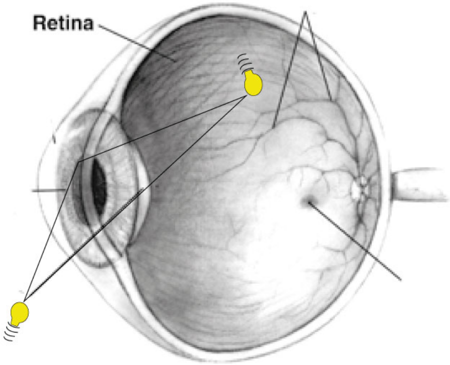
- "Communication acoustics – Introduction to Speech, Audio and Psychoacoustics" Textbook. Ch 12: Spatial hearing, Pulkki & Karjalainen 2015, Wiley
- "Parametric time-frequency-domain spatial audio" Contributed book with 15 chapters. eds Pulkki, Delikaris-Manias and Politis, Wiley, early 2017

Where and what?

- Localization of sources
- Beam-forming towards different directions

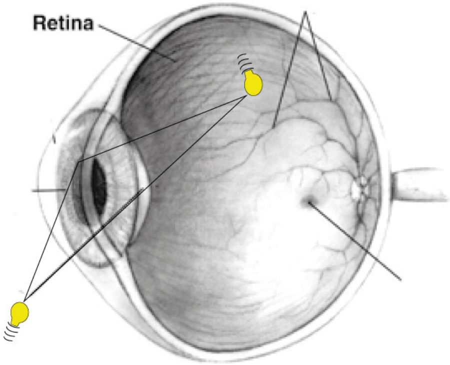


Human eye



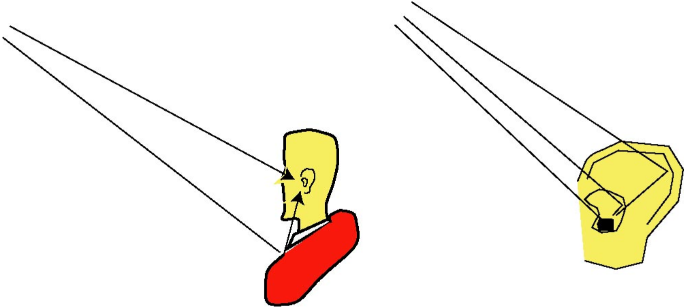
- The cells in the eye are a priori sensitive to direction of light

Human eye



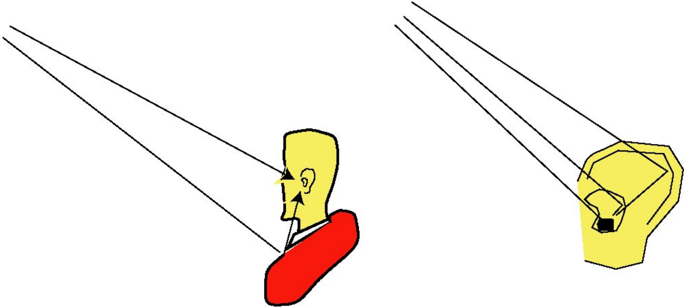
- The cells in the eye are a priori sensitive to direction of light
- Response to quite limited range of wavelengths (380-740nm)

Human spatial hearing



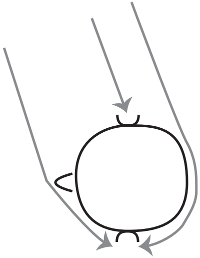
- Response to very large range of wavelengths (2cm–30m)
- Ear canal diameter $<$1cm, sound just bends into the canal

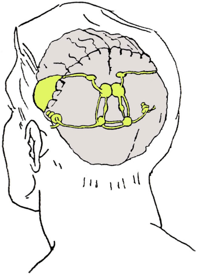
Human spatial hearing



- Response to very large range of wavelengths (2cm–30m)
- Ear canal diameter $<$1cm, sound just bends into the canal
- One ear alone knows quite little of the spatial position of the source

Human spatial hearing

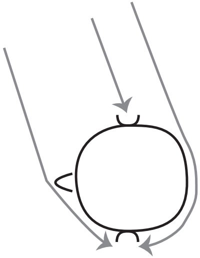


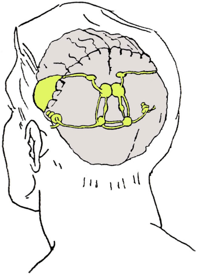


ⓒJ. Blauert

- The sources are localized by signal analysis by the brains

Human spatial hearing

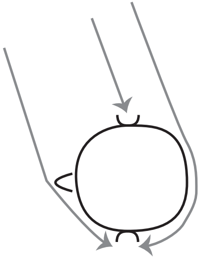


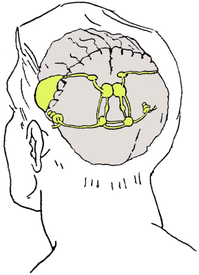


© J. Blauert

- The sources are localized by signal analysis by the brains
- Signal characteristics in one ear / Signal differences between two ears

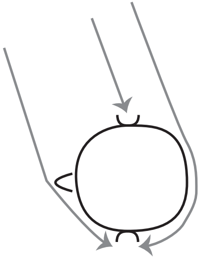
Human spatial hearing

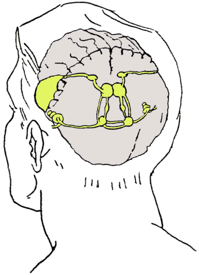




- The sources are localized by signal analysis by the brains
- Signal characteristics in one ear / Signal differences between two ears
- Hearing mechanisms estimate the most probable position for source

Human spatial hearing





©J. Blauert

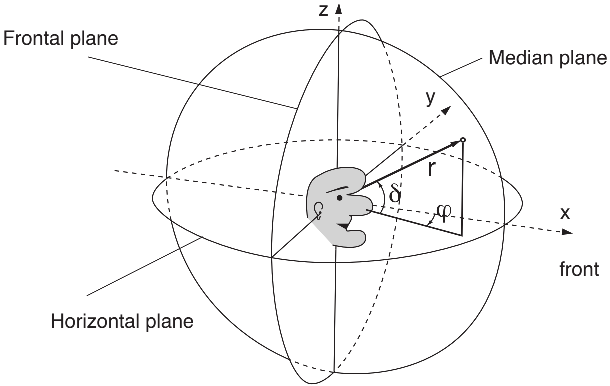
- The sources are localized by signal analysis by the brains
- Signal characteristics in one ear / Signal differences between two ears
- Hearing mechanisms estimate the most probable position for source
- Hearing can be fooled easily by audio techniques!

This chapter

- Basic concepts
- Head-related acoustics
- Localization cues
- Localization accuracy
- Perception of direction in presence of echoes
- Ability to listen selectively specific direction
- Distance perception

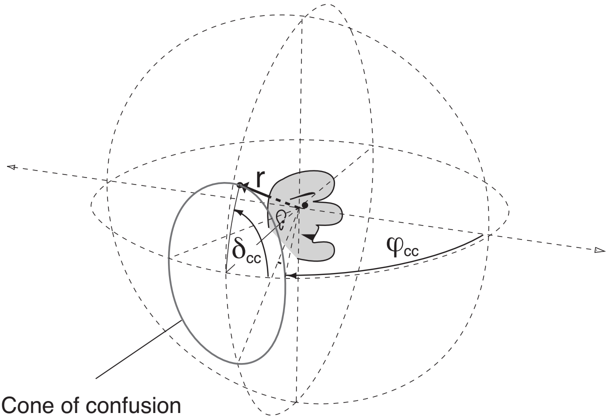
Coordinate system

- Azimuth-elevation / median plane



Coordinate system 2

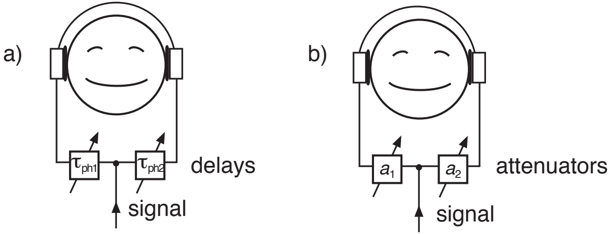
- Cone of confusion



Basic concepts

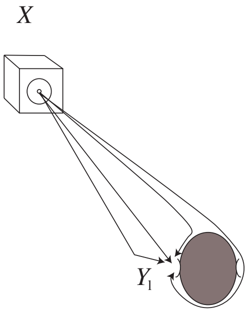
- Listening conditions
  - Monaural hearing (hearing processes and cues that need signal from only one ear)
  - Binaural hearing (differences in ear signals have also an effect)
- Spatial sound reproduction methods
  - Monotic (signal fed to only one ear)
  - Diotic (same signal fed to both ears)
  - Dichotic (different signal fed to ears)

Dichotic listening with headphones



Head-related acoustics

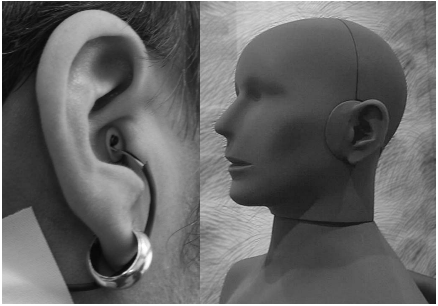
- Let us consider only free field first
- How does incoming sound change as it hits the listener?
- What is the transfer function from source to ear canal?



$$Y_{\mathrm{left}} = H_{\mathrm{left}} X \qquad y_{\mathrm{left}} = h_{\mathrm{left}}(t) * x(t)$$

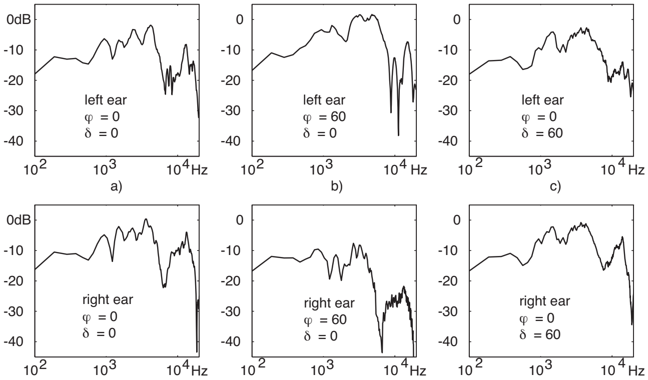
Head-related acoustics measurements

- Transfer function from source to ear canal
- Place a microphone to ear canal or use dummy heads
- Head-related transfer function, head-related impulse response
- Depends heavily on the direction of the source



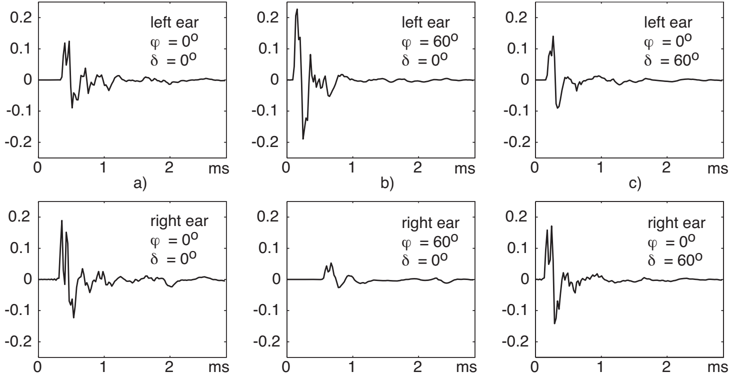
Head related transfer function (HRTF)

- Measured with real subject for three directions
- Magnitude response

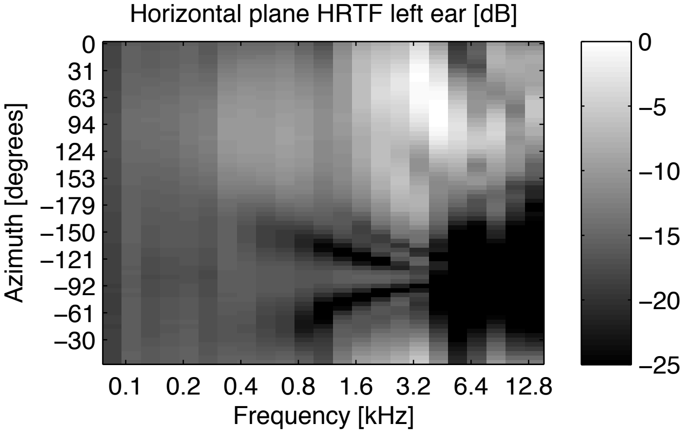


Head related impulse response (HRIR)

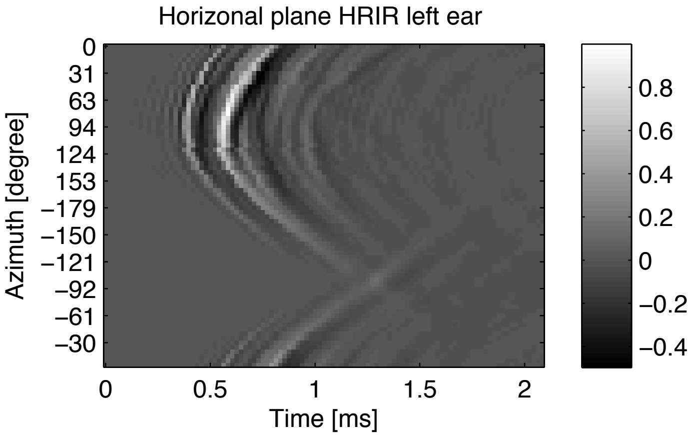
- HRIR == HRTF in time domain, quite often HRIRs are also called HRTFs



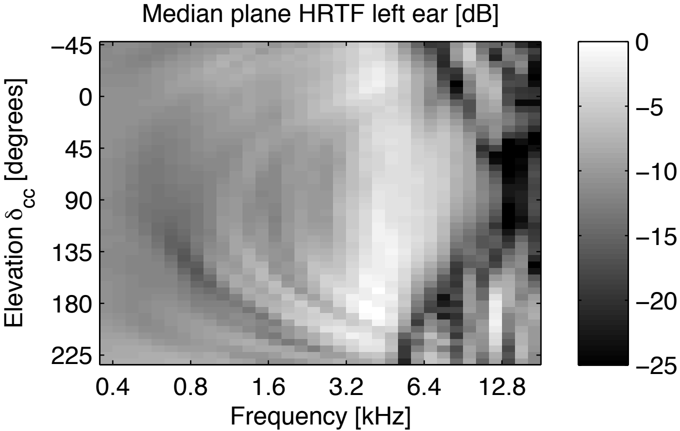
HRTF in horizontal plane



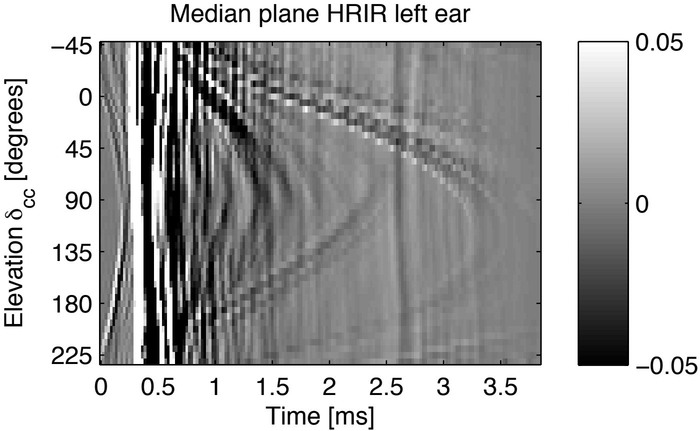
HRIR in horizontal plane



HRTF in median plane



HRIR in median plane



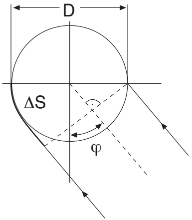
Localization cues

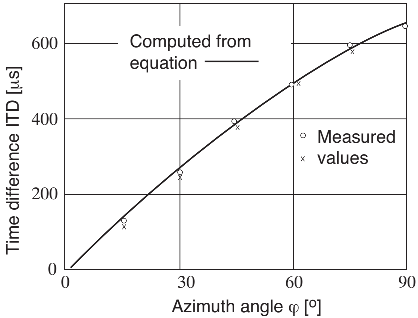
- HRTFs impose some spatial information to ear canal signals
- What information do we dig out from those?
- Binaural localization cues
  - Interaural time difference, ITD
  - Interaural level difference, ILD
- Monaural localization cues: spectral cues
- Dynamic cues

Interaural time difference (ITD)

- Sound arrives a bit earlier to one ear than the other
- ITD varies between -0.7ms and +0.7ms
- JND of ITD is of order of 20μs

$$\tau = \frac{D}{2c}(\varphi + \sin\,\varphi)$$

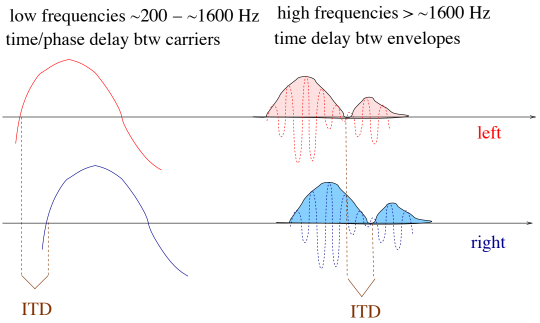




Interaural time difference (ITD)

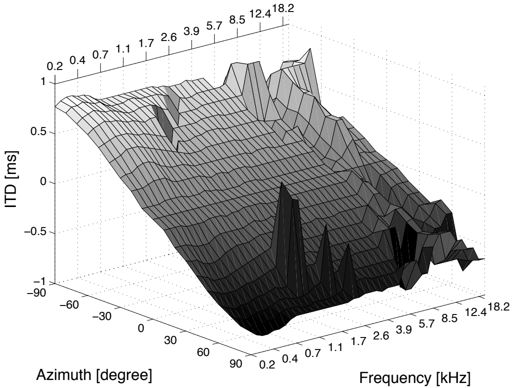
We are sensitive to

- phase differences at low frequencies
- time differences between envelopes at higher frequencies



Interaural time difference

- HRTFs measured from a human, ITD of noise sound source in free field computed with an auditory model

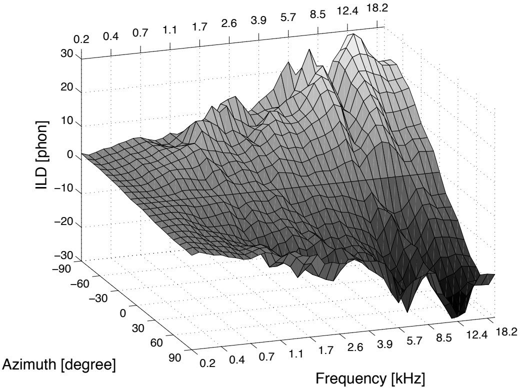


Interaural level difference (ILD)

- Head shadows incoming sound
- Effect depends on
  - wavelength, no shadowing at low frequencies
  - distance, larger ILD at very short distances (< 1m)
- ILD varies between -20dB and 20dB
- JND is of order of 1dB for sources near median plane

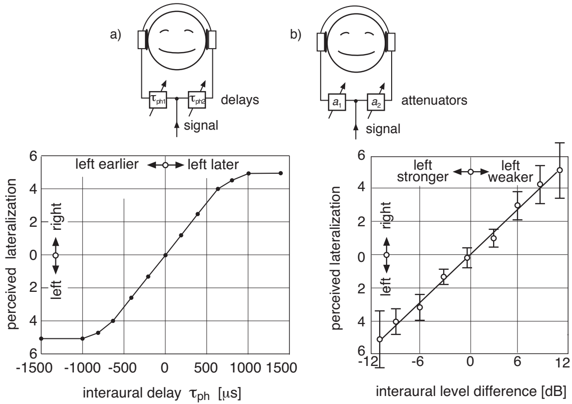
Interaural level difference

- HRTFs measured from a human, ILD of sound source in free field computed with an auditory model



Basic lateralization results

- Subjects report the position of internalized auditory source on interaural axis

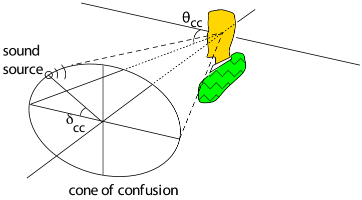


(Toole and Sayers, 1965)

(Sayers, 1964)

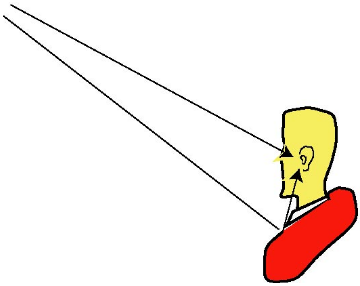
Addtional cues

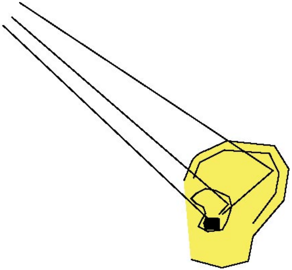
- Binaural cues (ITD and ILD) in principle resolve only the cone of confusion where the source lies
- Other cues are used to resolve the direction inside the cone
  - monaural spectral cues
  - dynamic cues (effect of head movements to cues)



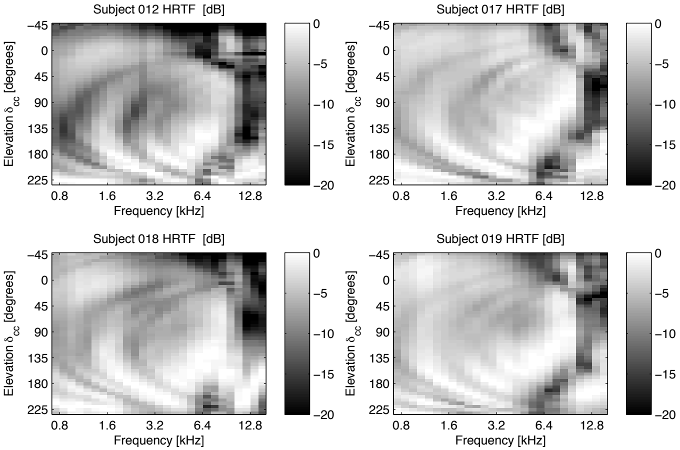
Monaural spectral cues

- Effect of pinna diffraction
- Effect of reflections/diffraction from torso





Monaural spectral cues

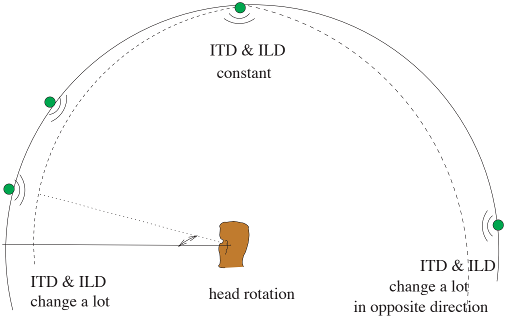


Monaural spectral cues

- Source has to have relatively flat spectrum
- Relatively reliable cue for most natural sounds
- Narrow-band sounds hard to localize (mosquito in dimmed room)
- Humans adapt relatively fast to new HRTFs, especially of visual cues are available
- The ears also grow throughout the life, constant adaptation

Dynamic cues

- When head rotates, ITD and ILD and spectral cues change
- Powerful though coarse cue
- Resolves efficiently front/back/inside-the-head locations, but not fine details



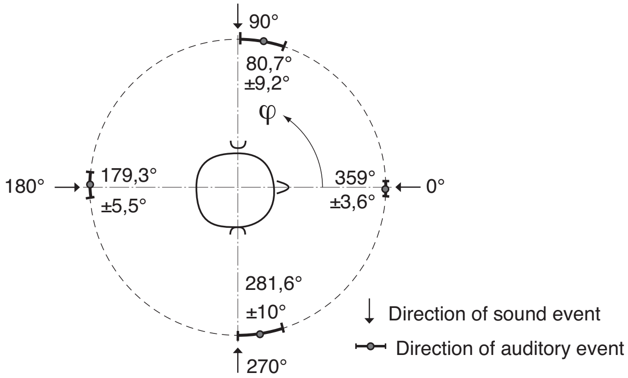
Interaction between spatial hearing and vision

- Both senses try to find out "where" is the source
- If visual cue is clear, vision dominates
- Ventriloquism, within about 30° area visual image captures auditory image
- If visual cue is blurry, or not prominent, auditory cue wins
- In some cases two events occur, visual event and auditory event

Accuracy of localization

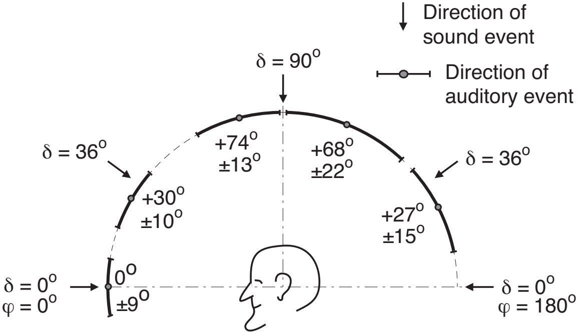
- How well do we localize point-like sources?
- What is the accuracy of directional hearing?
- Azimuth / elevation / 3D
- Accuracy of perception of spatial distribution of wide sound sources

Localization accuracy in horizontal plane



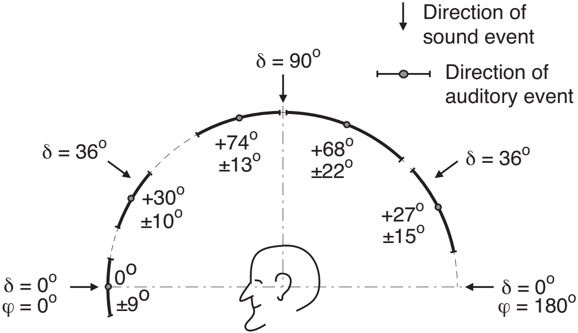
Adapted from Blauert (1996)

Localization accuracy in median plane



Adapted from Damaske and Wagener (1969)

Localization accuracy in median plane

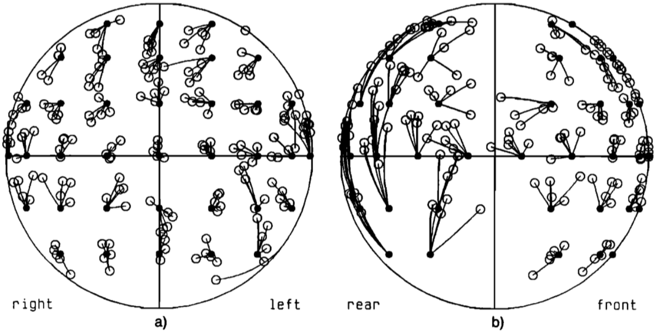


Adapted from Damaske and Wagener (1969)

- Monaural cues are effective only after adaptation with visual reference, thus field-of-vision has better accuracy

Accuracy of 3D localization

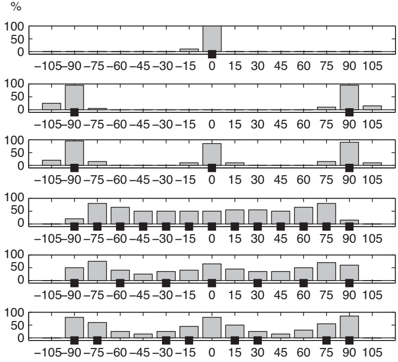
- Task: "Point with nose to the direction of auditory event"



Adapted from Middlebrooks (1992)

Accuracy of perception of spatial distribution of sources

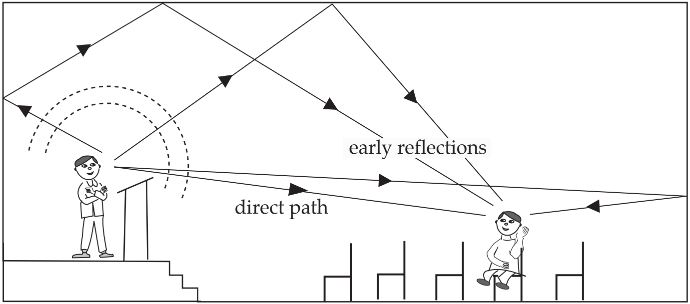
- 13 loudspeakers in free field, black squares denote loudspeakers that produced pink noise
- Task: "Tell which loudspeakers are on"
- Incorrect perception of distribution in complex cases
- Perception of spatial distribution of 1, 2, or 3 loudspeakers correct



Adapted from Santala and Pulkki (2011)

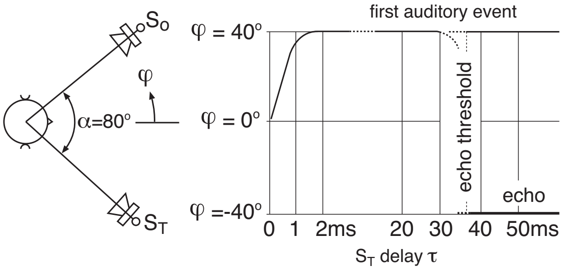
Directional hearing in enclosed spaces

- Previous results in free field
- What about rooms?
- Humans are relatively ok in localization in rooms. How come?



Precedence effect

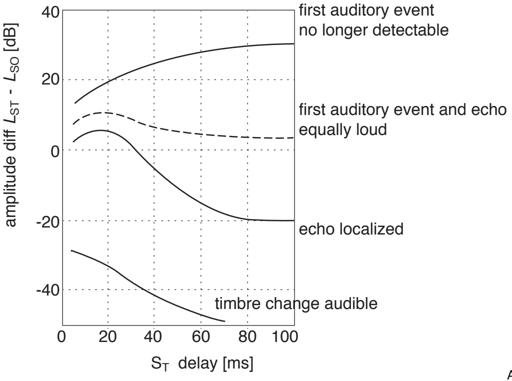
- Free-field exists only for short time 1–10ms after direct sound has arrived, and reflections not yet
- The short time dominates in direction perception
- Reflections (2 - 30ms) are perceived to arrive from the direction of direct sound



Adapted from Blauert (1996)

Precedence effect, experiments with two sounds

- Direct sound S_0: "lead"
- Reflected sound S_T: "lag"



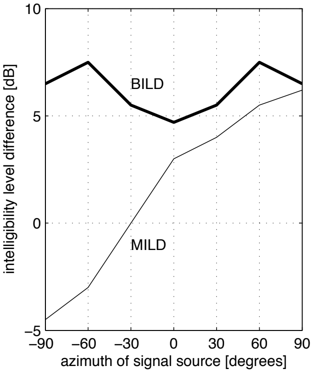
Adapted from Blauert (1996)

Binaural Advantages in Timbre Perception

- Try to listen selectively certain direction
- Binaural detection
- Binaural decolouration

Binaural intelligibility level difference

- Minimum understandable level of speech source in different directions in diffuse noise
- Reference condition: binaural listening with source in back
- Binaural intelligibility level difference (BILD)
- Monaural intelligibility level difference (MILD)
- MILD: best heard with source on same side
- BILD gives few decibels advantage to ipsilateral MILD
- "Better-ear" listening explains most of the effect
- Binaural hearing assists by few dB



Adapted from Blauert (1996)

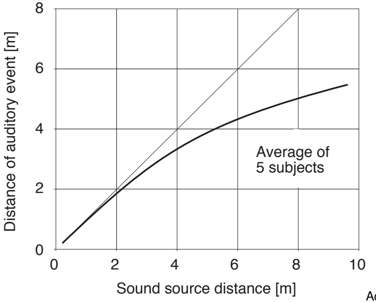
Perception of the distance of source

Cues

- Loudness
- Room effect
- Spectral content
- Binaural cues

Distance cue 1: Loudness

- Amplitude of direct sound decreases with $1/r$ law
- The sound energy carried by the surface of a sphere ($A = 4\pi r^2$) is constant, and pressure is related to square root of energy
- SPL decreases 6dB with every doubling of distance
- If we know the source (human talker, insect, walking sounds), the distance is perceived relatively accurately in short
- In free field with real human speaker, similar effect is found:



Adapted from Békésy (1949)

Distance cue 2: Effect of room

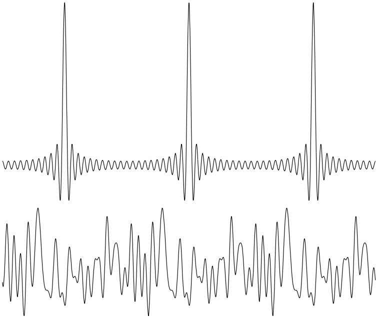
- Direct-to-reverberant ratio (DRR) is often mentioned as "perceptual cue", though it is rather a physical measure
- If the listener has heard a source in a specific room, the change in DRR leads into perception of approaching or distancing source
- Effect depends on signal.
- Easily perceivable on harmonic tone complexes

Distance cue 2: Effect of room

- The characteristics in ear canal signals change with DRR = one of distance cues
- The cue is not known well / which modification in the signal produces the perception
- One possibility is the sensitivity of ear to phase

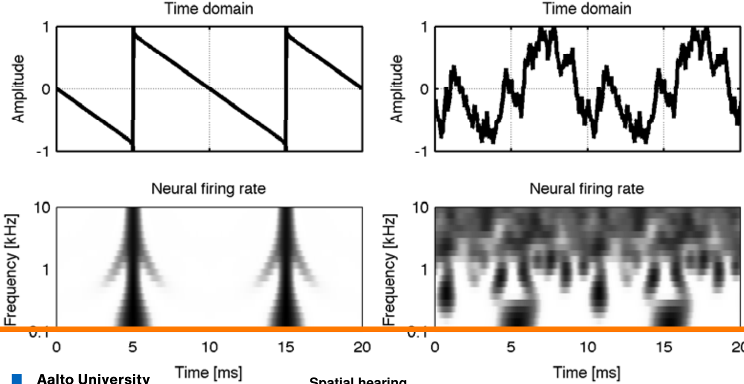
Zero-phase cosine signal

Random-phase (scrambled by the room effect) version



Response of cochlea to 100Hz sawtooth with phase modifications

- Hypothesis: what more "buzzy" is signal, that closer it is perceived (in a room)
- Original sound   phase scrambled with flat magnitude response



Adapted from Laitinen et al. 2013

Distance cue 3: Effect of air absorption

- shear viscosity, thermal conductivity or heat dissipation, and molecular relaxation due to oxygen, nitrogen, and water vapor vibrational, rotational, and translational energy
- depends on temperature, humidity, static pressure
- low-pass effect
- can for instance have values [1-100]dB/km
- known sounds are perceived closer if they have more energy at high frequencies
- hissing is perceived closer than normal speech

Distance cue 4: short-range binaural cues

- with plane waves, the ILD at low frequencies is negligible
- e.g., when source is 3cm from one ear, it is 30cm from the other ear
- $1/r$ law makes ILD to have high magnitude
- excess-ILD re ITD brings perceived source closer

Accuracy of distance perception

- In many studies
  - source is perceived too far in short distances
  - source is perceived too close in high distances
- Acoustic horizon, maximum perceived distance of auditory event
- Perception depends on signal, listening conditions and source directivity
- Absolute accuracy low
- Relative accuracy good (Is the source approaching?)

References

These slides follow corresponding chapter in: Pulkki, V. and Karjalainen, M. Communication Acoustics: An Introduction to Speech, Audio and Psychoacoustics. John Wiley & Sons, 2015, *where also a more complete list of references can be found.*

References used in figures:

Blauert, J. (1997) Spatial Hearing – Psychophysics of Human Sound Localization. MIT Press.

Damaske, P. and Wagener, B. (1969) Directional hearing tests by the aid of a dummy head. Acta Acustica United with Acustica, 21(1), 30–35.

Middlebrooks, J.C. (1992) Narrow-band sound localization related to external ear acoustics. J. Acoust. Soc. Am., 92, 2607–2624.

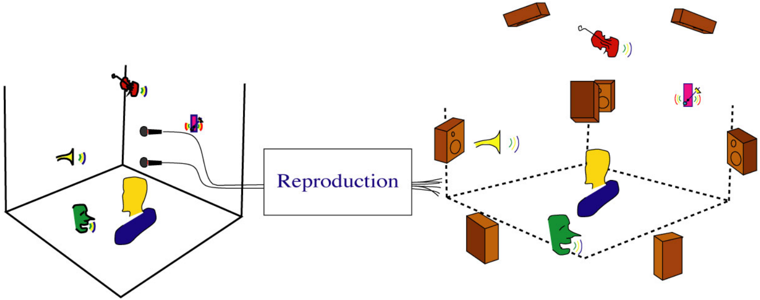
Santala, O. and Pulkki, V. (2011) Directional perception of distributed sound sources. J. Acoust. Soc. Am., 129, 1522.

Sayers, B.M. (1964) Acoustic-image lateralization judgments with binaural tones. J. Acoust. Soc. Am., 36(5), 923–926.

Toole, F. and Sayers, B.M. (1965) Lateralization judgments and the nature of binaural acoustic images. J. Acoust. Soc. Am., 37(2), 319–324.

von Békésy, G. (1949) The moon illusion and similar auditory phenomena. Ame. J. Psychol., 62(4), 540–552.

Spatial sound reproduction



Target: relay the perception of sound!

Spatial sound reproduction

Could we do the same with sound than with video camera

- Create narrow beam for each loudspeaker
- Audible sound includes wave lengths from 2 cm to about 30 m
- Impossible to build a microphone having constant narrow beam width without coloration and noise problems
- Higher-order Ambisonics try to do it

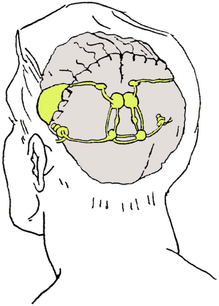
Spatial sound reproduction

Holography then, perhaps?

- Lots of spaced microphones
- Lots of loudspeakers
- Wave field synthesis
- Problems
  - High price
  - Requirements for microphones and loudspeakers are high

Human spatial hearing

- Signals from different sources summed in ear canals
- Sound localization is based on *signal analysis* in brains
- At one auditory frequency band one can perceive directions in limited manner



ⓒJ. Blauert

Human spatial hearing

- Directional cues
  - Interaural time difference (ITD)
  - Interaural level difference (ILD)
  - Pinna- and torso-related spectral cues
- Dynamic change of cues with head movements
- Suppression of effect of early reflections on directional cues, precedence effect

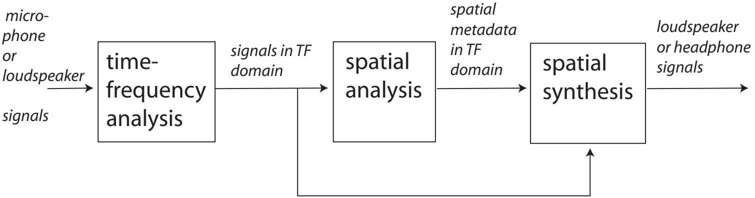
Spatial sound reproduction

Can we exploit knowledge of human spatial hearing?

- Hearing can be fooled easily
- E.g. two coherent sources produce one virtual source in the middle
- Compare with vision: coherent sources do not produce virtual sources
- Assumption: at one frequency band humans perceive only one direction and one coherence cue

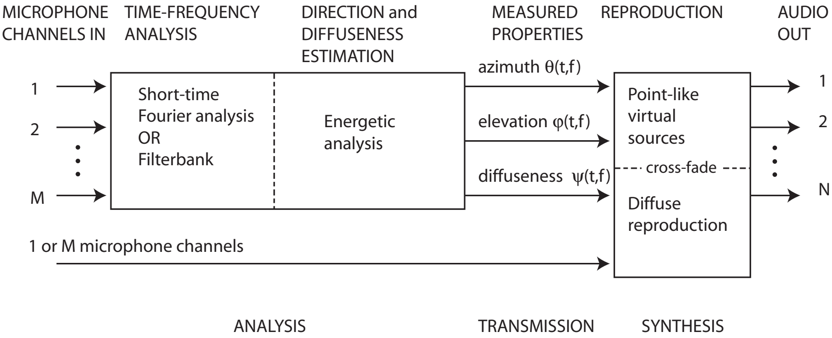
Parametric spatial sound reproduction

- Capture the sound
- Analyze spatial parameters
- Reproduce the sound in a way which recreates the spatial parameters
- Design the system to avoid any timbral artifacts, sacrifice spatial properties first

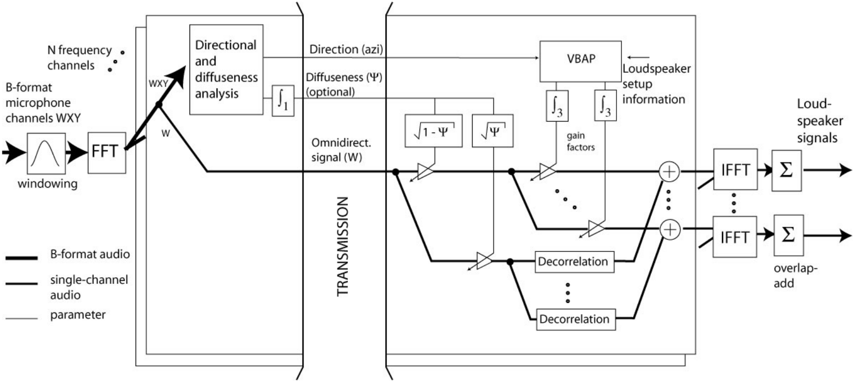


Directional audio coding

Basic flow diagram



"Teleconference" implementation

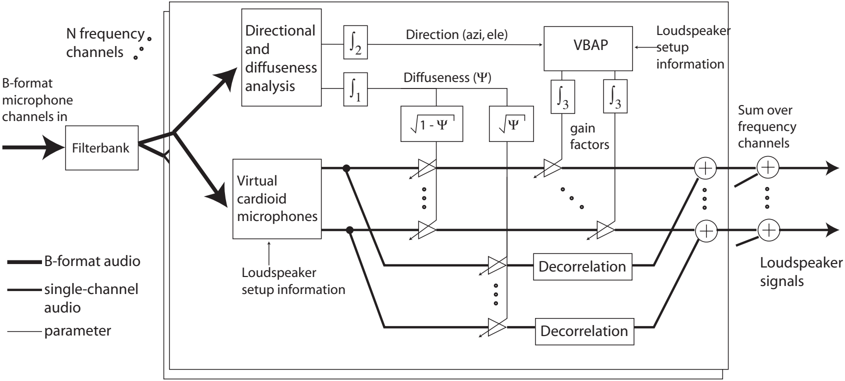


Properties of teleconference-DirAC

- Perfect quality with few sources in free field
- Diffuse reverberation subject to spatial and timbral artifacts
- With several simultaneous sources sharing the same time-frequency position
  - Timbral artifacts: "added room effect", "smearing of transients"
  - Spatial artifacts: "sources pull each other"
  - Sources near noise masking threshold: impossible to localize

Why these artifacts?

"HQ" implementation



This works better, but dont exactly know why (2007).

Properties of HQ-DirAC

- All teleconference-DirAC artifacts are mitigated largely
- Some artifacts still present
- Challenging acoustical conditions
  - Surrounding applause signals
  - Small rooms with strong early reflections
  - Strong unwanted sources
- Potential loss of energy

What did we find out

- In challenging acoustical conditions sound arrives from multiple directions in one time-frequency position
    - diffuseness will be analyzed to be high
        - sound arrives from many directions, the physical properties of the field resemble diffuse field
        - original sound scene is still perceived to be not similar with diffuse reverberation
    - sound is routed to non-diffuse stream
- Decorrelation of free-field components causes artifacts, mainly timbral ones

Avoid decorrelation!

How to avoid decorrelation

- Processing of transients separately
  - Recognize transients
  - Use better time resolution / bypass decorrelation
- Covariance-domain processing
  - minimize decorrelated energy
- Divide sound field into sectors from higher-order recording
  - perform separate analysis for each sector
- Perform more complex analysis to sound field (multiple DOA values etc)

Processing transients

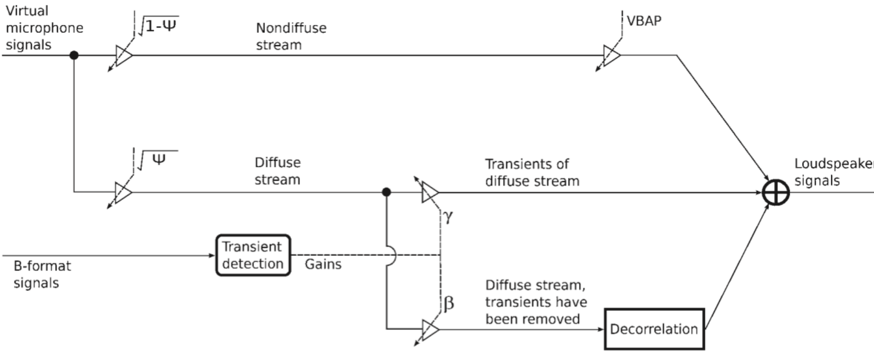


Fig. 4. Block diagram of DirAC processing with transient detection.

J. Audio Eng. Soc., Vol. 59, No. 1/2, 2011 January/February

Processing transients separately

- remove transients, reproduce using simple matrixing.
- mitigates "transient smearing" effects
- "added room" -effects still present with some signals
- needs high temporal resolution in processing
- solves "surrounding applause" cases

[Laitinen et al: JAES 59:1/2]

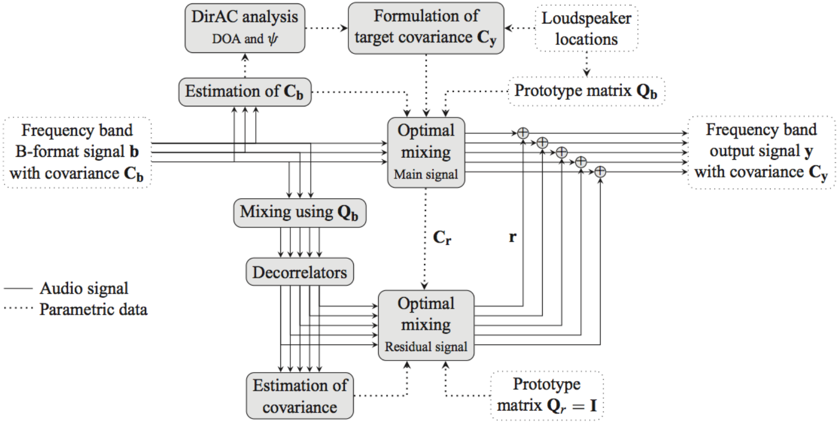
Covariance-domain processing

Least-squares optimized solution for synthesis

- the covariance matrix of output is dictated by directional parameters
- optimized mixing solution leads to minimization of decorrelated energy
- applicable to many other spatial sound rendering tasks

[Vilkamo et al: JAES 61:6]

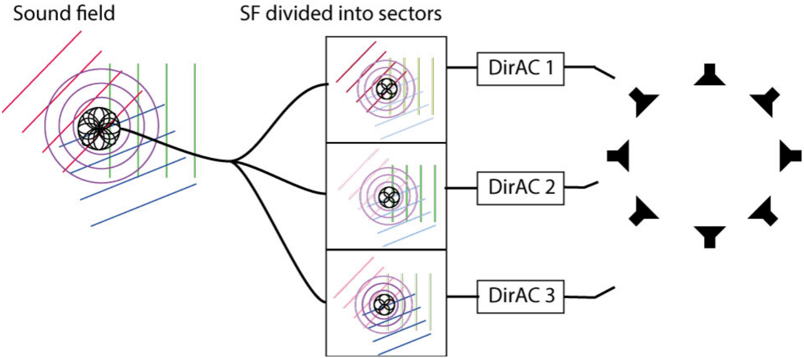
Covariance-domain processing



Solutions with different model of the sound field

- Higher number of microphones gives more information about sound field
- How to use that information in sound reproduction?
- Divide sound field into sectors (Pulkki, Politis), perform lower-order reproduction for each
- Analyze multiple DOAs, and then reproduce (FhG, FORTH, Harpex)

Sector-based parametric spatial sound reproduction



[Pulkki et al: AES 134], [Politis et al: IEEE manuscript]

Sector-based parametric spatial sound reproduction

"Higher-order DirAC"

- Challenging acoustical conditions occur rarely within sectors
- Parameters computed with N:th -order input
- Audio signals used in synthesis obtained with (N-1):th -order input
- Self-noise issue of higher-order microphones are also avoided
- System does not lose acoustic energy in any case