Capturing 360° VR Audio Using Equal Segment Mic Array (ESMA)

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- Background
- Psychoacoustics for microphone array design
- Proposed technique
- Perceptual evaluations and Demo

Background

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- Stereophonic microphone techniques

	Coincident pair	Near-Coincident	Spaced pair
Polar pattern	Uni-directional	Uni-directional	Omni-directional
Configuration	XY, Blumlein, MS	ORTF, NOS	AB, Decca Tree
Stereo cue	ICLD (Leve diff)	ICLD + ICTD	ICTD (Time diff)
Localisability	High	Mid-High	Low-Mid
Spaciousness	Low	Mid-High	High

Background

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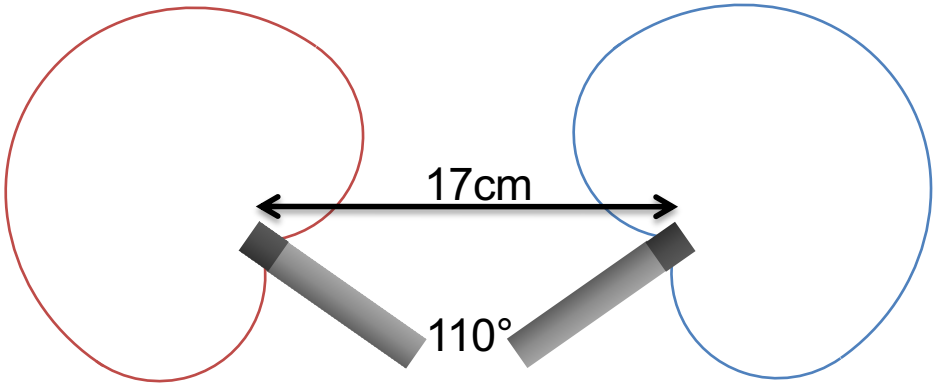
- Near-coincident microphone techniques
  - ORTF, NOS, etc.
  - Popular microphone techniques among recording engineers.
  - Best of both worlds! (Localisability & Spaciousness).



ORTF configuration

Background

- Brown or White?

Background

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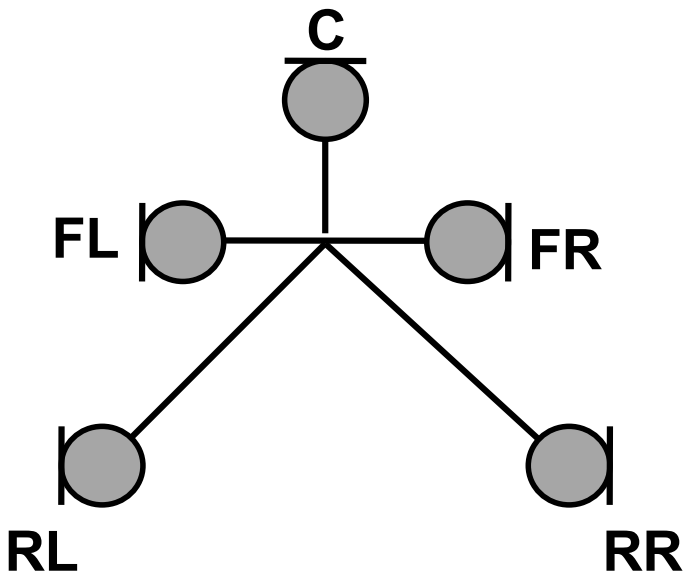
- Near-coincident microphone techniques
  - Also popular for surround microphone techniques.
  - Generally, directional microphones are used for balanced localisation and spatial impression.
  - OCT [Theile/Wittek], ICA [Williams], Fukada Tree, etc.



How to design a near-coincident mic array for 360VR?

Requirements for VR mic arrays

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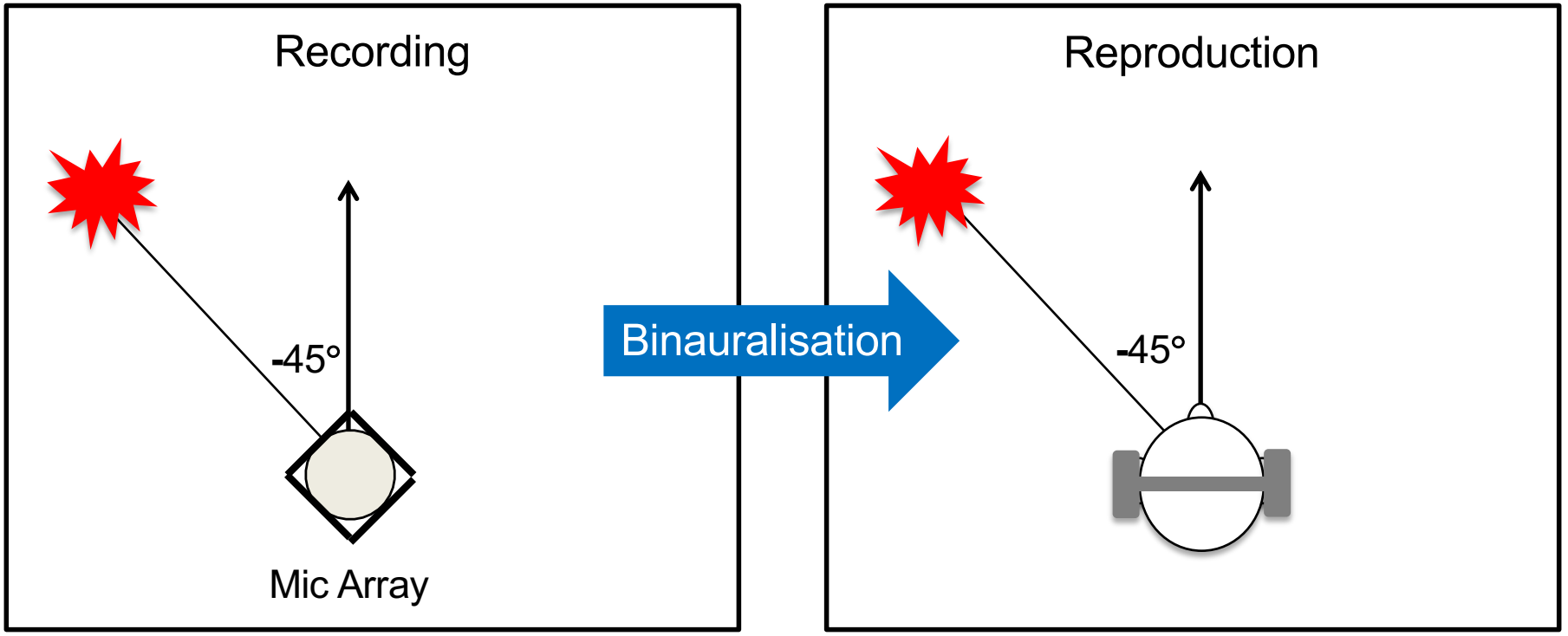
1. The actual and perceived image positions should match (ideally!).



Requirements for VR mic arrays

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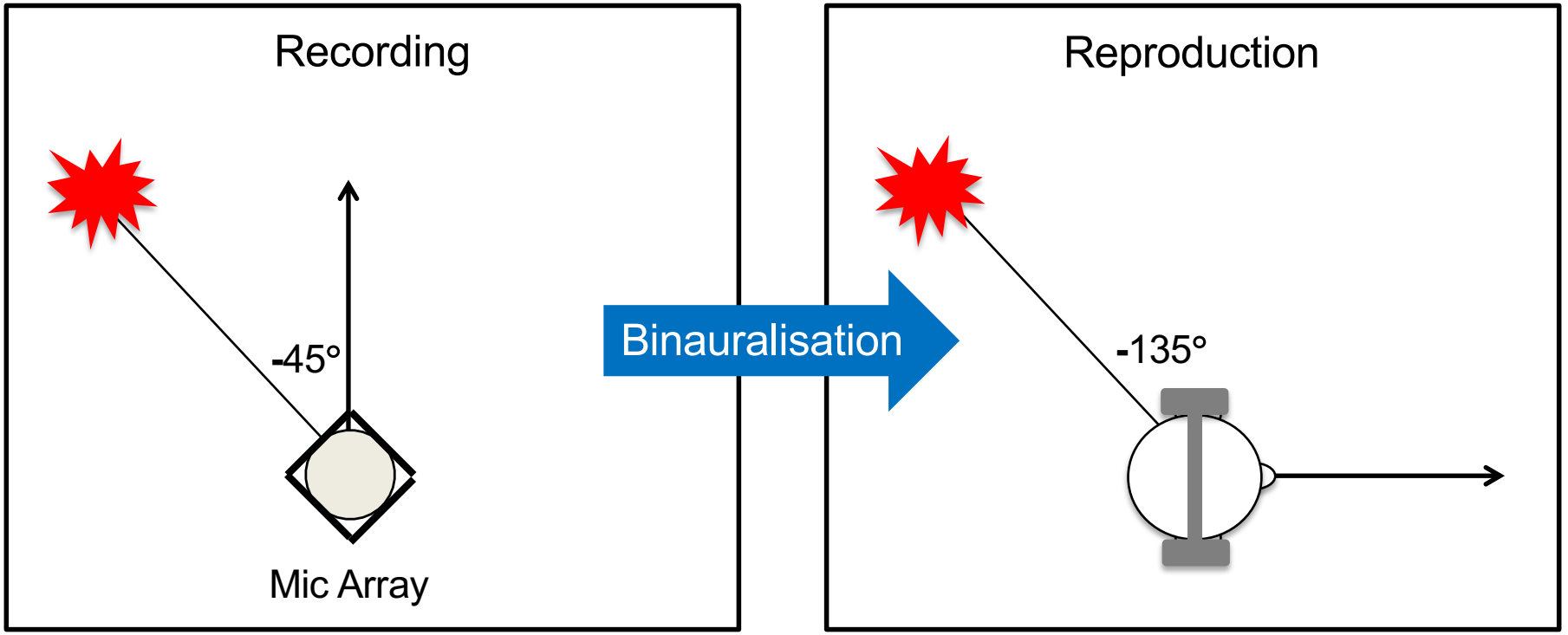
2. The perceived source position should stay the same when the head rotates.



Requirements for VR mic arrays

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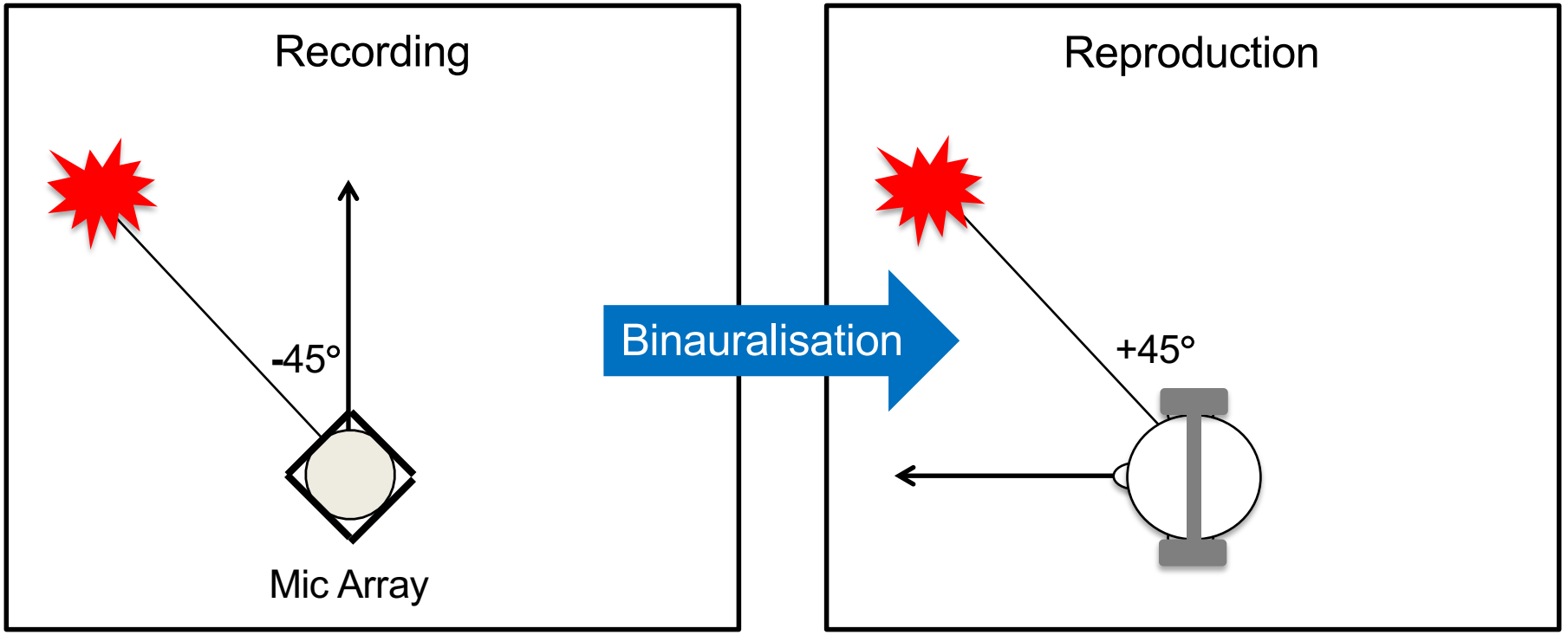
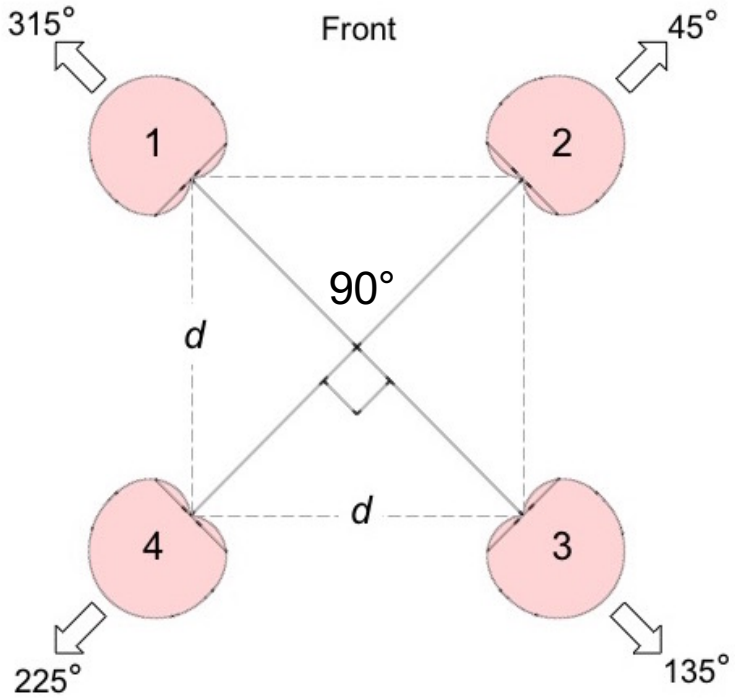


Proposed technique

- Equal Segment Microphone Array (ESMA)
  - The original concept by Williams [1991] developed for quadraphonic surround sound.
  - IRT-Cross for ambience capture.

→ Adapted for VR here.



Proposed technique

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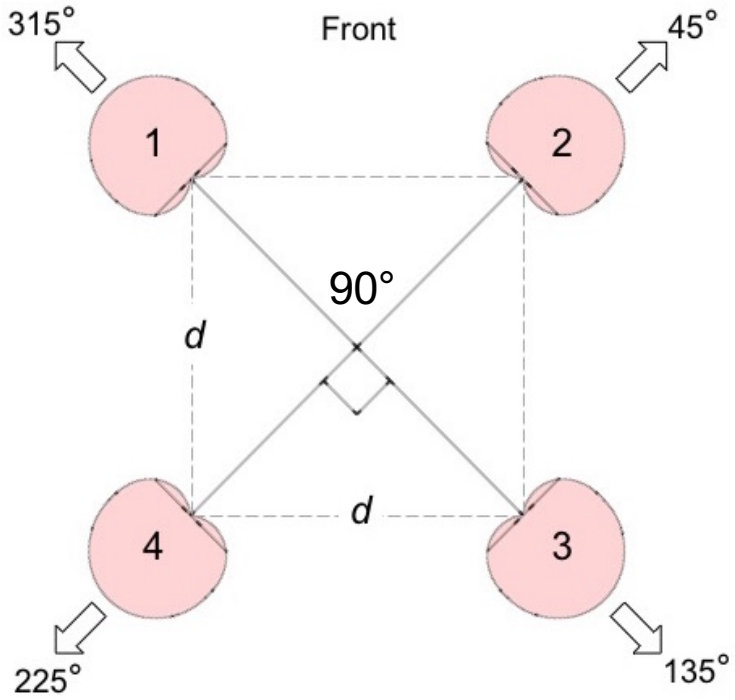
- Equal Segment Microphone Array (ESMA)

Constraints

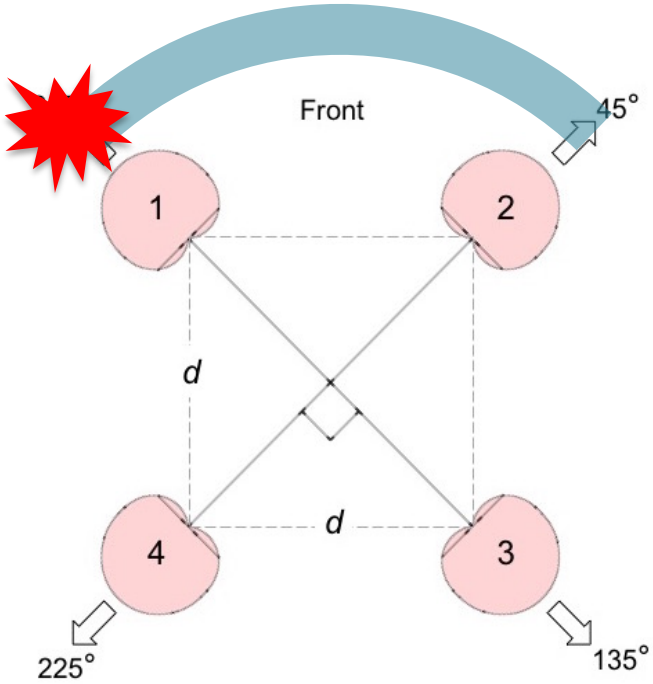
– Equal subtended angle (90°) and mic spacing for all stereo segments

– The stereophonic recording angle (SRA) for each segment should match the subtended angle of the segment (90°).

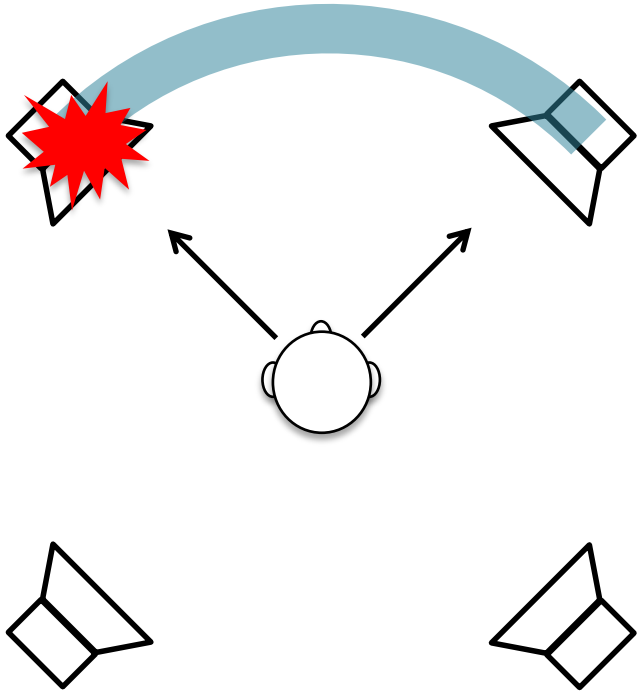


Proposed technique

- Stereophonic recording angle (SRA)
  - Coverage of a sound field that produces sufficient ICLD and ICTD for a full image shift between two loudspeakers.

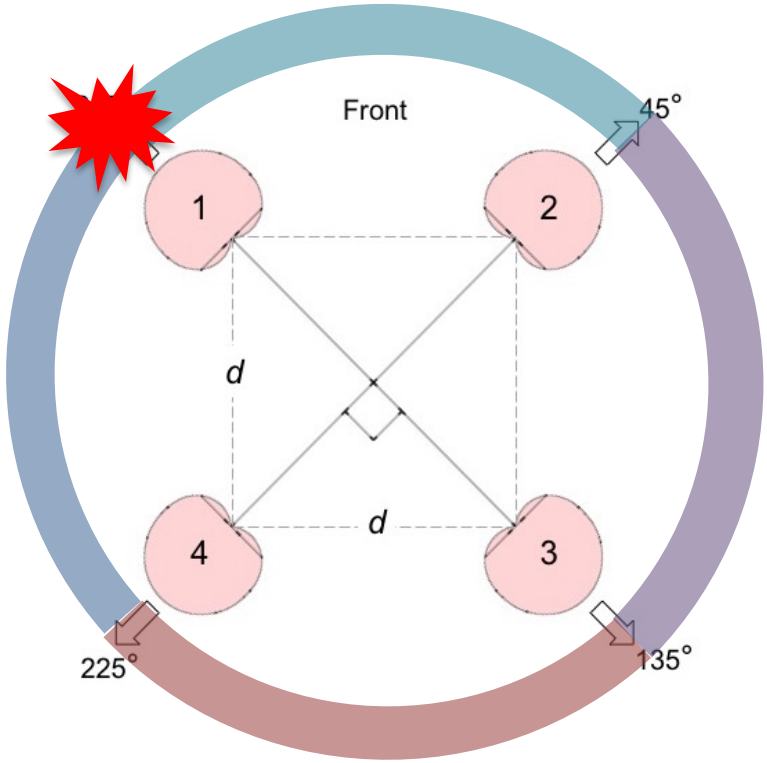


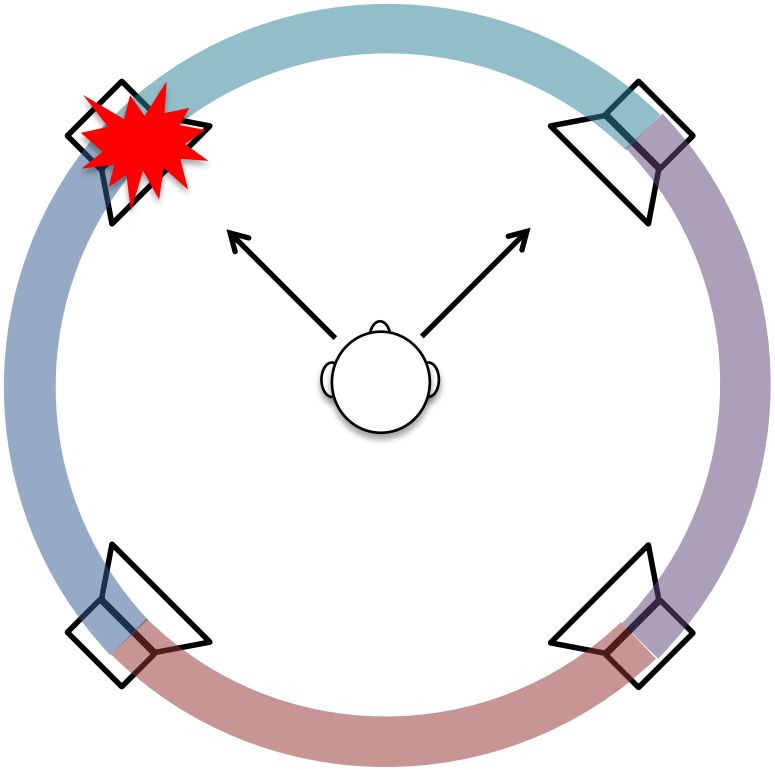
SRA = 90°



Proposed technique

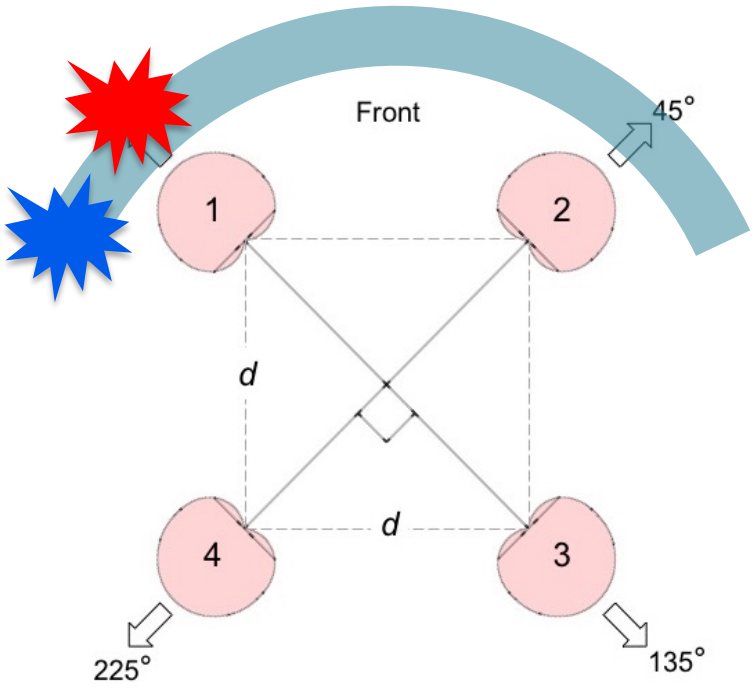
- SRA should not overlap between each stereo segment.
  - To maintain the perceived image position with head rotation.

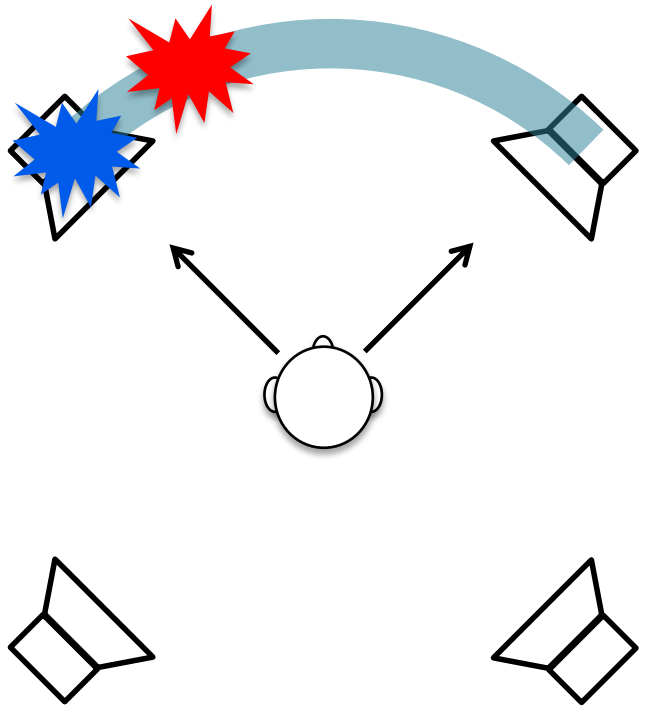




Proposed technique

- Problem with an SRA overlap
  - Localisation of the target source at a narrower angle.
  - Image position moves as the head rotates.





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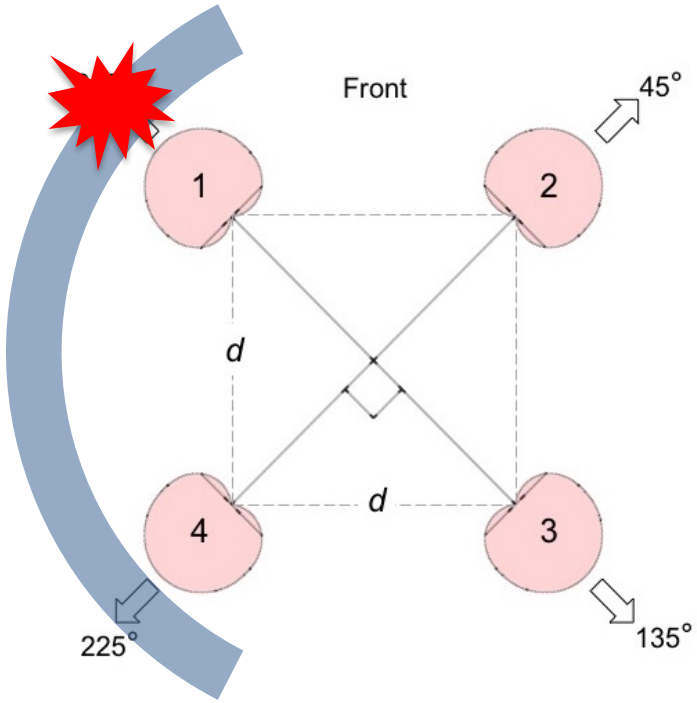
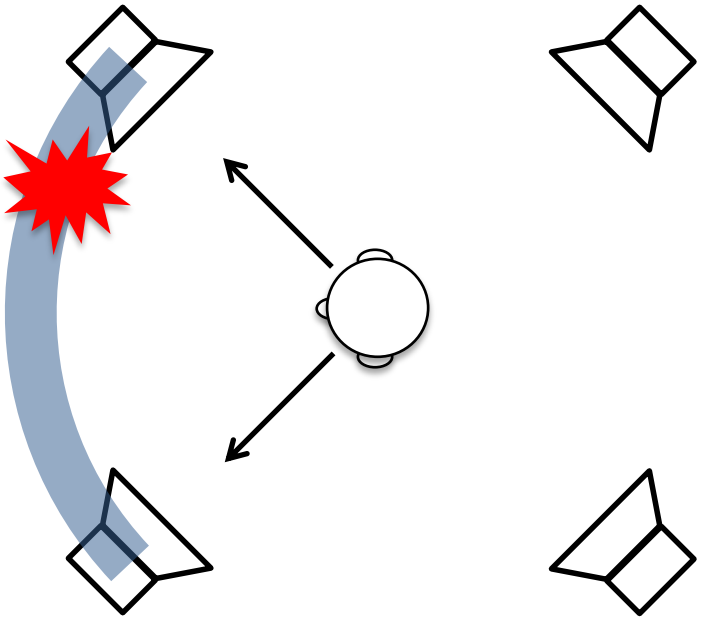
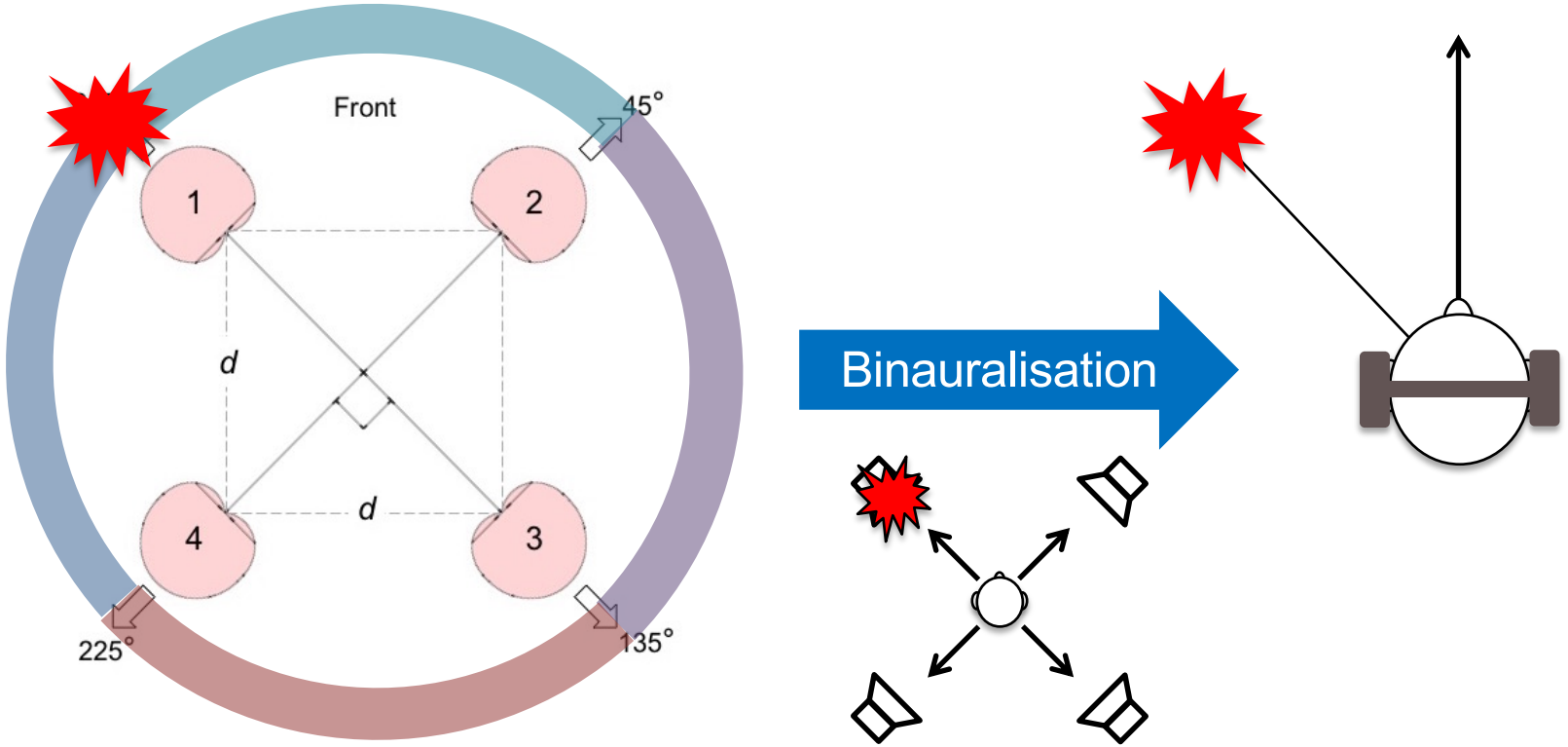


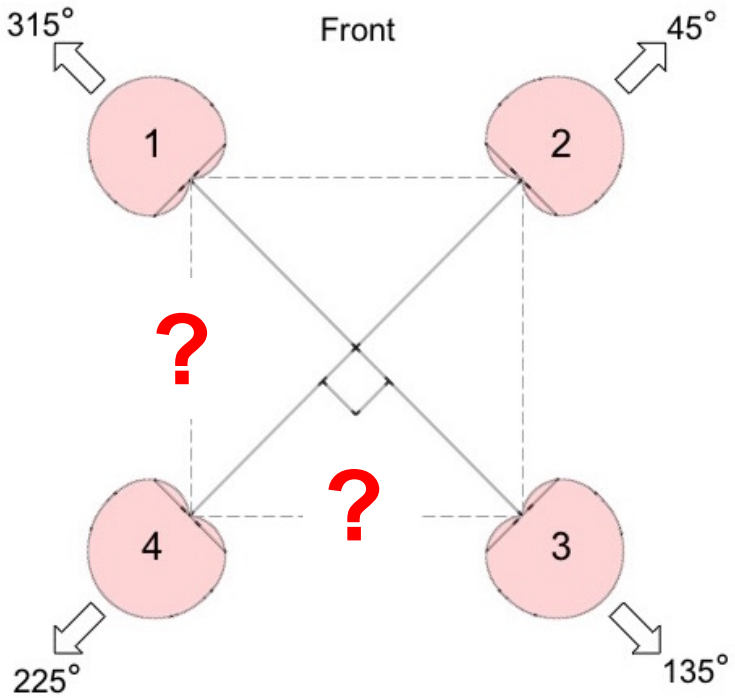


Proposed technique

- Binauralisation of ESMA
  - Convolve the mic signals with quadraphonic HRIRs.



Now, what should be the spacing between the microphones?



Psychoacoustic principles

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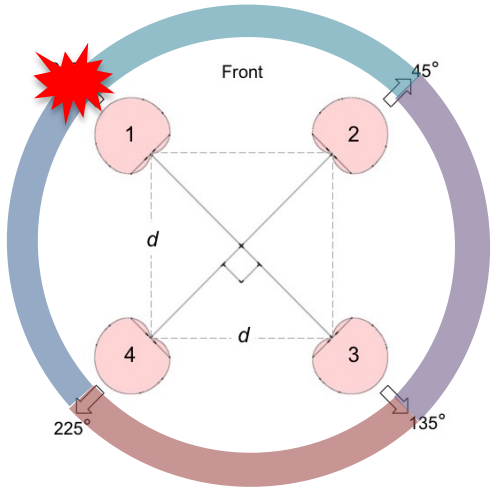
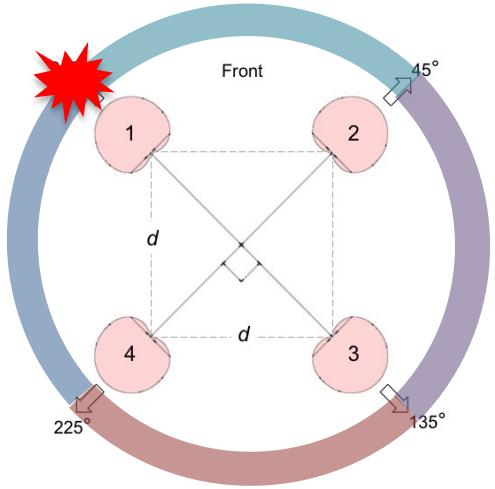
- ICTD and ICLD trade-off
  - The spacing and angle between two directional microphones determine interchannel time and level differences encoded between the signals.
  - ICTD and ICLD complement each other in shifting the perceived image [Theile 2001].

Total image shift = shift(ICTD) + shift(ICLD)



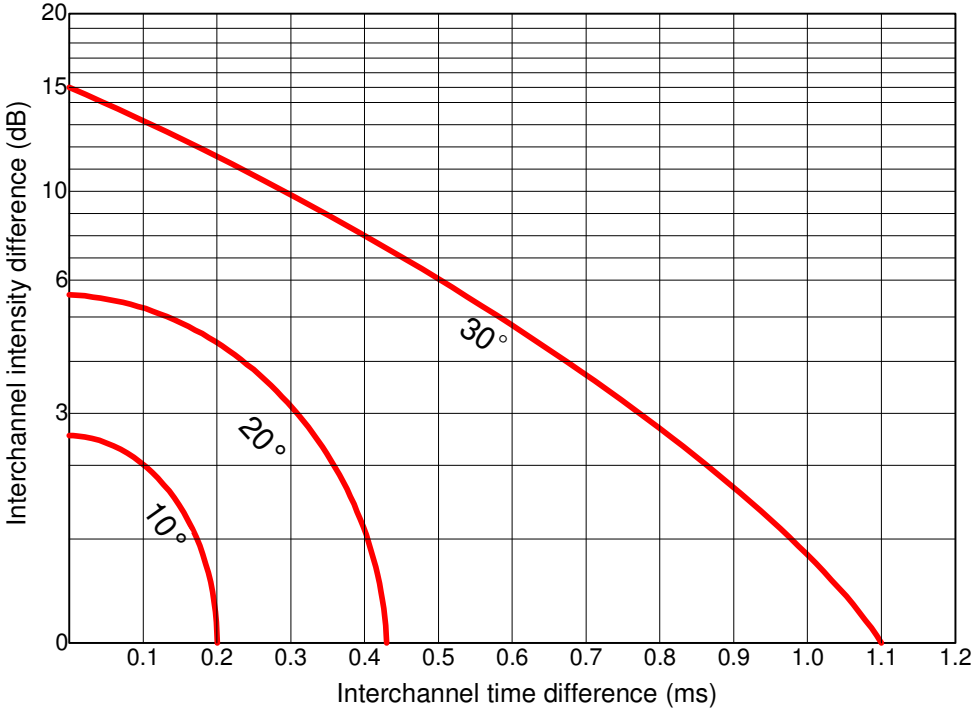
Psychoacoustic principles

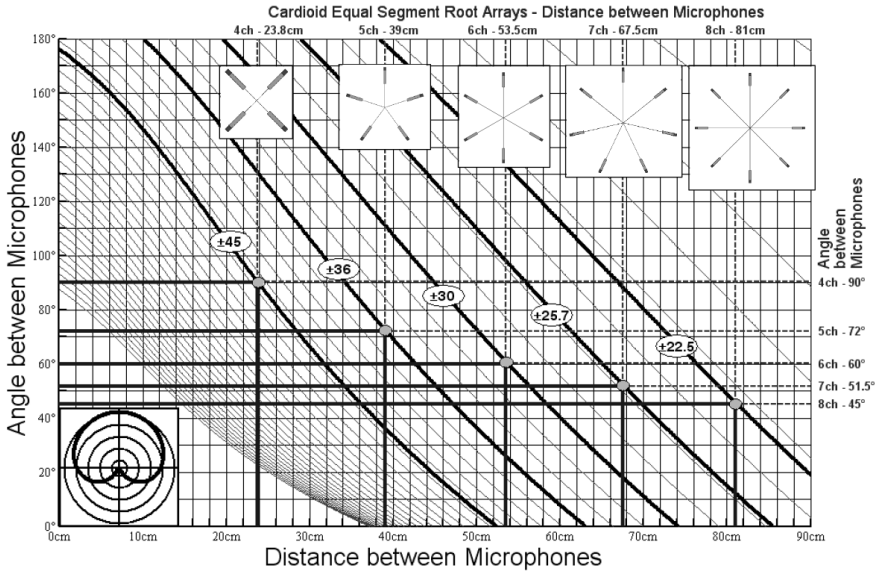
- ICTD and ICLD trade-off
  - With the 4ch ESMA design, the goal is to achieve the SRA of 90° for each segment.
  - The subtended angle is given as 90°.
  - The spacing needs to be determined so that the resulting ICTD and ICLD are just enough to produce the full ±45° image shift.
  - There exist several ICTD-ICLD trade-off models.



Psychoacoustic principles

- Williams [1987]
  - Interpolation of ICTD and ICLD data obtained for 10°, 20° and 30°.
  - Used to calculate the SRA for different mic techniques (so-called the Williams curves)





Williams [2008]

Psychoacoustic principles

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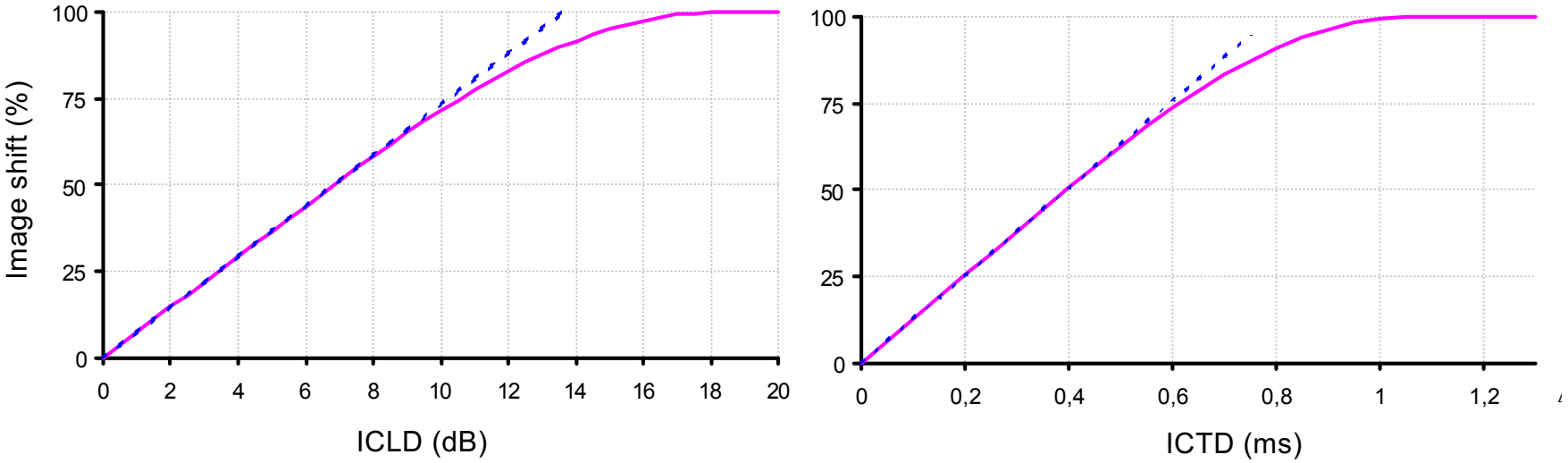
- Wittek/Theile [2001]
  - Total image shift = shift(ICLD) + shift(ICTD)
  - Up to the linear 75% of the whole shift region.
  - Basis for the “Image Assistant” tool for mic array design.



Wittek [2001]

Psychoacoustic principles

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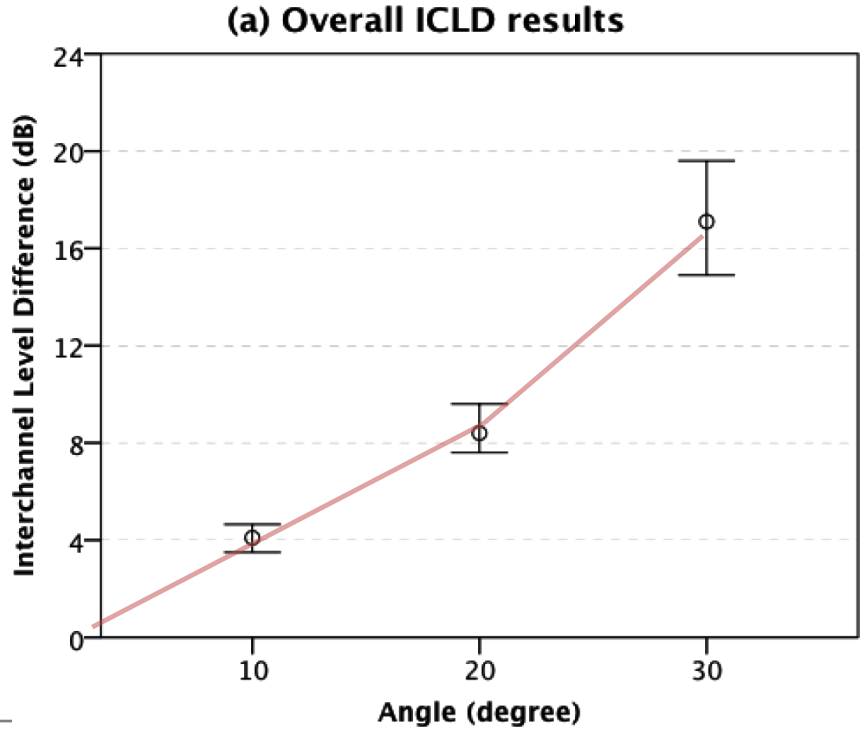
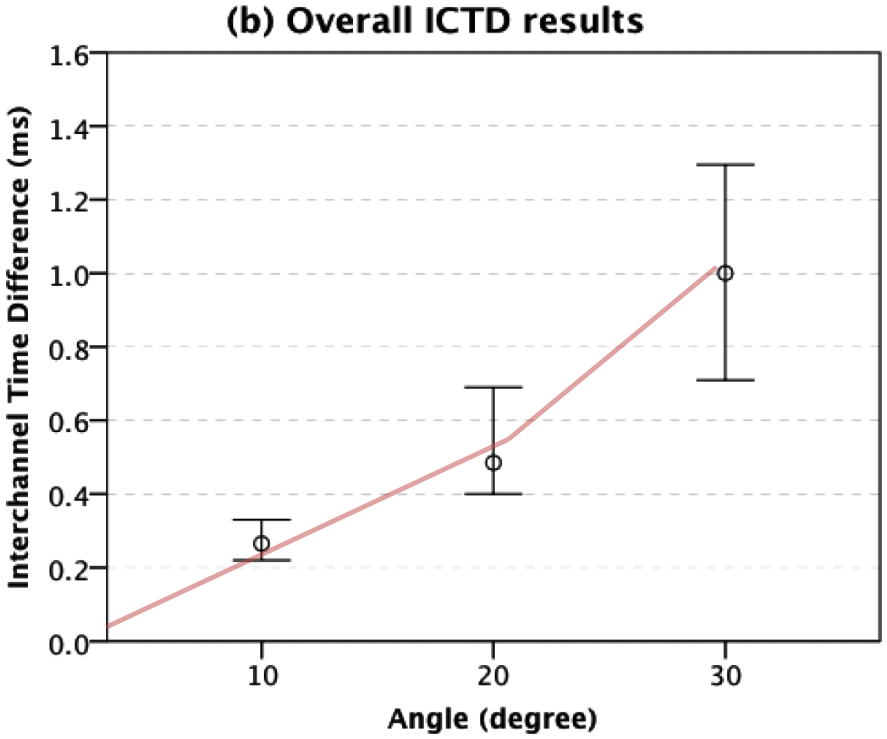
- Lee and Rumsey [2013]
  - Two linear shift regions: 0° to 20° & 20° to 30°

$$ICLD(\alpha) = \begin{cases} 0.425\alpha & [dB],\ \alpha \leq 20 \\ 0.85\alpha - 8.5\ [dB],\ 20 < \alpha \leq 30 \end{cases}$$

$$ICTD(\alpha) = \begin{cases} 0.025\alpha & [ms],\ \alpha \leq 20 \\ 0.05\alpha - 0.5\ [ms],\ 20 < \alpha \leq 30 \end{cases}$$





Psychoacoustic principles

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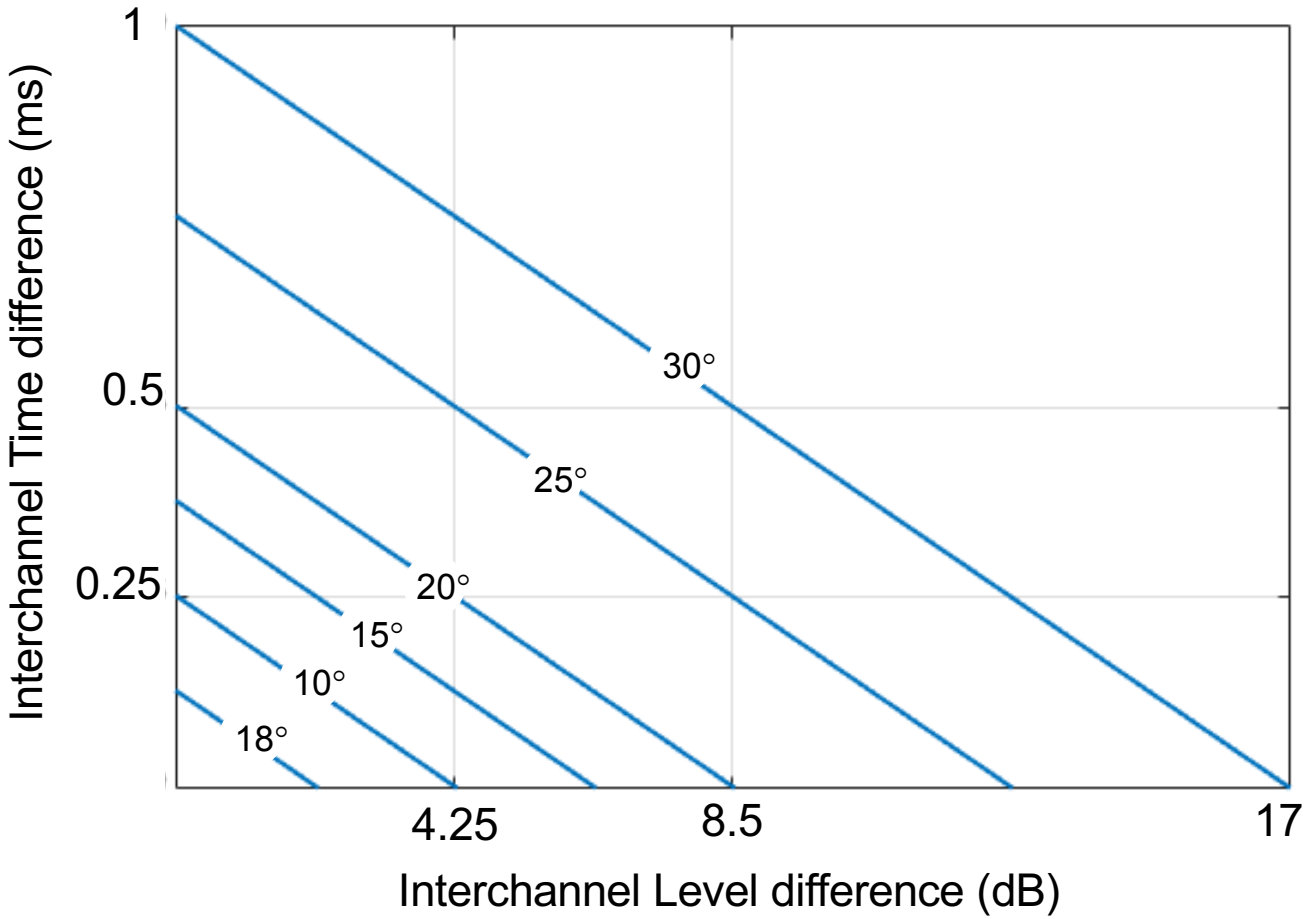
- Linear ICTD-ICLD Trade-off functions [Lee 2016]



Psychoacoustic principles

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- Limitations
  - The previous models are based on the **60°** loudspeaker base angle.
  - They assume that the same model can apply to other base angles also.
  - e.g., 17dB for 30° shift with the 60° base → 17dB for 45° shift with the 90° base.

Psychoacoustic principles

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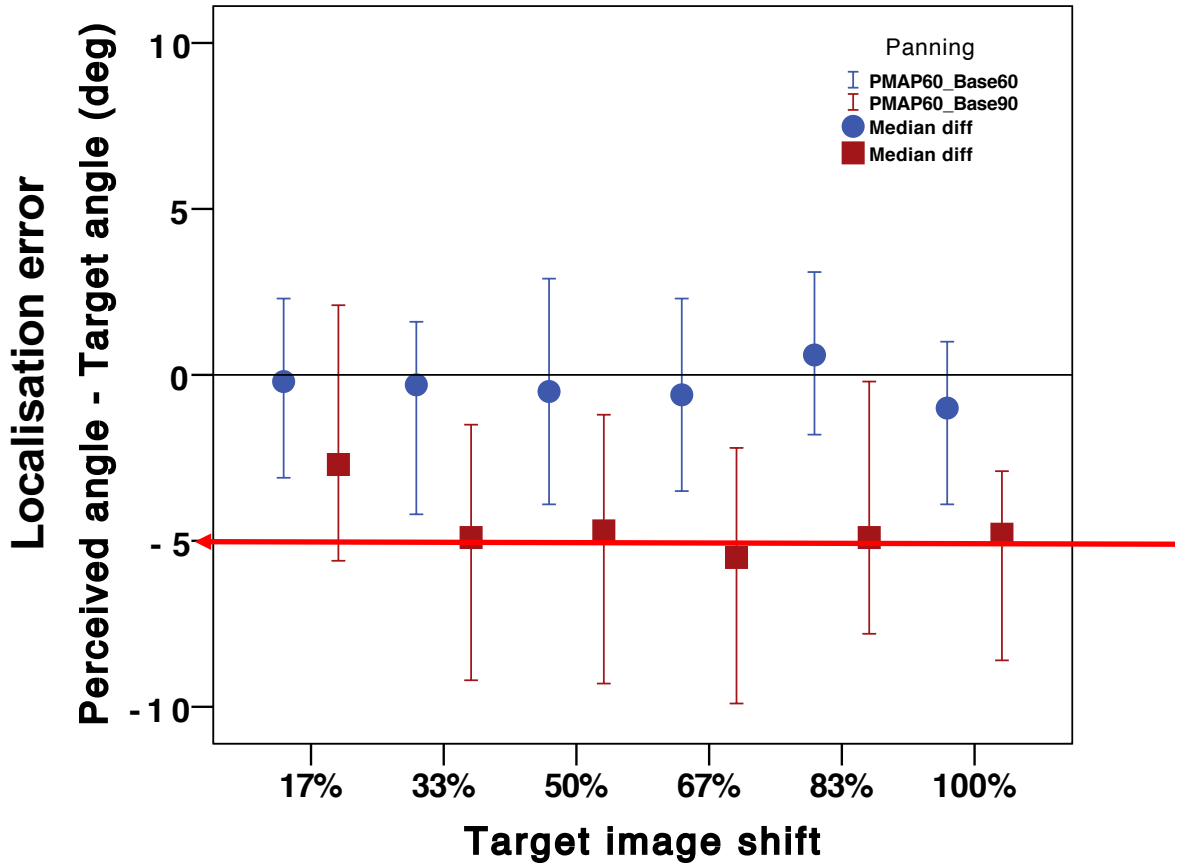
- Limitations
  - However, this does not work in practice!
  - More ICTD and ICLD values are required to achieve a full image shift with the 90° loudspeaker setup.

Psychoacoustic principles

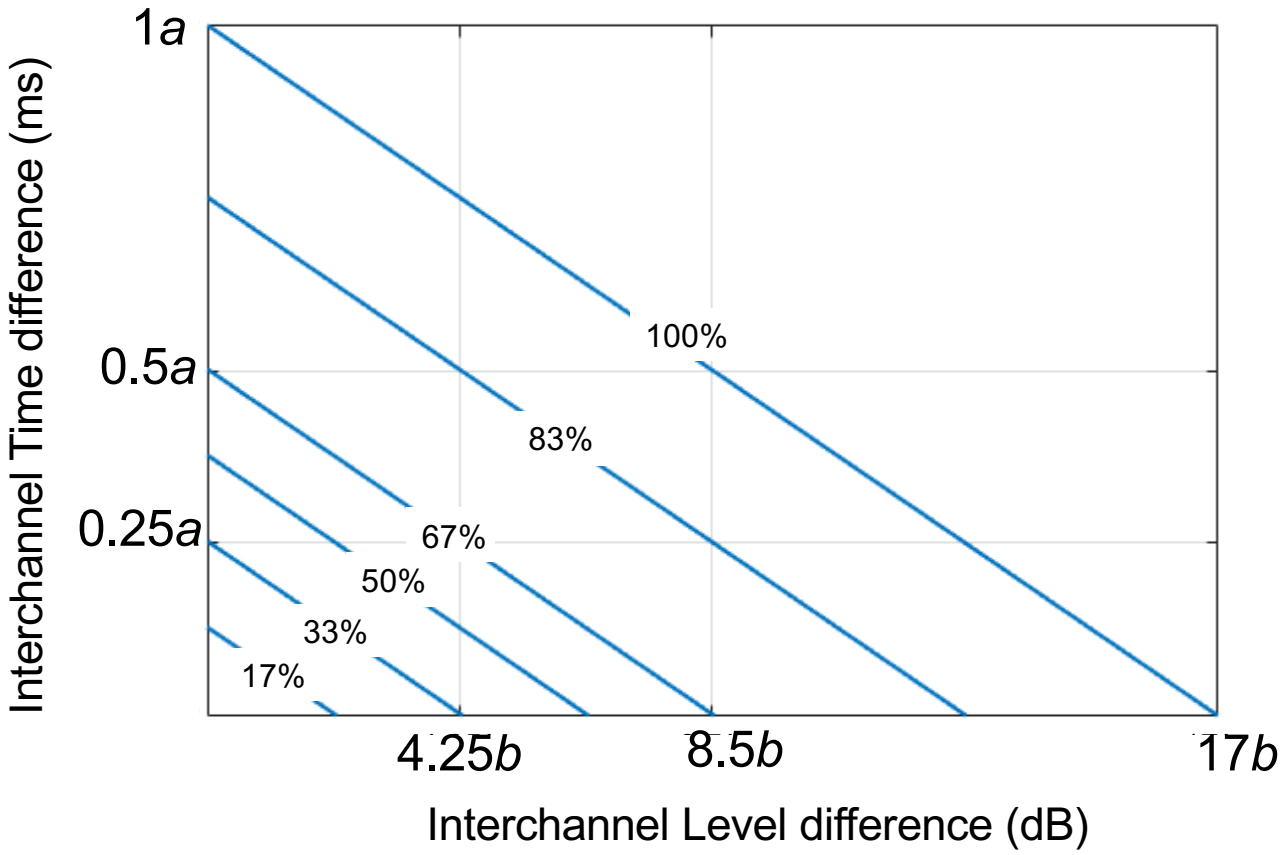
- PMAP: a new amplitude-panning law [AES142 2017]
  - Based on Lee and Rumsey [JAES 2013]
  - Accurate for the 60° base angle, but not for the 90°.



Around 5° localisation error

Psychoacoustic principles

- Perceptual scaling based on ILD and ITD matching [Lee AES WIMP 2016]
  - Trade-off for an arbitrary base angle ($\boldsymbol{\theta}$).



Psychoacoustic principles

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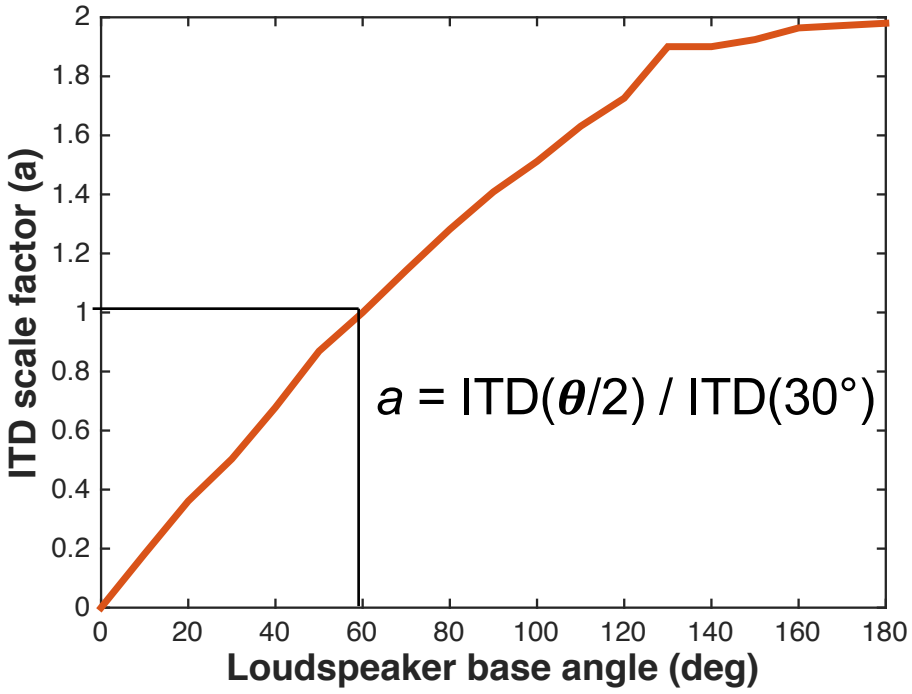
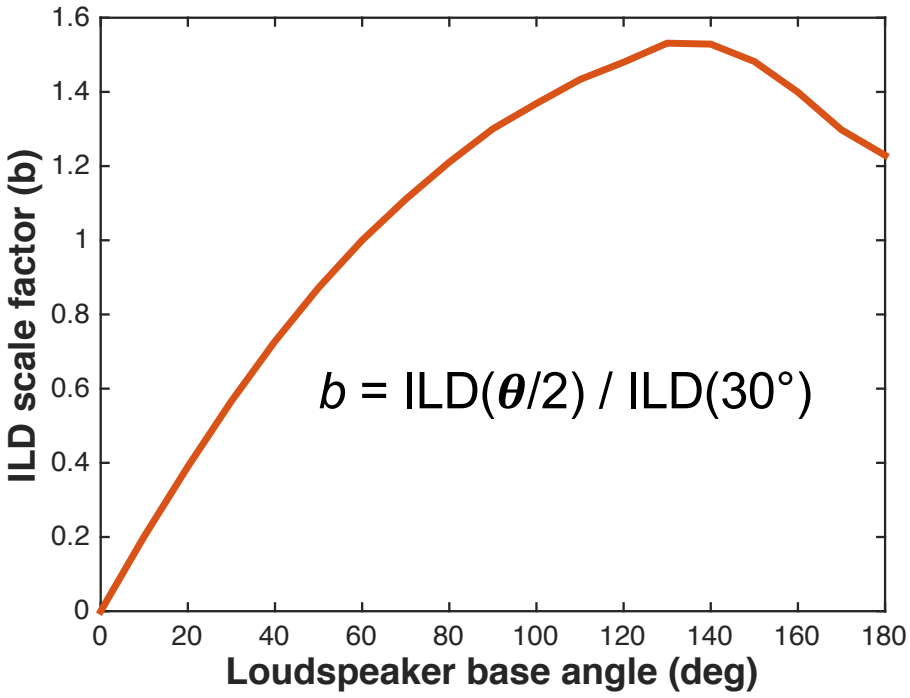
- Perceptual scaling based on ILD and ITD matching.
  - Scale factors a and b
  - Ratio of the ITD from real source to the ITD from phantom source at half the base angle.





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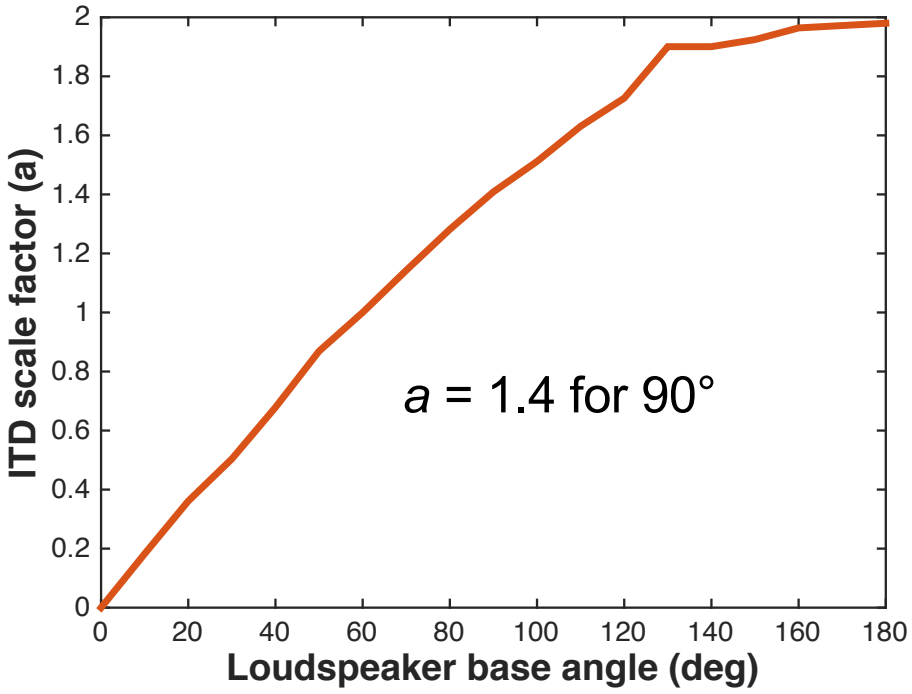
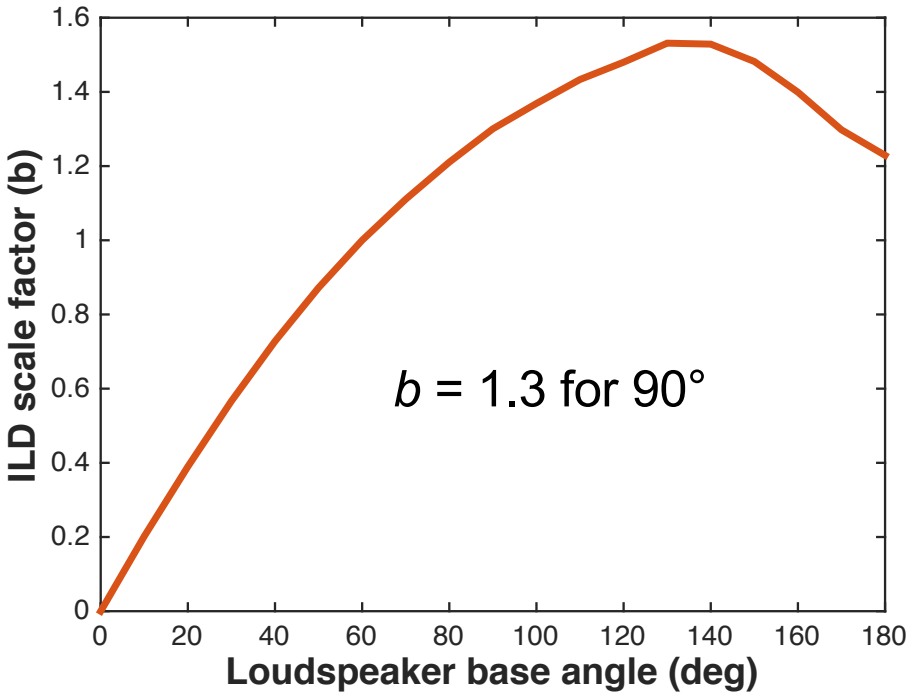




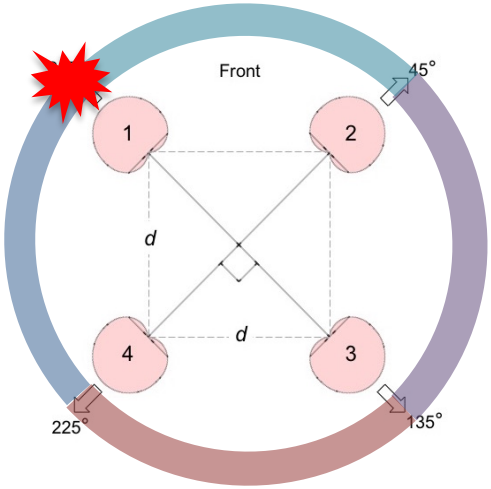
Psychoacoustic principles

- The appropriate spacing between microphones to produce the 90° SRA for the ESMA.
  - Depends on the model.

Model	Microphone spacing
Williams	23.8cm
Sengpiel	25cm
Wittek + Theile	24cm
Lee + Theile	30cm
Lee	50cm

Based on the 60° setup

Optimised for the 90° setup



Proposed mic array

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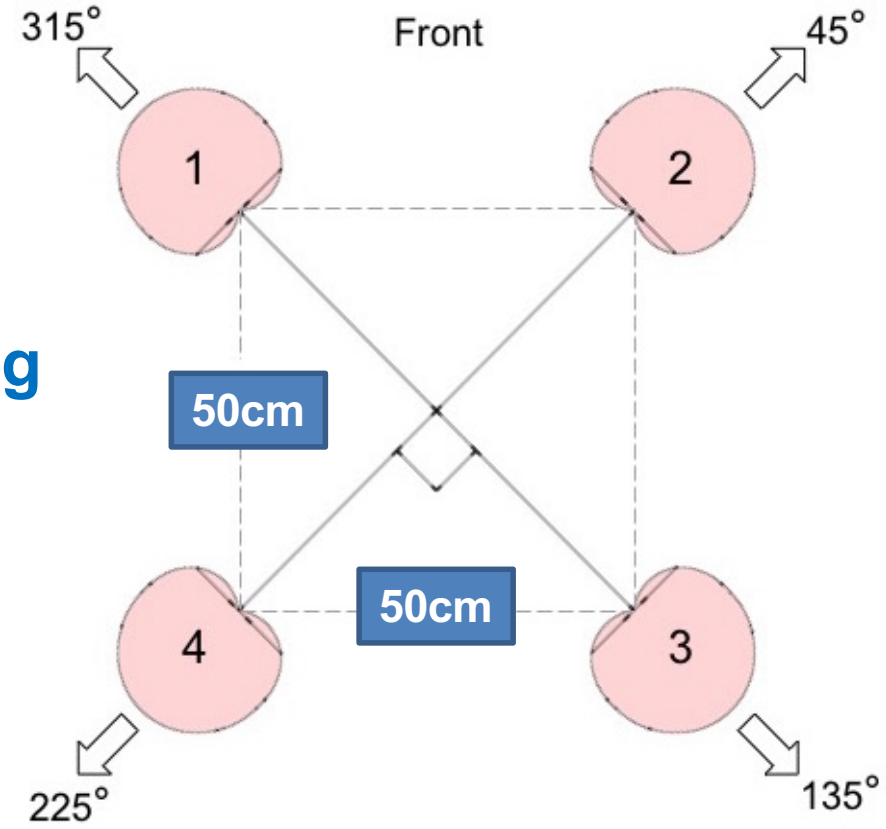
- ESMA optimised for quadraphonic reproduction

Optimal spacing = 50cm



Proposed mic array

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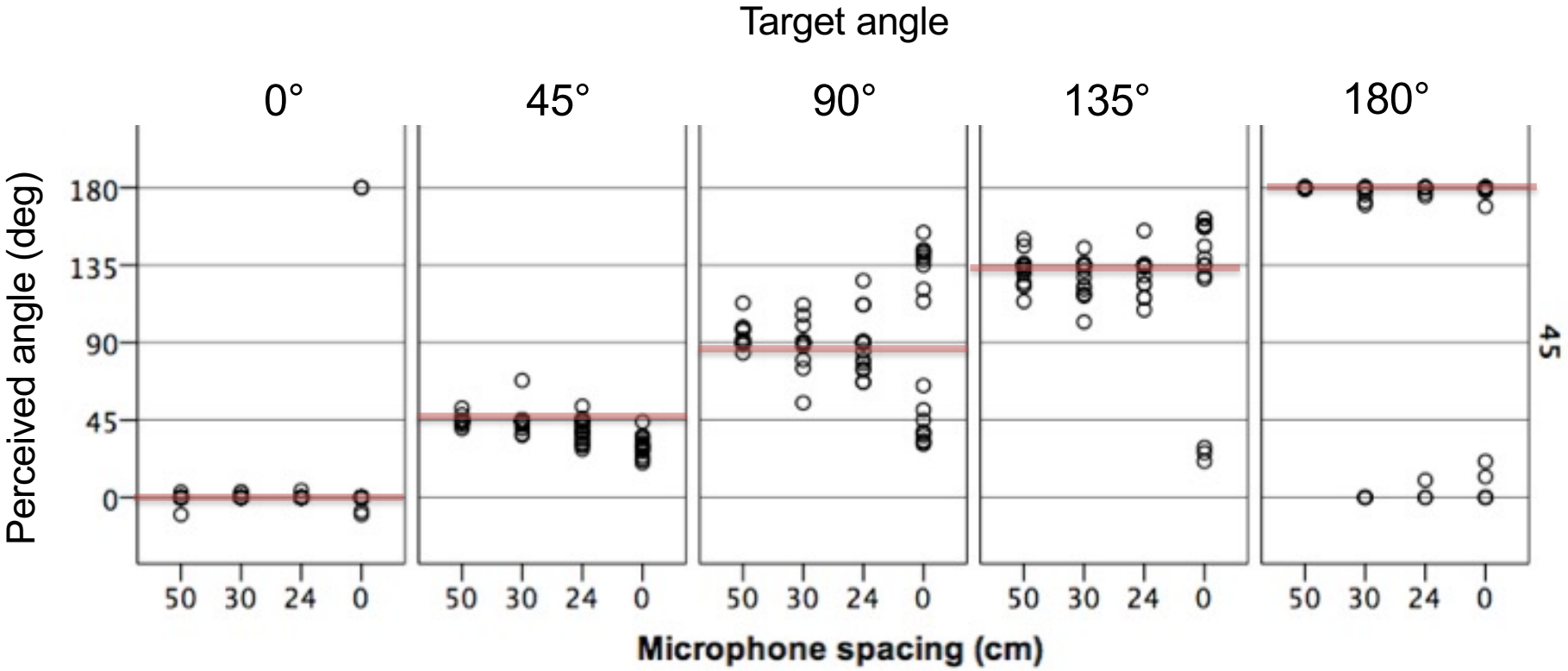
- Localisation accuracy test [Lee AES 2019]
  - Dry speech
  - ESMA 50cm, 30cm, 25cm & 0cm (FOA In-Phase)



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Now let’s have a listen!

Perceptual Evaluations

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- Demo: *Recording of 3D 9.1 playback in a listening room*
  - Recording originally maded in Queens Elizabeth Hall, London.
  - 9.1 channel playback in the APL listening room.

Perceptual Evaluations

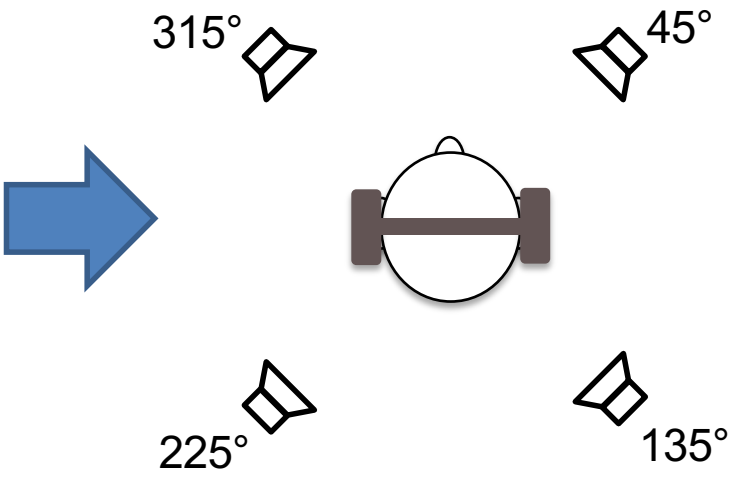
University of HUDDERSFIELD

- Demo: *Recording of 3D 9.1 playback in a listening room*
  - Reproduced sound was captured at the listening position, using
  - ESMA50cm (Nuemann KM184s), FOA (Soundfield SPS422b), Neumann KU100

9.1 Playback captured using mic arrays

Binauralised for Quad Reproduction

HRIR from www.sadie-project.co.uk

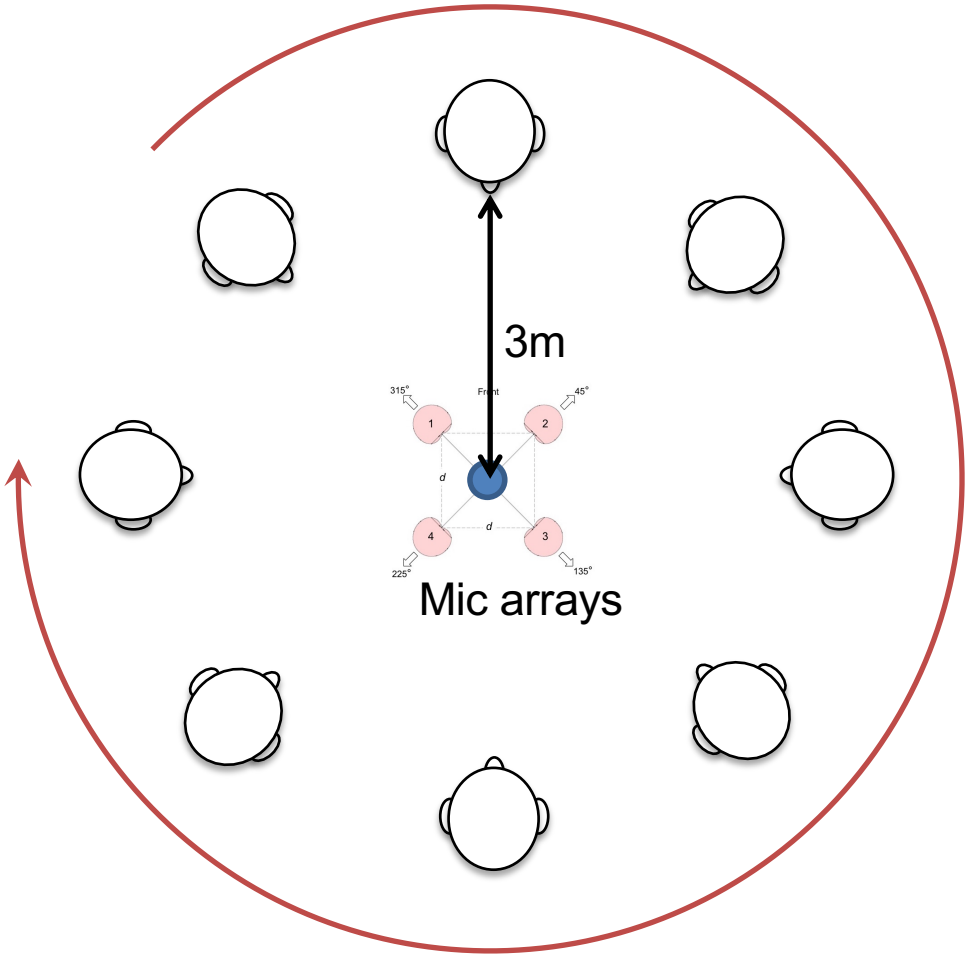


Perceptual Evaluations

University of HUDDERSFIELD

- Demo: *Early music choir*
  - St.Paul's concert hall, Huddersfield (RT = 2.1s).
  - ESMA 50cm (Neumann kk184 cardioid)
  - FOA (Sennheiser Ambeo); *MaxRe* decoder from www.sadie-project.co.uk

- Demo: *Early music choir*



Perceptual Evaluations

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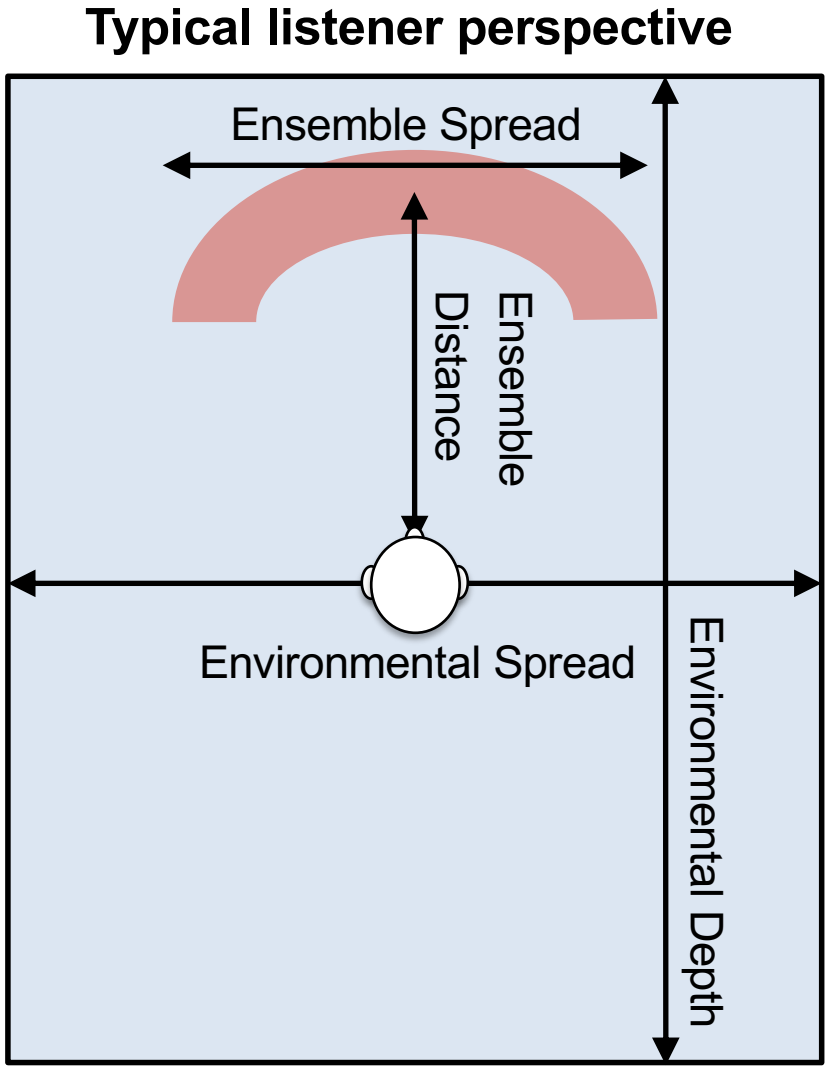
- Spatial attribute evaluations [Millns and Lee 2017]
  - Ensemble Spread
  - Ensemble Distance
  - Environmental Spread
  - Environmental Depth

- Scene Based Paradigm
  - Rumsey [2001]
  - Source & Environment-related attributes for surround sound reproduction



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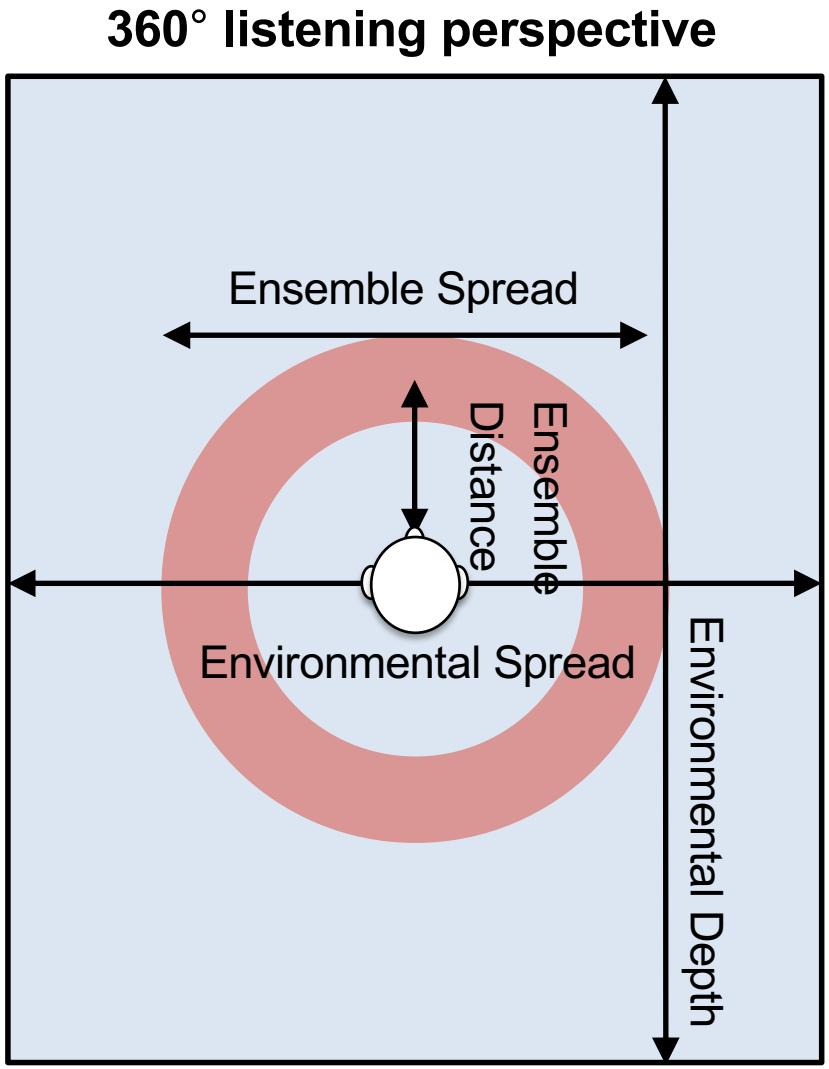

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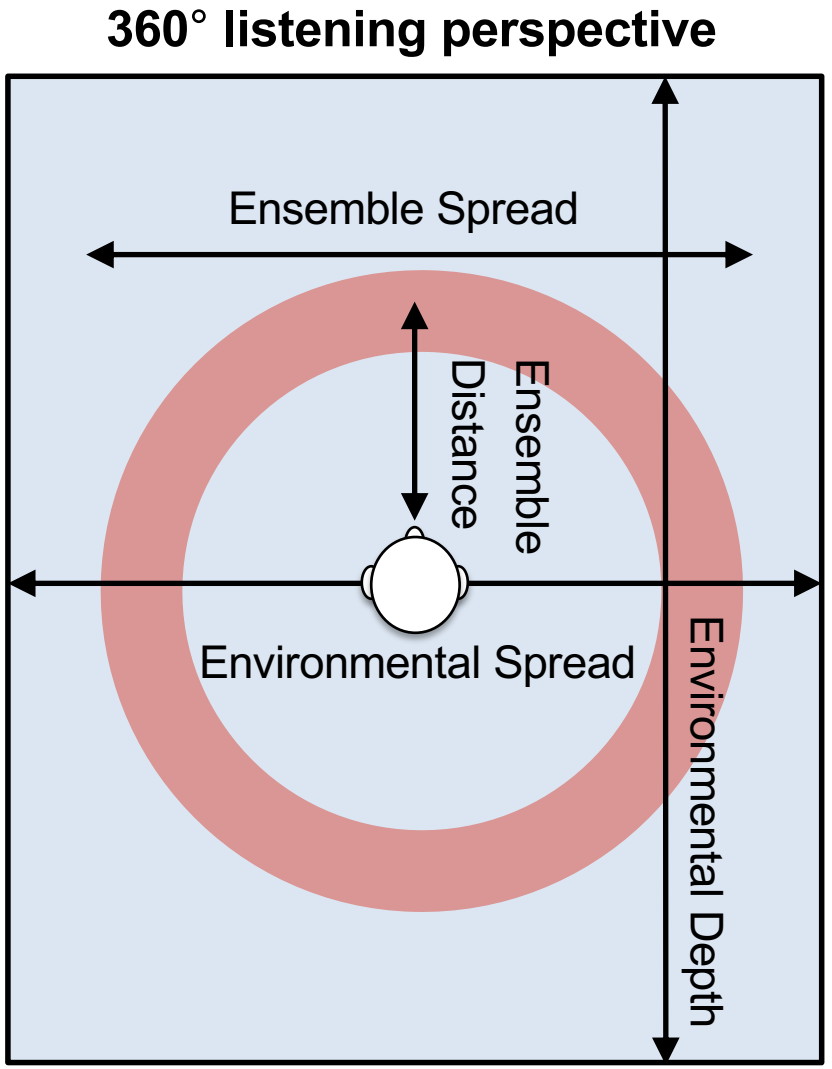


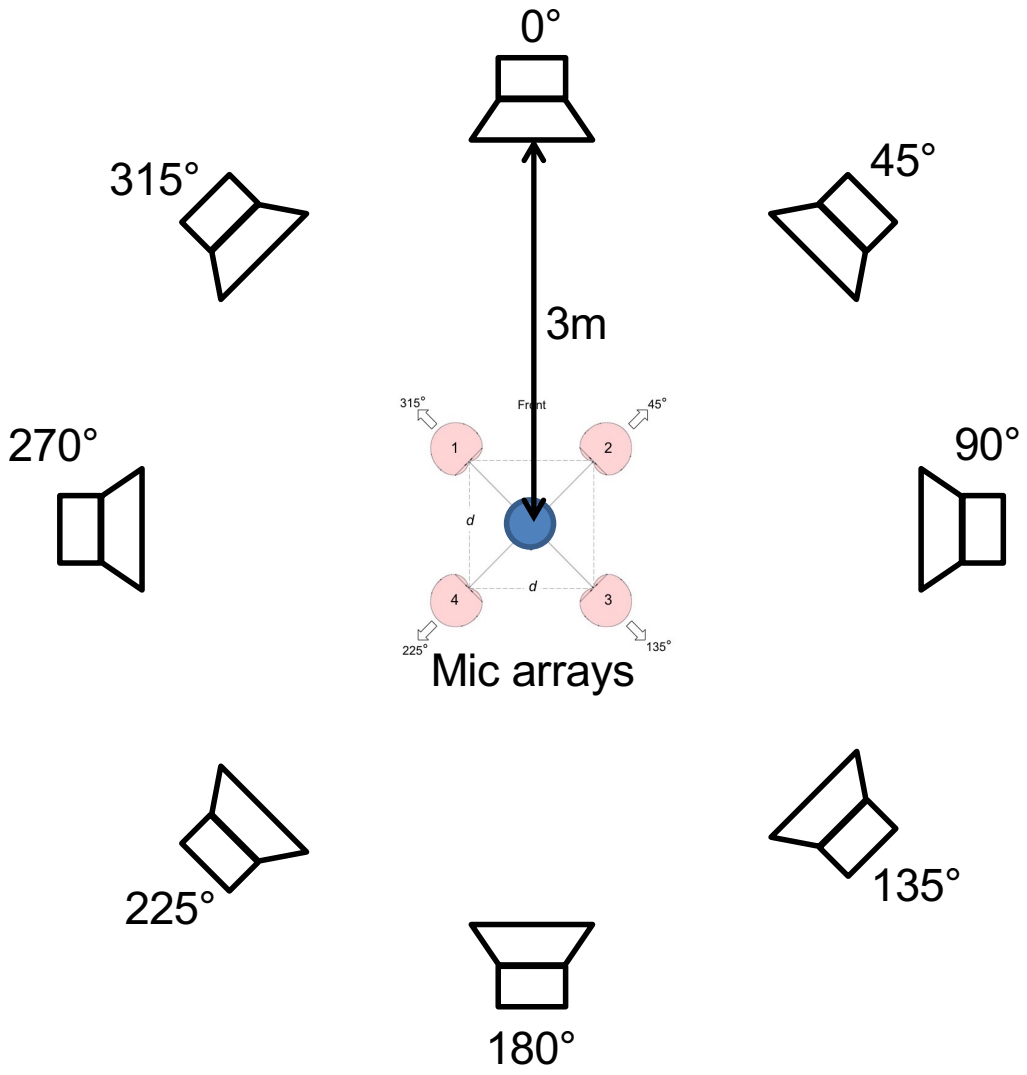
Perceptual Evaluations

University of HUDDERSFIELD

- Recording simulation using mic array impulse responses

Perceptual Evaluations

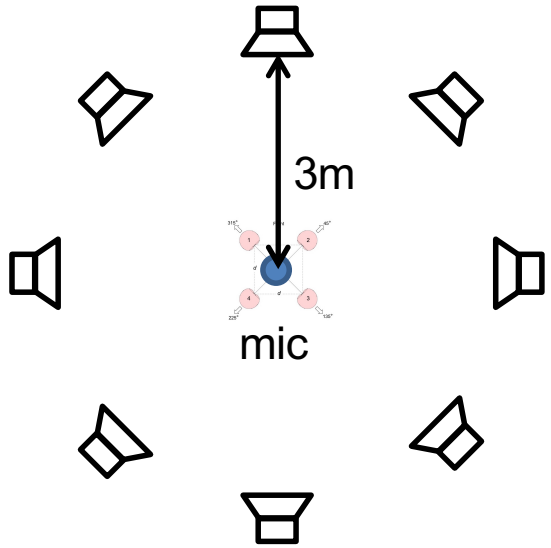
- Room impulse response capture using mic arrays
  - ESMA 50cm, ESMA 25cm (Neumann kk184)
  - FOA (Sennhesier Ambeo)
  - Dummy head (Neumann KU100)



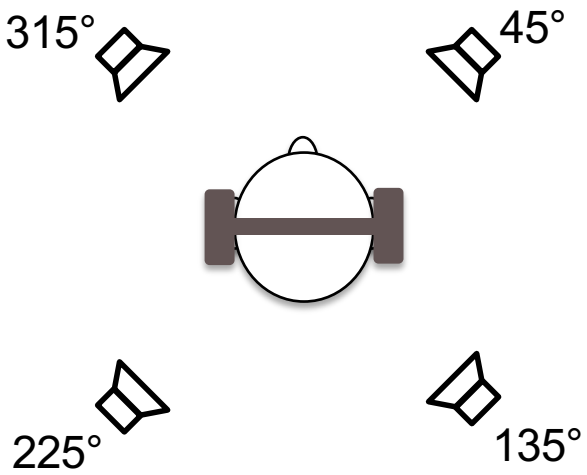
Perceptual Evaluations

- Binaural synthesis
  - Mic array RIRs were convolved with dry mono and multichannel recordings.
  - Then binauralised for the quadraphonic setup using the SADIE HRIR database www.sadie-project.co.uk.

4ch Mic Array RIRs * Dry Sources



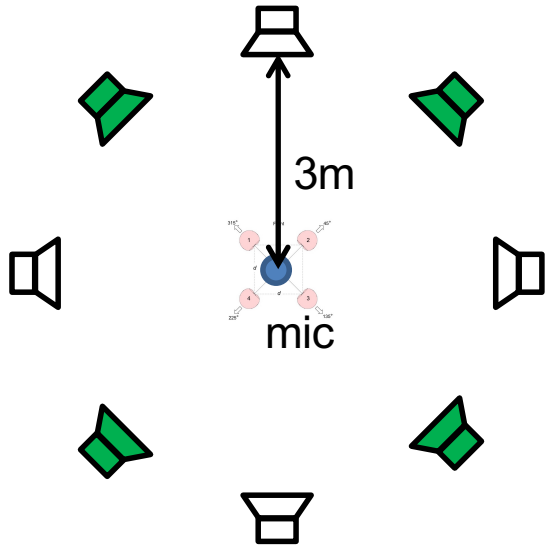
Binauralised for Quad Reproduction



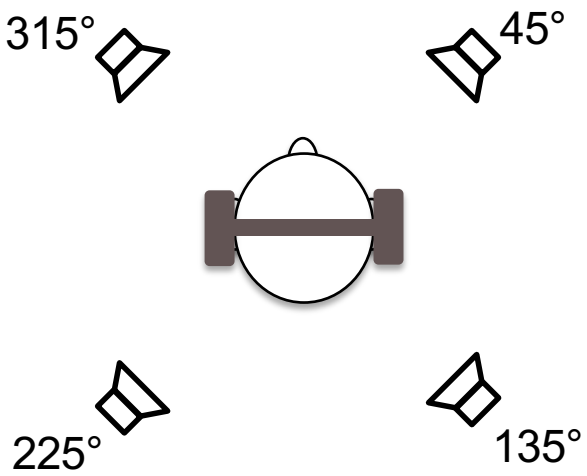
Perceptual Evaluations

- Demo: *Rounders 1* (4 singers at ±45° and ±135°)
  - KU100
  - ESMA 50cm, ESMA 25cm
  - FOA (MaxRe), FOA (Mode-Matching)

4ch Mic Array RIRs * Dry Sources



Binauralised for Quad Reproduction



Perceptual Evaluations

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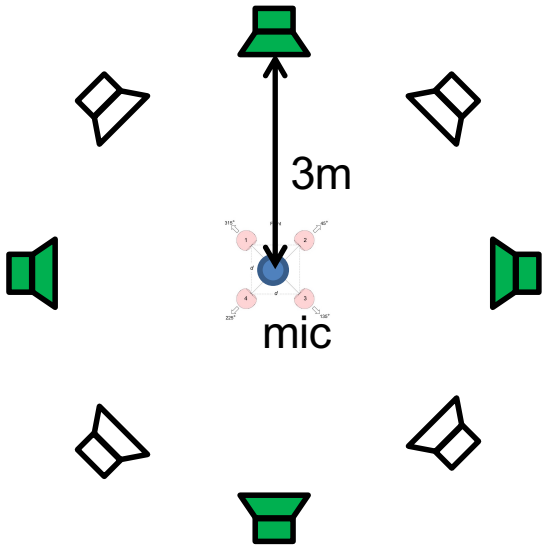
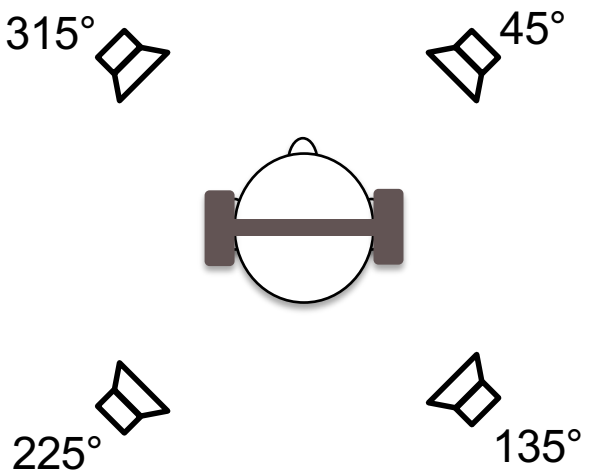
- Demo: *Rounders 2* (4 singers at 0°, ±90° & 180°)
  - Dummy head
  - ESMA 50cm, ESMA 25cm
  - FOA (MaxRe), FOA (Mode-Matching)

4ch Mic Array RIRs * Dry Sources



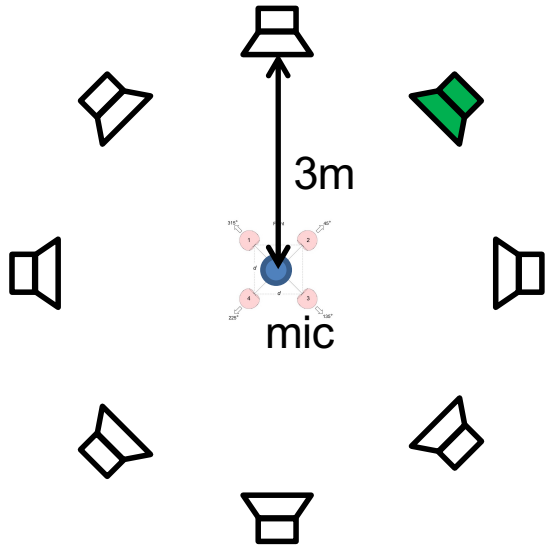
Binauralised for Quad Reproduction



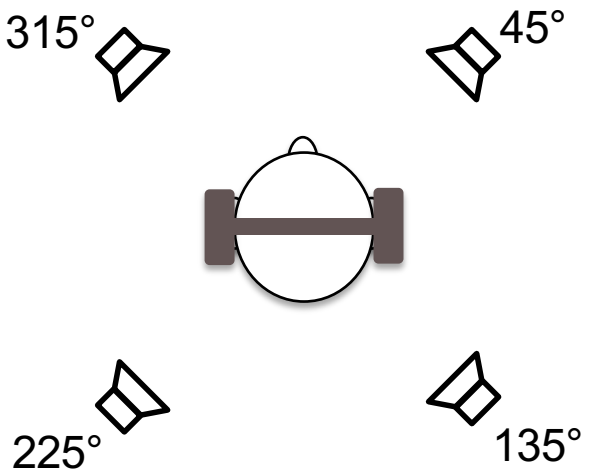
Perceptual Evaluations

- Demo: *Rounders 3* (Female speech at -45°)
  - Dummy head
  - ESMA 50cm, ESMA 25cm
  - FOA (MaxRe), FOA (Mode-Matching)

4ch Mic Array RIRs * Dry Sources



Binauralised for Quad Reproduction



Perceptual Evaluations

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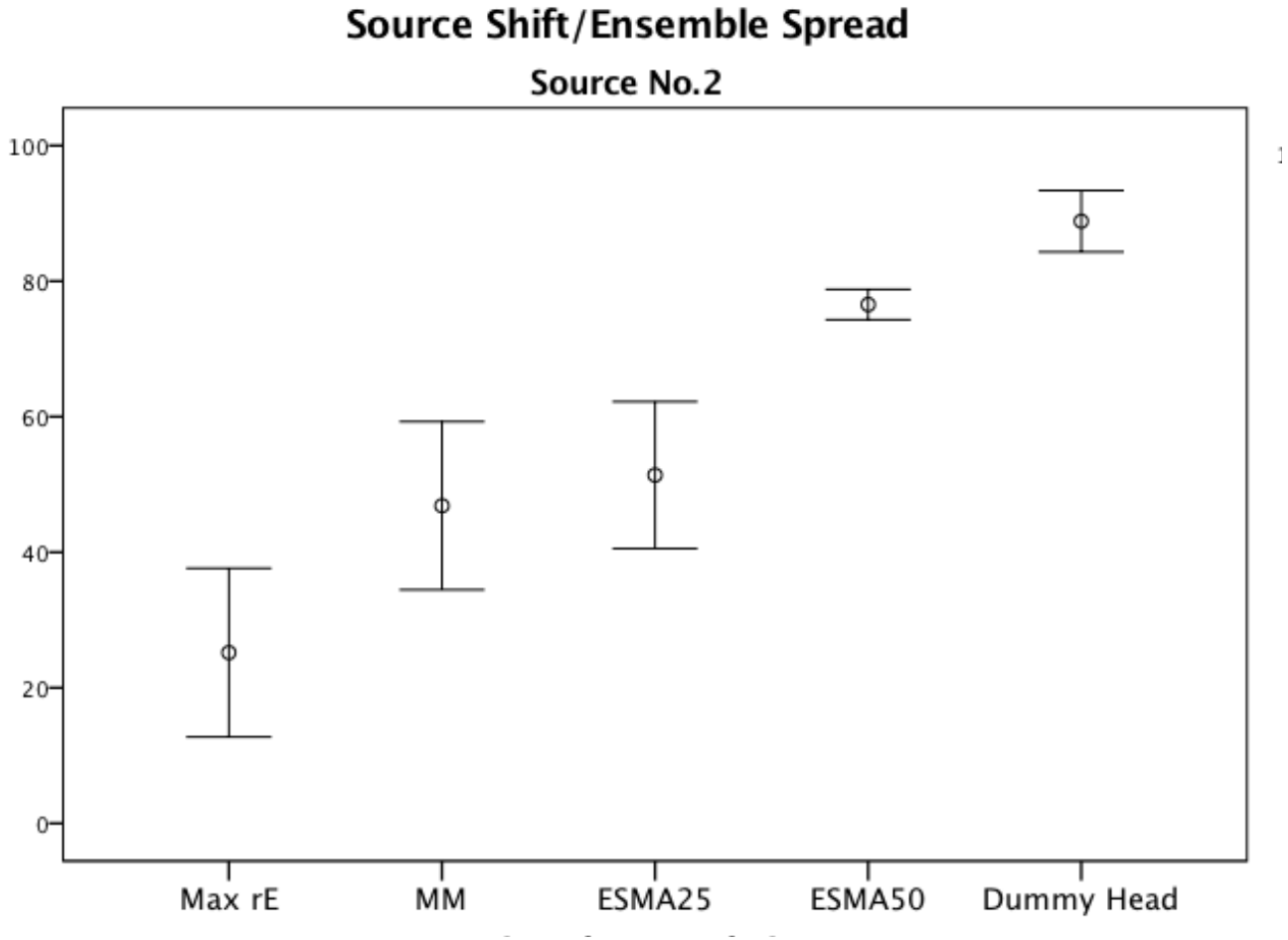
- Results – Ensemble Spread



Millns, C. and Lee, H (2018) 'An Investigation into Spatial Attributes of 360° Microphone Techniques for Virtual Reality'. *In: AES the 144th International Convention, 23 – 26 May 2018*, Milan, Italy.

Perceptual Evaluations

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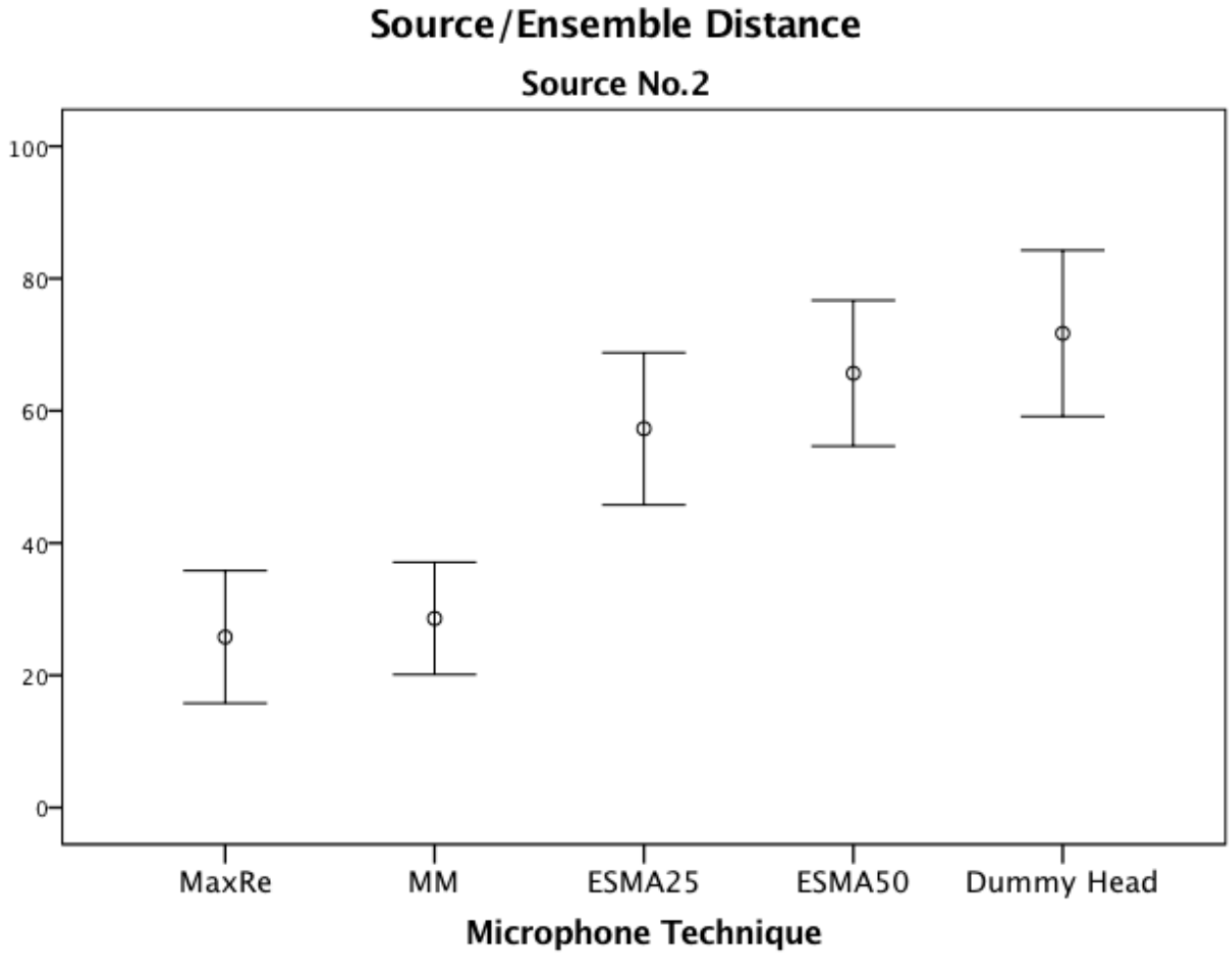
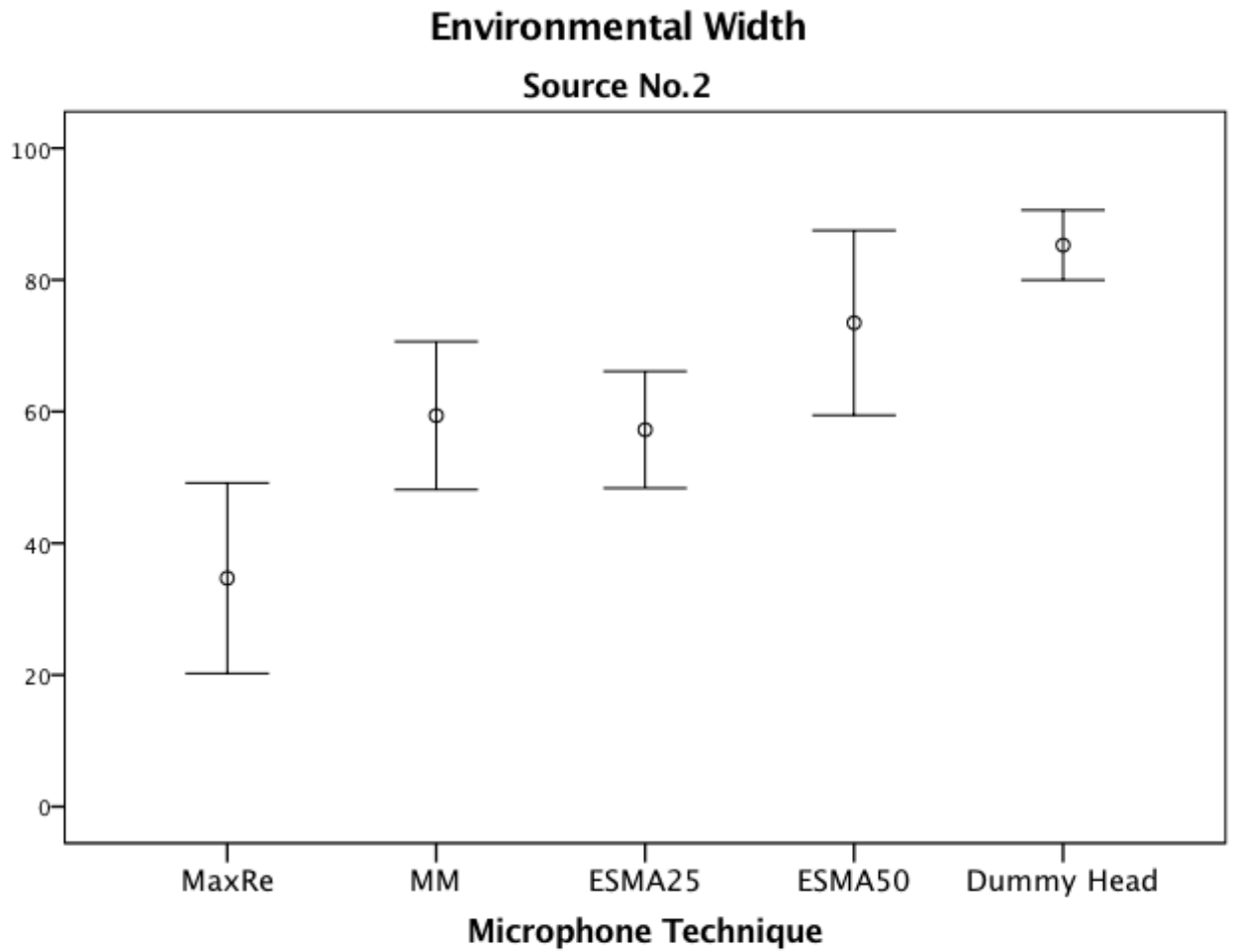
- Results – Ensemble Distance



Perceptual Evaluations

University of HUDDERSFIELD

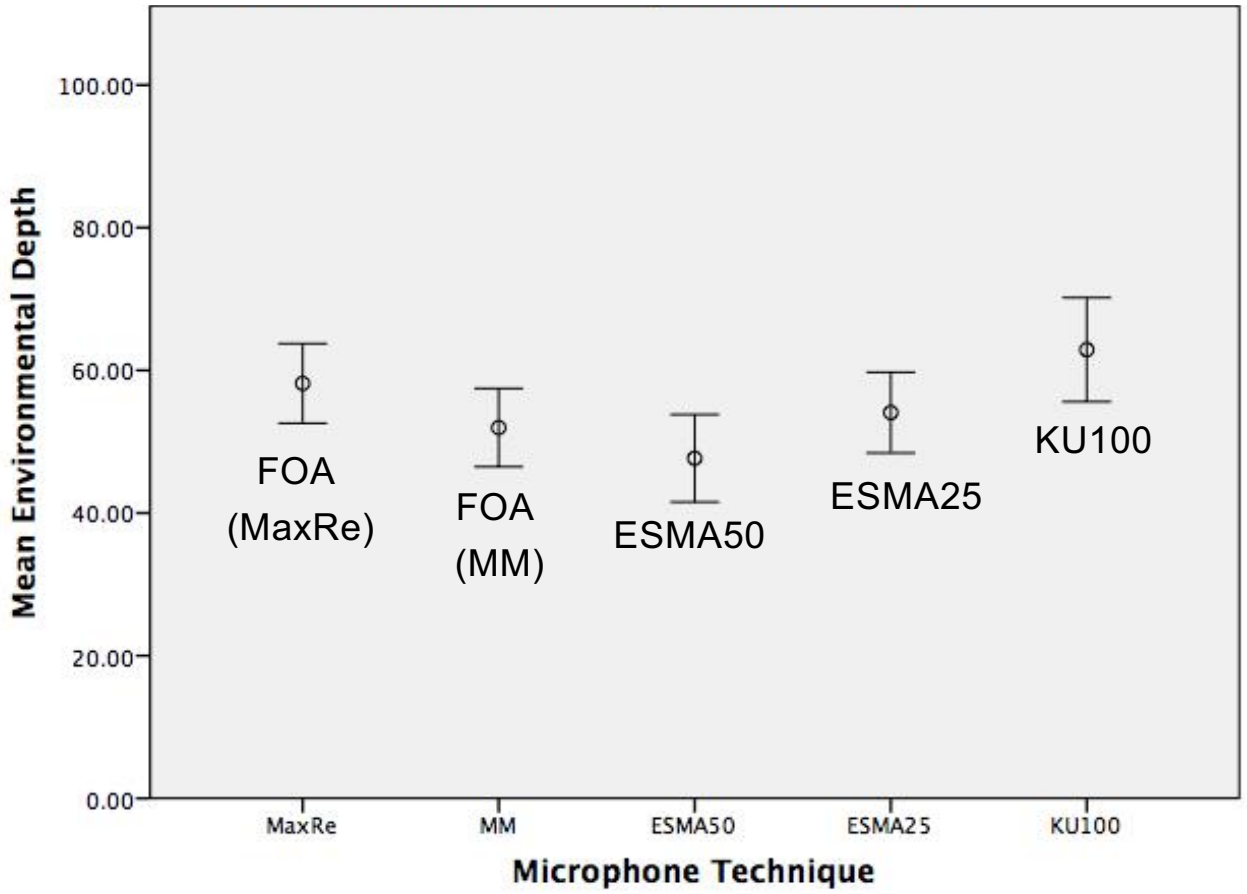
- Results – Environmental Width



Perceptual Evaluations

University of HUDDERSFIELD

- Results – Environmental Depth



ESMA-3D (with height)

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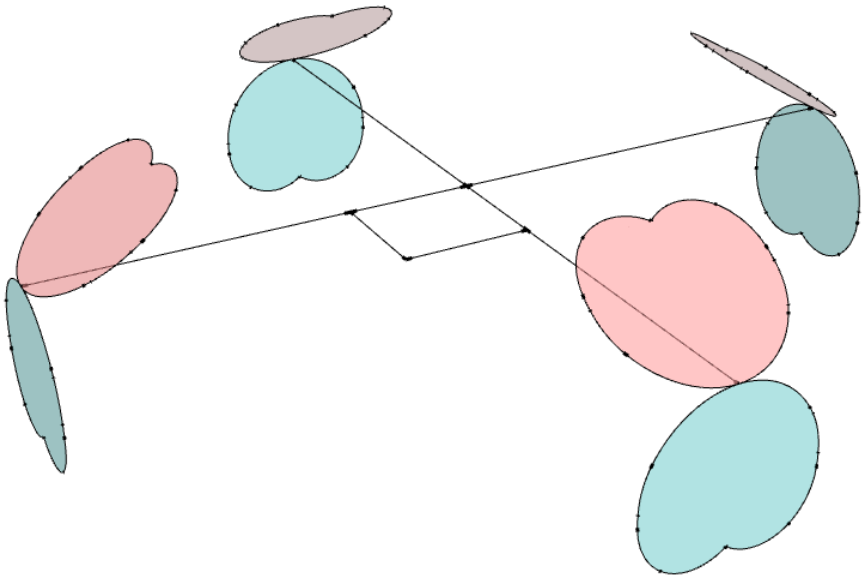
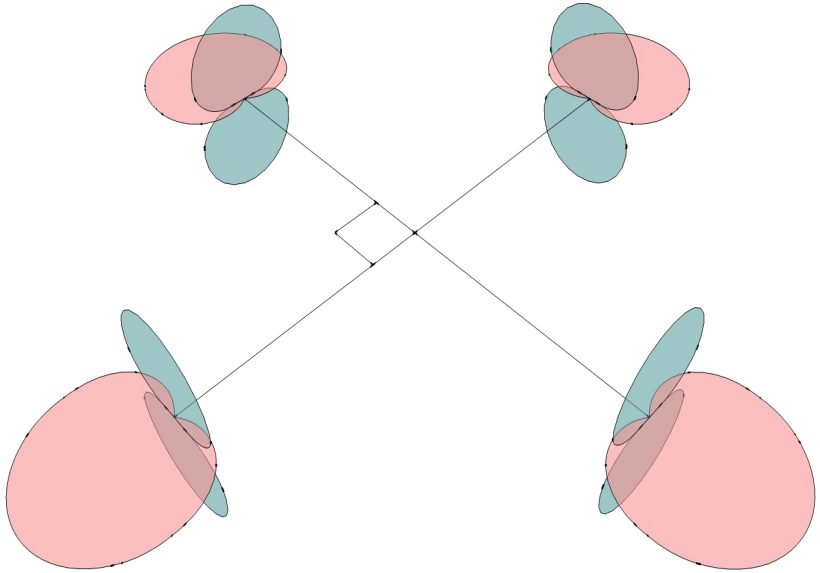
- Augmented with upward-facing supercardioid or figure-of-8 microphones.



1 to 1 routing to speakers



Vertical Mid-Side decoding

ESMA-3D

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- Vertical time panning is highly unstable [Wallis and Lee JAES 2015].
- Vertical microphone spacing has little effect on LEV [Lee and Gribben JAES 2014].
- Vertical level panning can still work with a limited resolution [Barbour 2003, Mironovs and Lee 2016].

ORTF-3D

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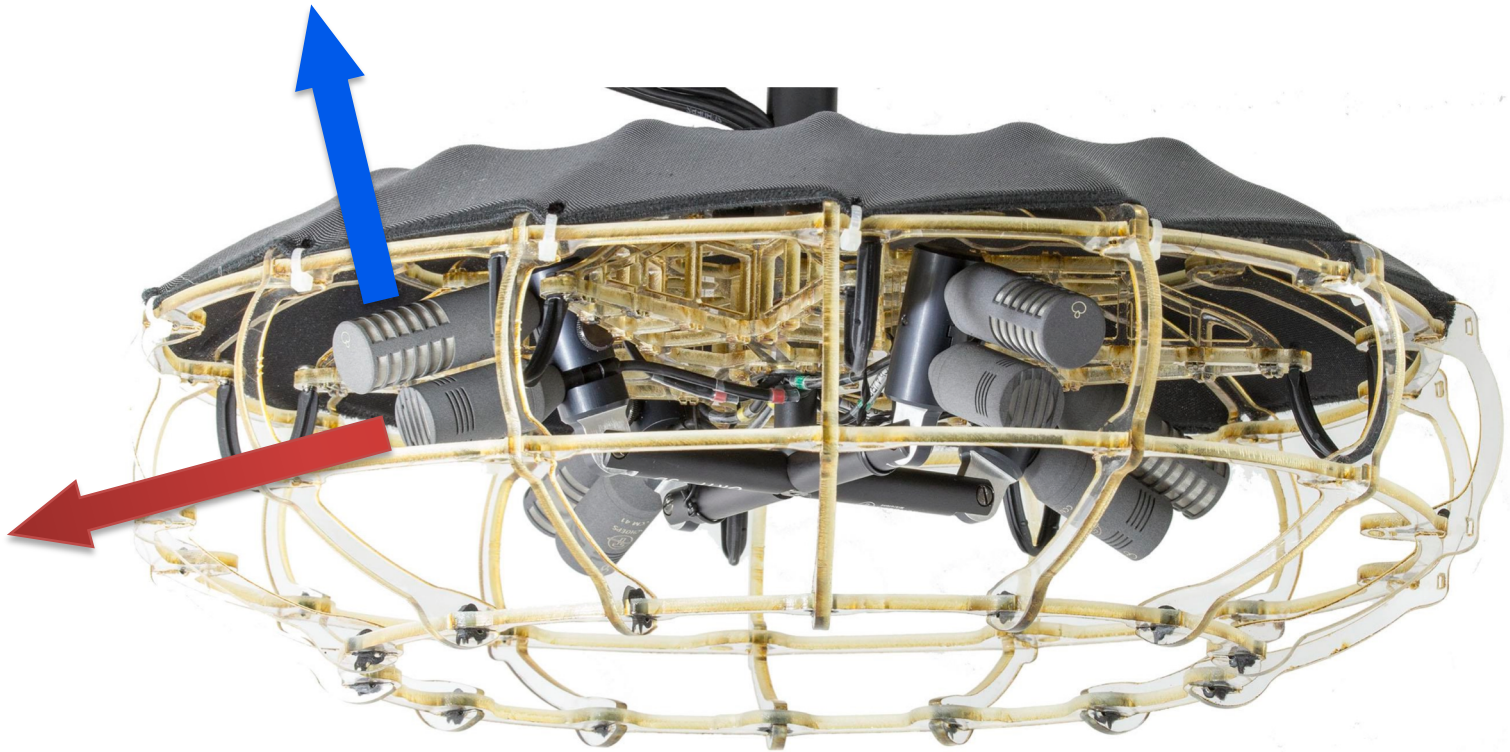
- Schoeps ORTF 3D
  - Share the same design concept.
  - Based on Lee and Gribben [JAES 2014]



ESMA-3D

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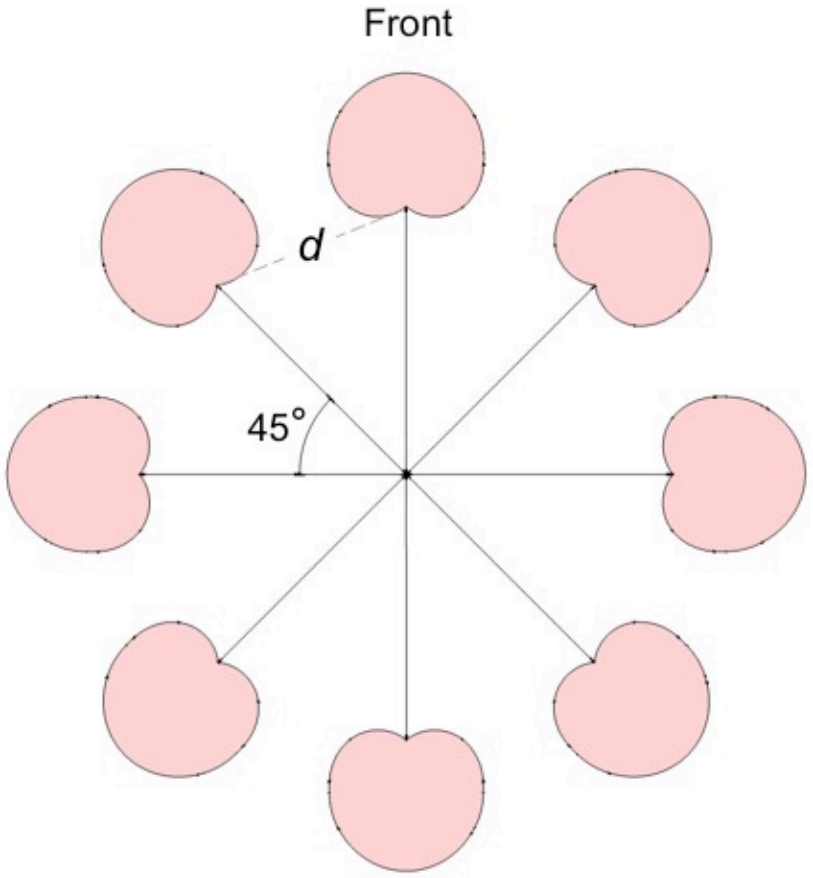
- 4 supercardioid height microphones facing upwards.
- The height mic should have at least 7 to 10dB less direct sound than the main mic to avoid vertical image shift [Lee 2011; Wallis and Lee 2017]

Higher Order ESMA

- Higher Order ESMA
  - For an octagonal setup, each segment should have the SRA of 45°.
  - Can potentially solve the problem of unstable side image localisation.
  - Mic spacing *d*
    - *Williams: 82cm*
    - *Lee: 55cm*



Higher Order ESMA

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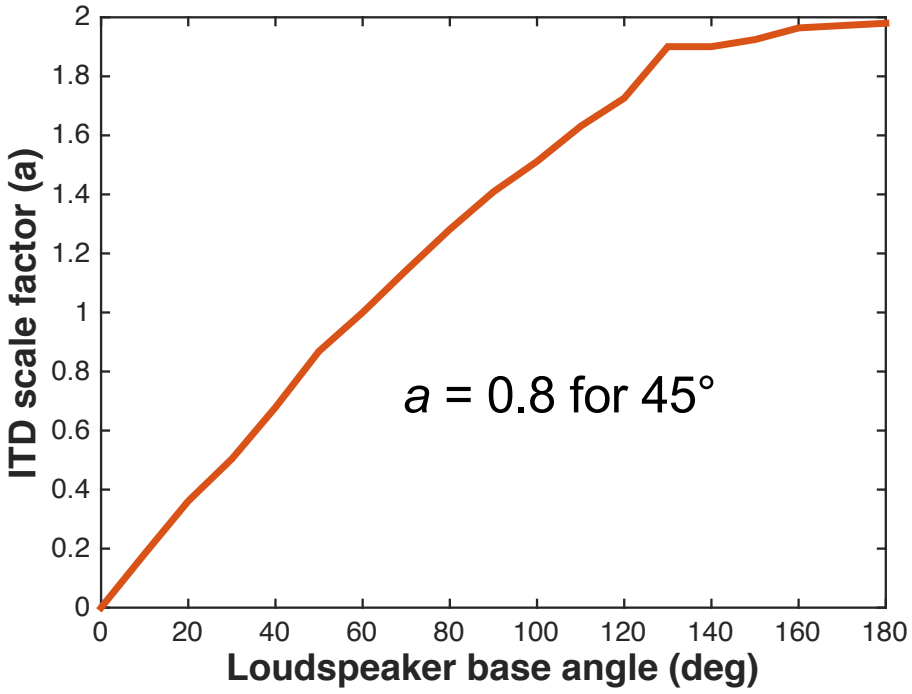
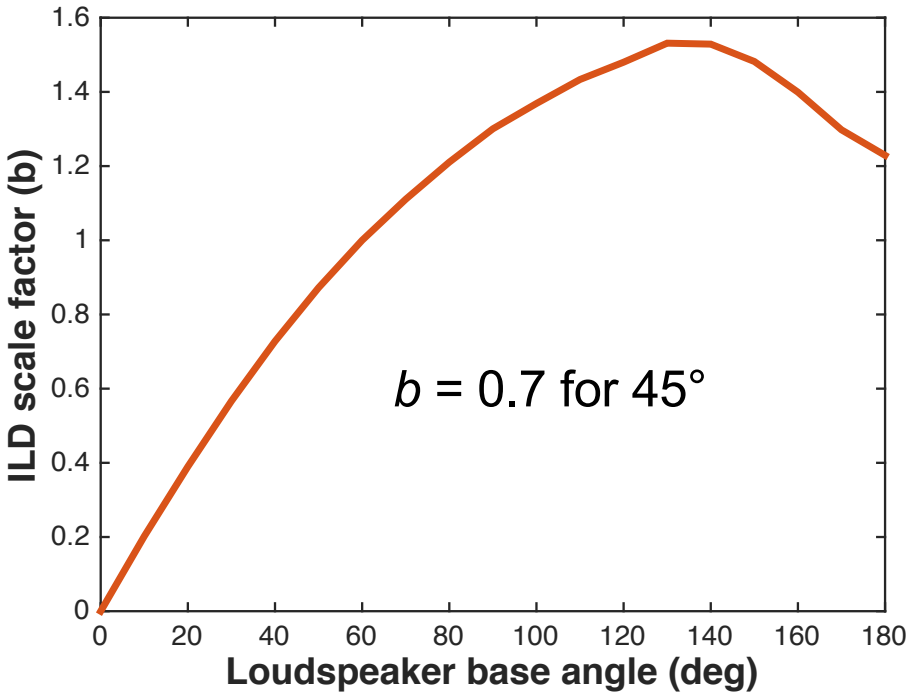
- Perceptual scaling based on ILD and ITD matching.
  - Scale factors a and b
  - Ratio of the ITD from real source to the ITD from phantom source at half the base angle.





Thanks for listening.

Questions?