Psychoacoustics of 3D ad VR Sound Recording: Research and Practice

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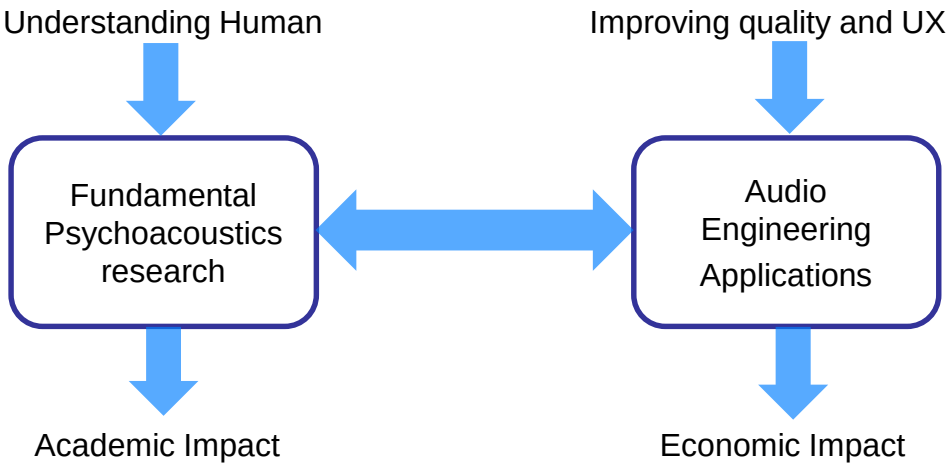
About me

- Senior Lecturer (i.e. Associate Professor) in Music Technology at the University of Huddersfield, UK (2010 – Present).
- Leader of the Applied Psychoacoustics Lab (2013 – Present).
- Senior Research Engineer at LG Electronics, Korea (2006 – 2010).
- PhD in surround sound psychoacoustics, University of Surry, UK (2002 – 2006).
- BMus in Sound Recording (Tonmeister), University of Surrey (1998 – 2002).
- Freelance sound engineer (2002 – Present).
- Assistant sound engineer at Metropolis studios, London, UK (2000 – 2001).
- Intern sound engineer at Aspen Music Festival, Colorado, USA (1999, 2000).
- Assistant sound engineer at Sound Hill studios, South Korea (1997 – 1998).

Applied Psychoacoustics Lab (APL)

- The APL aims to provide solid psychoacoustic bases for audio engineering applications.

- To bridge gap between perception and engineering.



About Applied Psychoacoustics Lab (APL)

- Members
  - 3 staff researchers.
  - Currently 5 PhD, 2 Masters and 4 Undergraduate students.
  - 3 PhD and 2 Masters graduated.

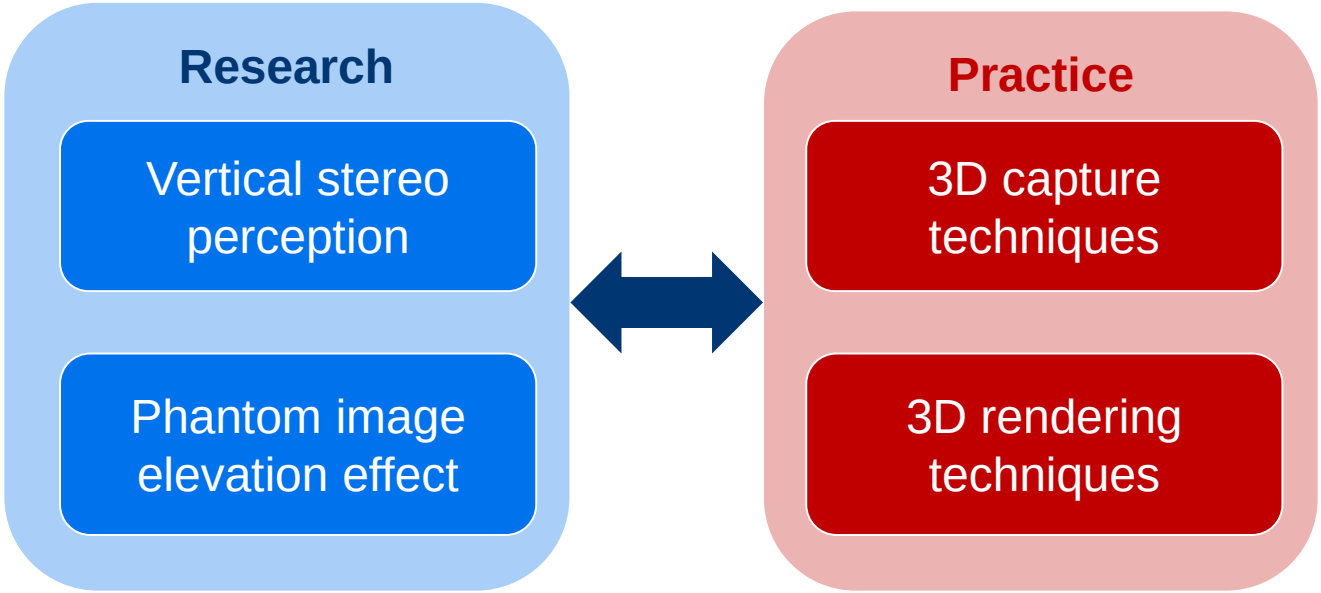
- Current research focus
  - Sound recording and reproduction techniques for 3D and VR audio.
  - Binaural and multichannel auditory localisation mechanism.
  - Perceptually optimised virtual acoustics.
  - Auditory-visual interaction on the quality of experience.
  - Development of objective sound quality metrics.

- More information on *www.hud.ac.uk/apl*

Applied Psychoacoustics Lab (APL)

- ITU-R BS.1116-compliant listening room.
- 3D formats (22.2, Dolby Atmos, Auro-3D, etc.).

Today’s talk and demo

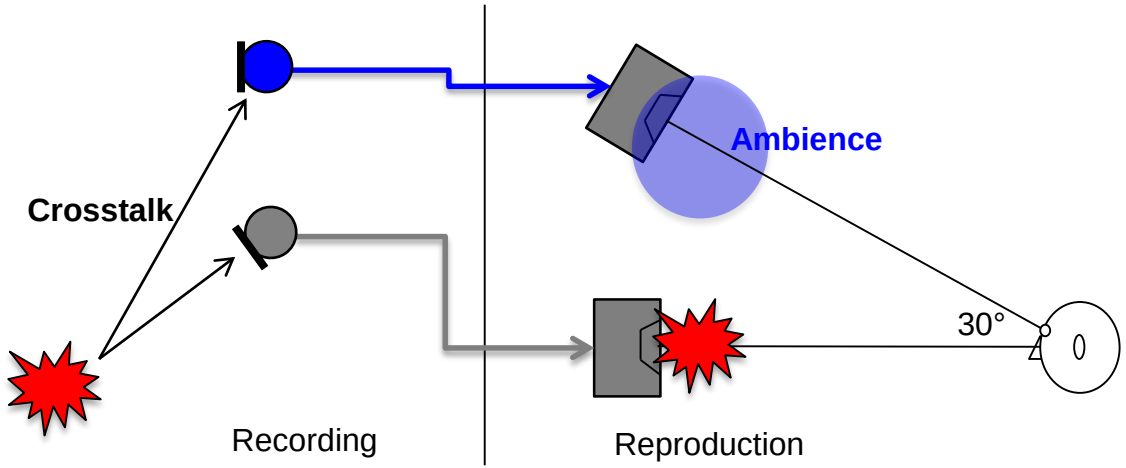


With 9-channel 3D demos

Vertical Stereo Perception
&
3D Microphone Techniques

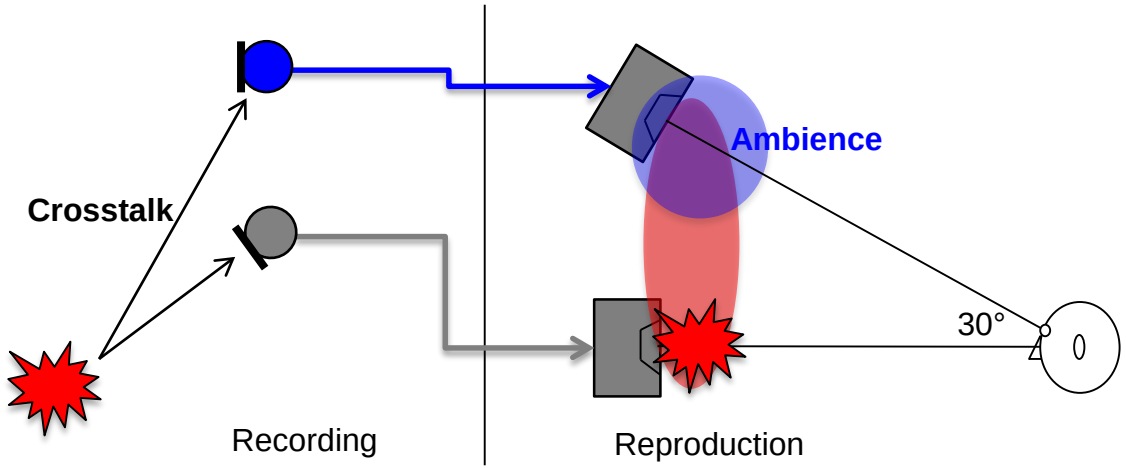
Vertical interchannel crosstalk

- What is vertical interchannel crosstalk?
  - A (delayed) direct sound captured by a height microphone that aims to capture ambience.



Vertical interchannel crosstalk

- What is vertical interchannel crosstalk?
  - A (delayed) direct sound captured by a height microphone that aims to capture ambience
  - Perceptual effects: Localisation shift, loudness, vertical image spread, etc.

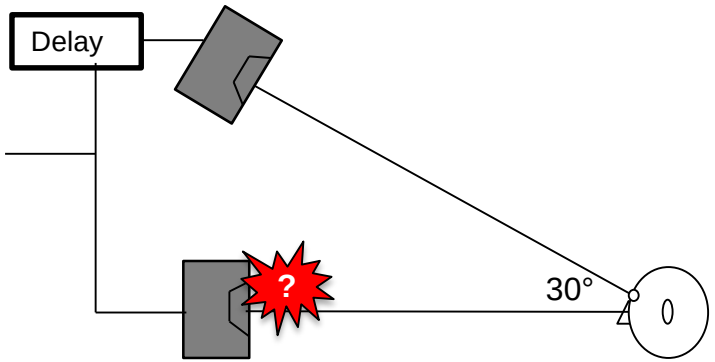


Vertical Interchannel Time Difference

- Question 1: Can the image be localised at the ear-height by applying time delay between the vertically arranged microphones?

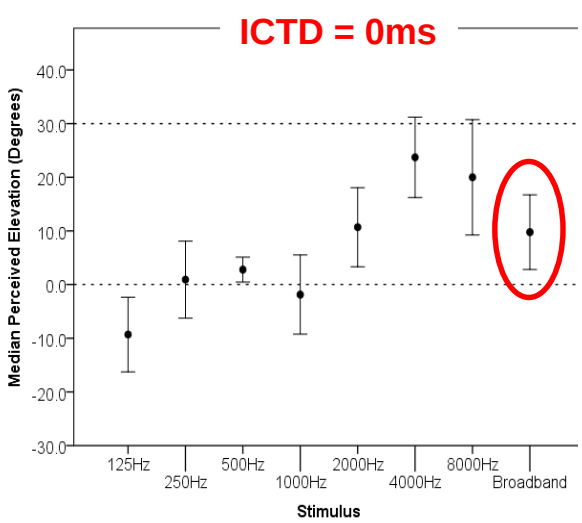
e.g. Omni mic for height

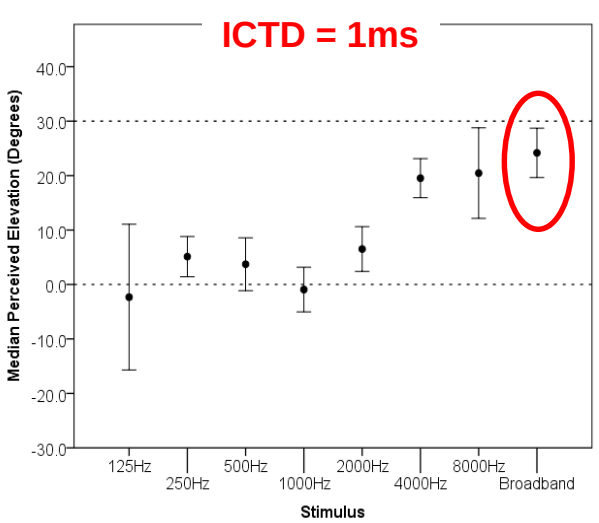
(no level diff but only time diff)

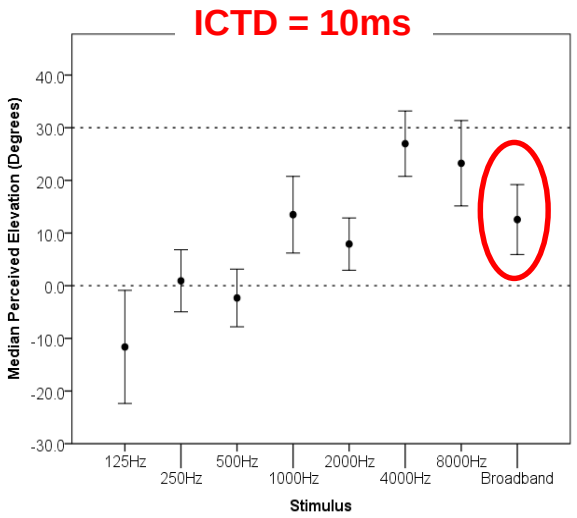


Vertical Interchannel Time Difference

- Interchannel time difference (ICTD) is a very unstable cue for vertical localisation (Wallis and Lee 2015).
- The precedence effect does NOT operate vertically.



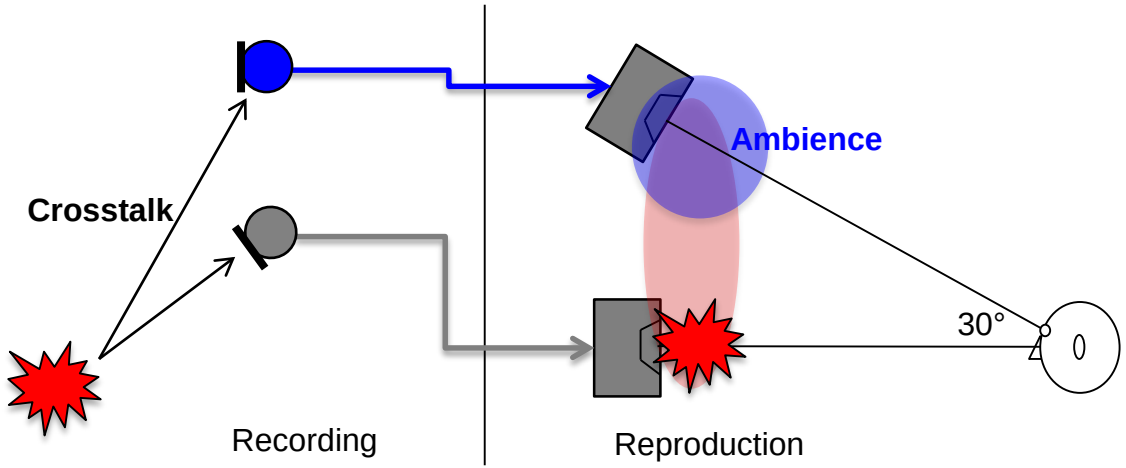




Wallis, R. and Lee, H. (2015) 'The Effect of Interchannel Time Difference on Localisation in Vertical Stereophony' *Journal of the Audio Engineering Society* , 63 (10), pp. 767-776. ISSN 1549-4950

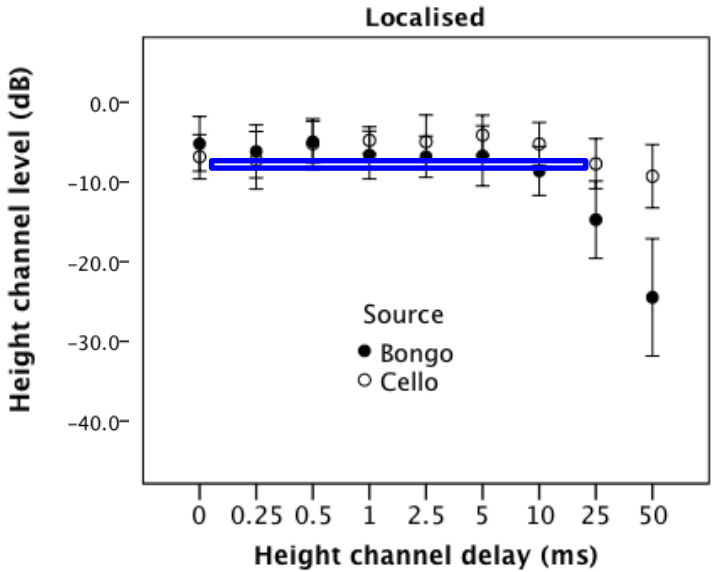
Vertical Localisation Threshold

- Question 2: How much level attenuation of vertical crosstalk is required for the image to be "*localised*" around the ear-height?



Vertical Localisation Threshold

- Localised threshold (Lee 2011, Wallis and Lee 2017)
  - **Up to ICTD of 10ms**, the height channel level should be attenuated by at least **7dB** compared to the main channel level.

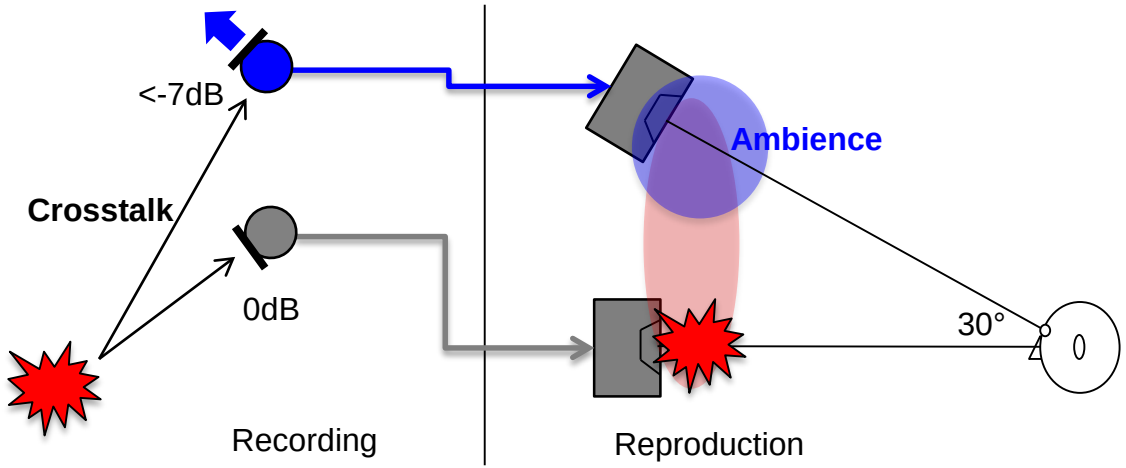


-7dB

Lee, H (2011) '[The Relationship between Interchannel Time and Level Differences in Vertical Localisation and Masking]'. *In: 131st Audio Engineering Society Convention*

Vertical Localisation Threshold

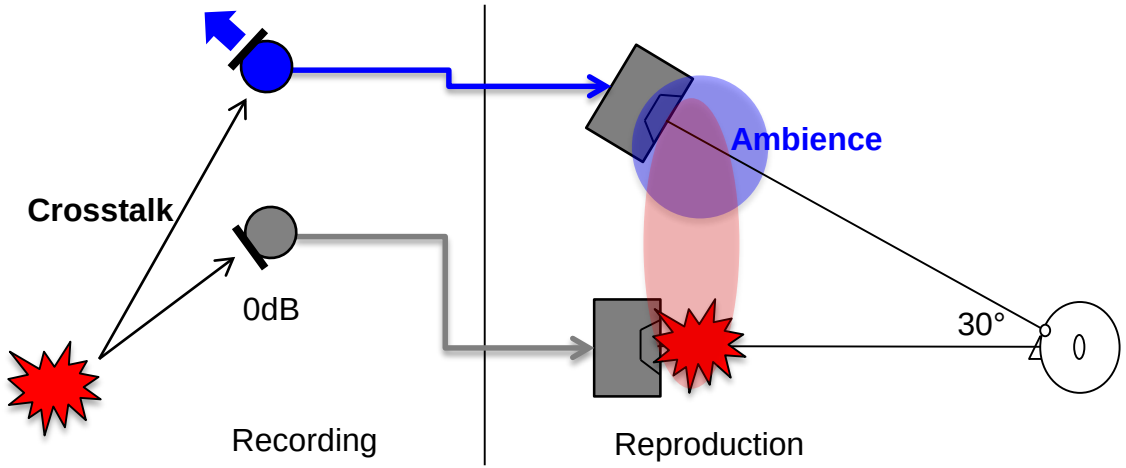
- Localised threshold (Lee 2011, Wallis and Lee 2017)
  - The height microphone should be angled so that its ICLD to the main microphone becomes at least **-7dB**.



Lee, H (2011) '[The Relationship between Interchannel Time and Level Differences in Vertical Localisation and Masking]'. *In: 131st Audio Engineering Society Convention*

Vertical Masking Threshold

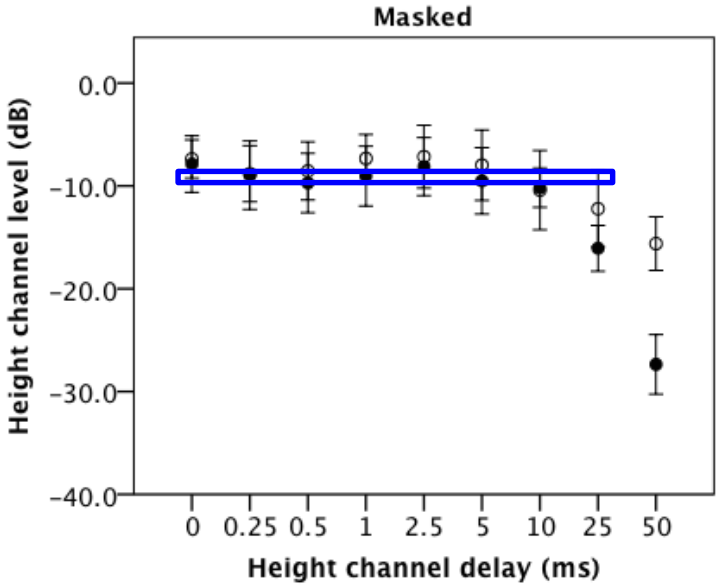
- Question 3: How much level attenuation of direct sound is required for the perceptual effects of vertical crosstalk to be "*completely inaudible*"?



Lee, H (2011) 'The Relationship between Interchannel Time and Level Differences in Vertical Localisation and Masking'. *In: 131st Audio Engineering Society Convention*

Vertical Masking Threshold

- Masked threshold (Lee 2011)
  - **Up to ICTD of 10ms**, the height channel level should be attenuated by at least **10dB** to make the crosstalk inaudible.

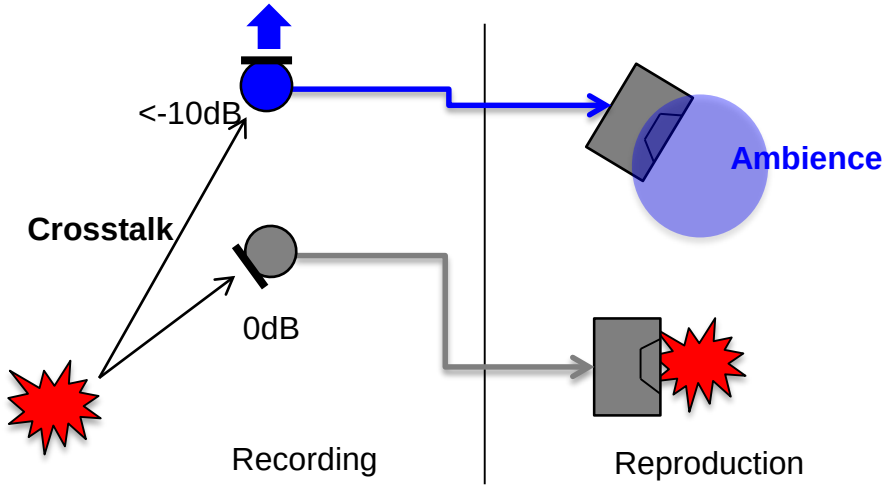


-10dB

Lee, H (2011) '[The Relationship between Interchannel Time and Level Differences in Vertical Localisation and Masking]'. *In: 131st Audio Engineering Society Convention*

Vertical Masking Threshold

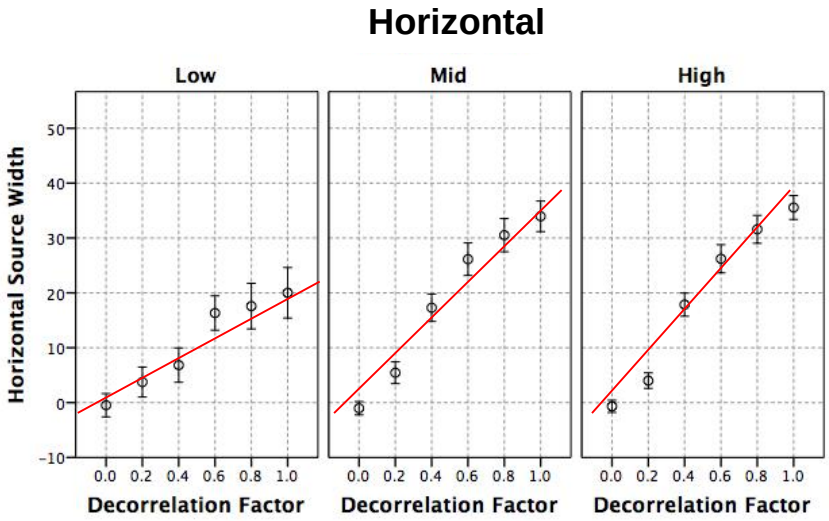
- Masked threshold (Lee 2011)
  - The height microphone should be angled so that its ICLD to the main microphone becomes at least **-10dB**.

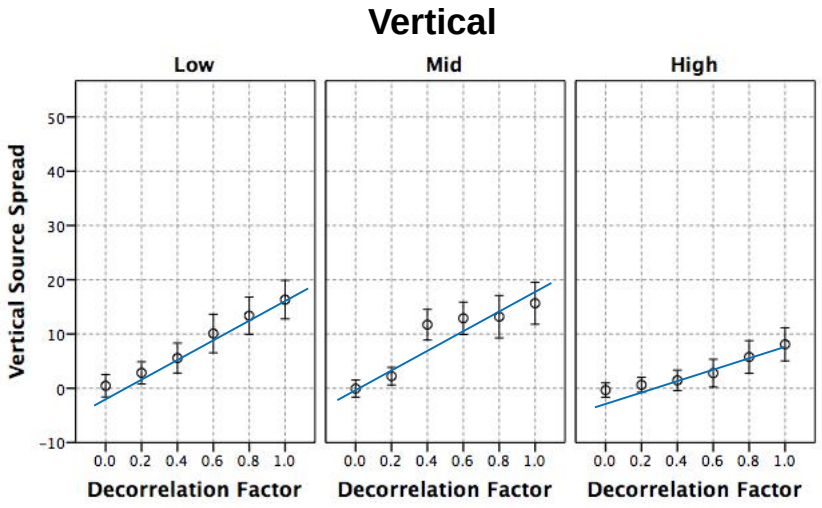


Lee, H (2011) '[The Relationship between Interchannel Time and Level Differences in Vertical Localisation and Masking]'. *In: 131st Audio Engineering Society Convention*

Vertical Decorrelation

- The effect of vertical decorrelation on vertical image spread (VIS) is audible, but not as large as that of horizontal decorrelation (Gribben and Lee 2017).

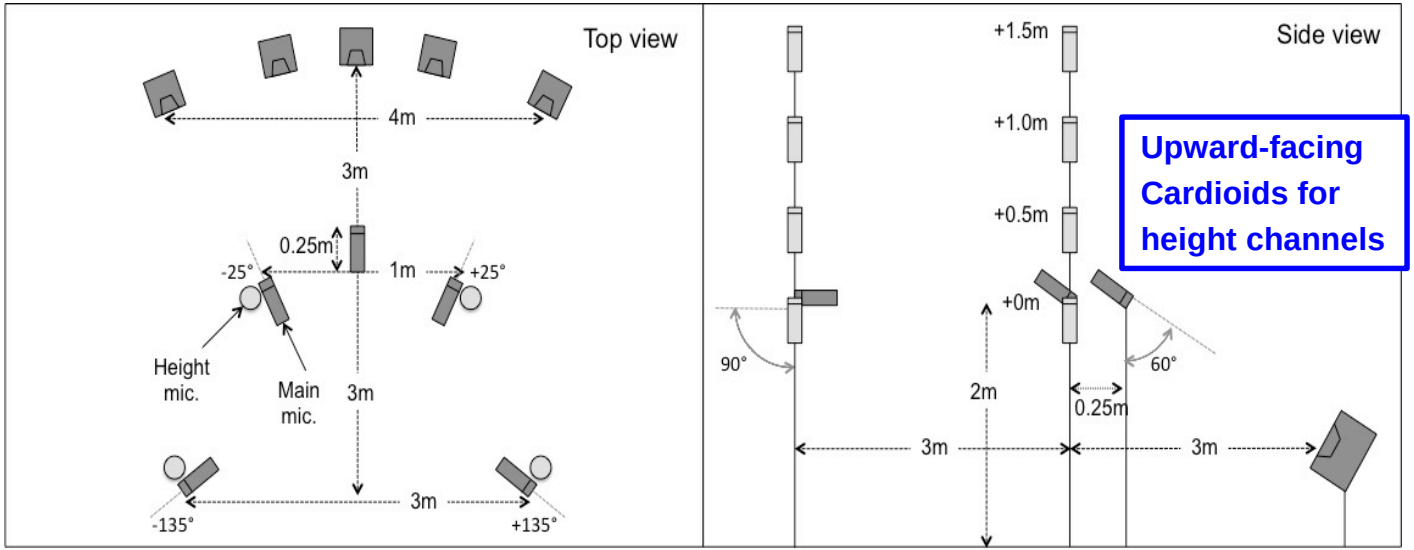




Gribben, C. and Lee, H. (2017) '[A Comparison between Horizontal and Vertical Interchannel Decorrelation]' *Applied Sciences* , 7 (11), p. 1202. ISSN 2076-3417

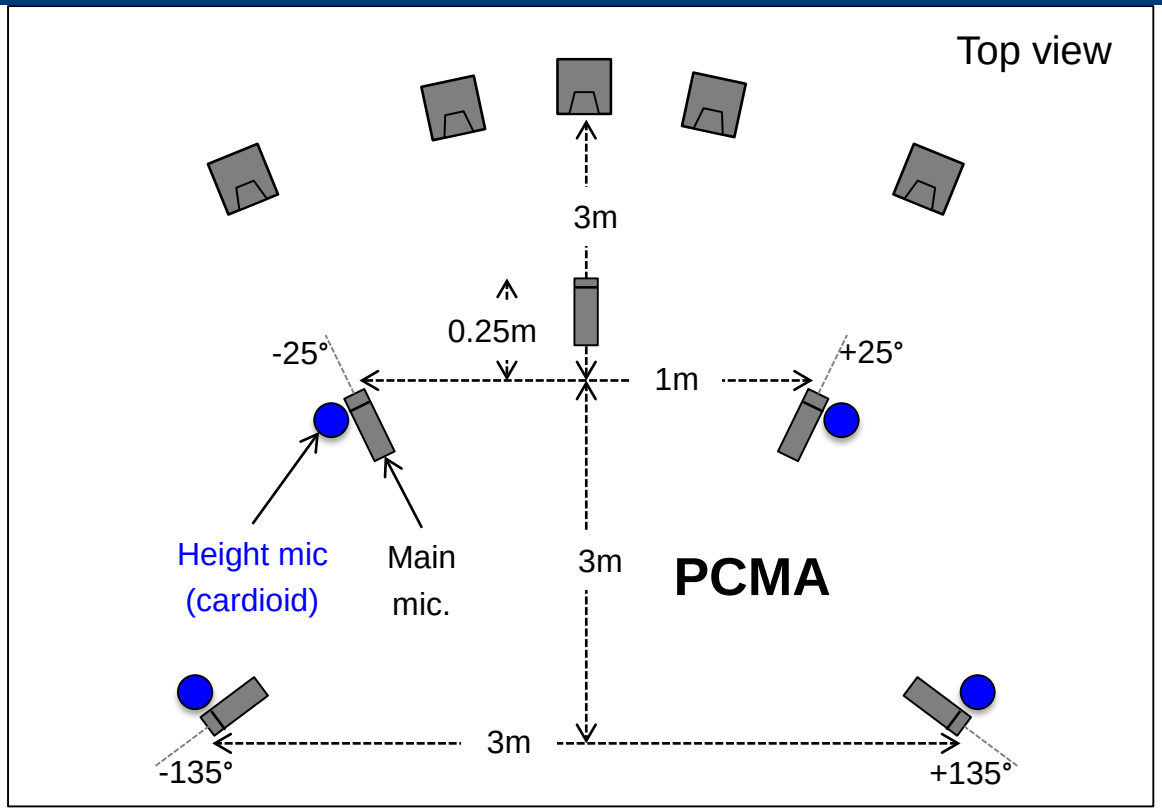
Vertical Microphone Spacing

- The effect of vertical microphone spacing on spatial impression (Lee and Gribben 2014)



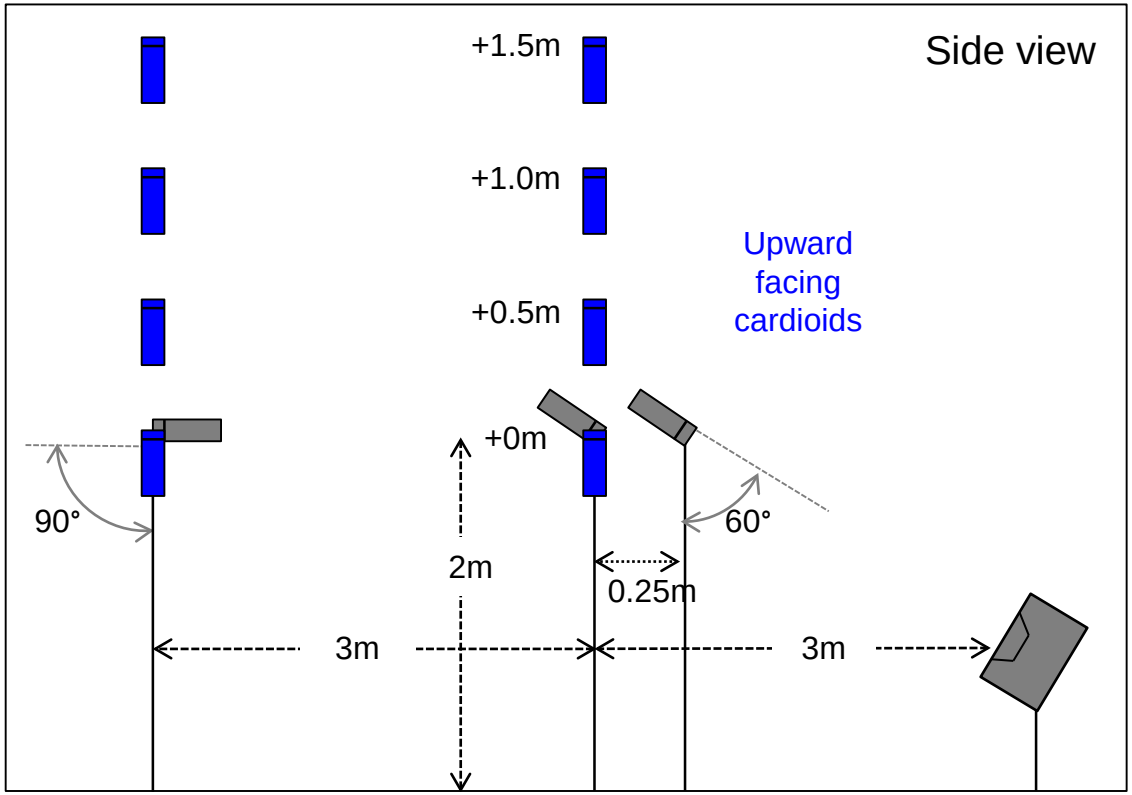
Lee, H. and Gribben, C. (2014) '[Effect of Vertical Microphone Layer Spacing for a 3D Microphone Array]' *Journal of the Audio Engineering Society* , 62 (12), pp. 870-884. ISSN 15494950

Recording Setup



Lee, H. and Gribben, C. (2014) 'Effect of Vertical Microphone Layer Spacing for a 3D Microphone Array' *Journal of the Audio Engineering Society* , 62 (12), pp. 870-884. ISSN 15494950

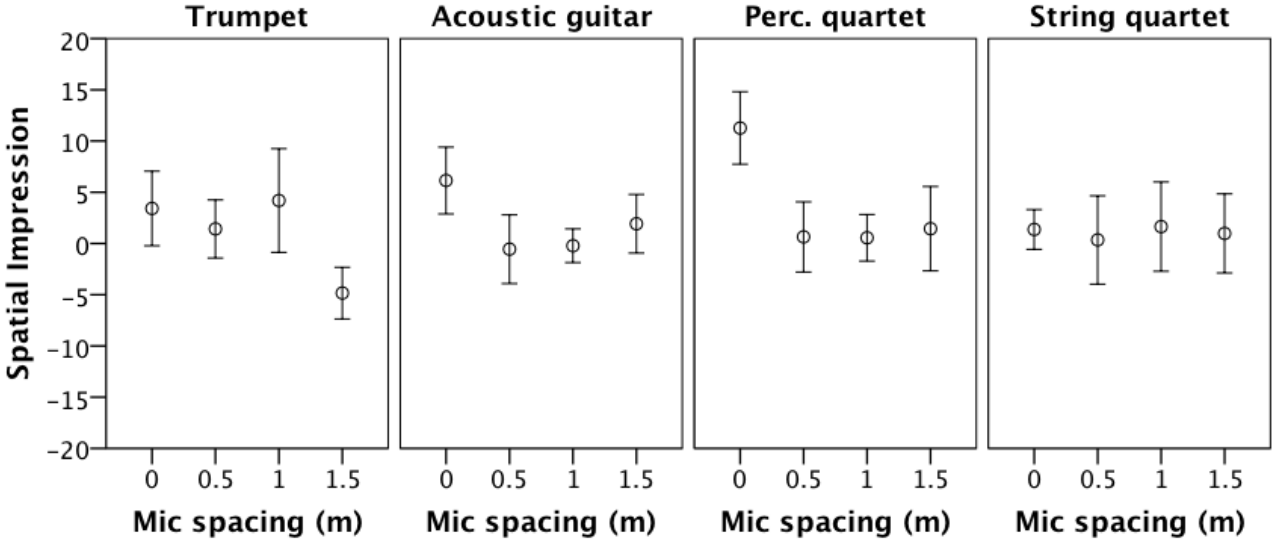
Recording Setup



Lee, H. and Gribben, C. (2014) 'Effect of Vertical Microphone Layer Spacing for a 3D Microphone Array' *Journal of the Audio Engineering Society* , 62 (12), pp. 870-884. ISSN 15494950

Vertical Microphone Spacing

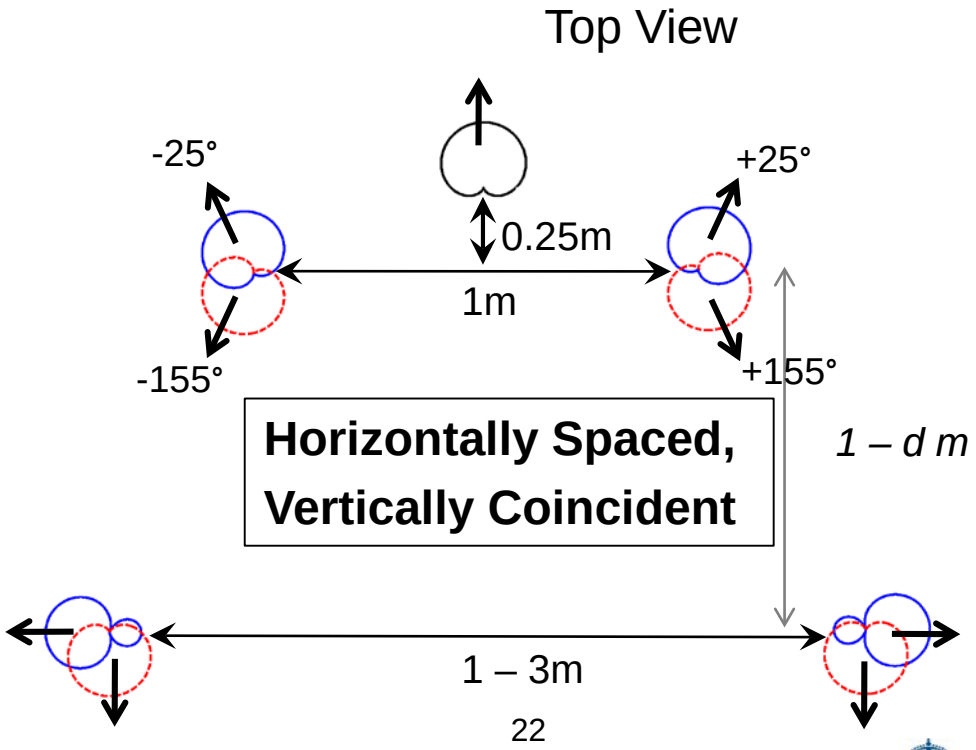
- Vertical microphone spacing does not have a significant effect on perceived spatial impression.
- 0m spacing (vertically coincident) produced greater spatial impression for percussive sources.



Lee, H. and Gribben, C. (2014) 'Effect of Vertical Microphone Layer Spacing for a 3D Microphone Array' *Journal of the Audio Engineering Society* , 62 (12), pp. 870-884. ISSN 15494950

PCMA-3D Microphone Array

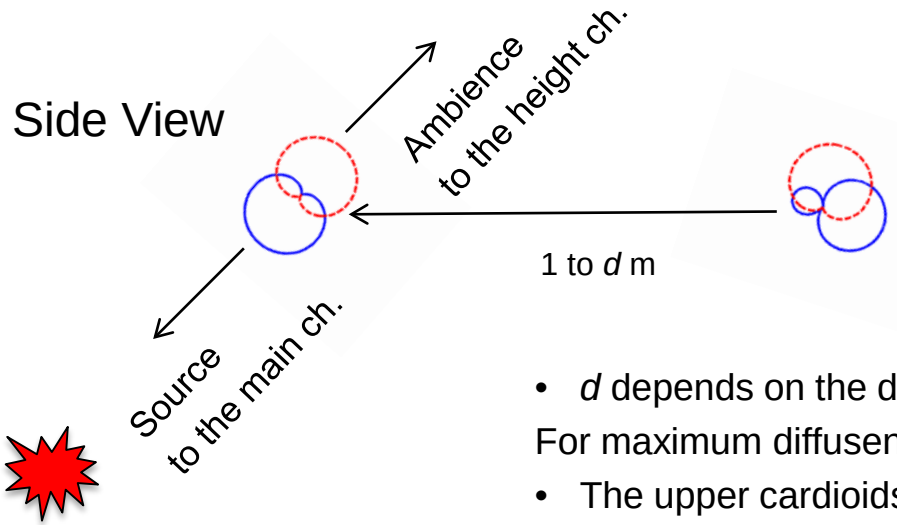
- Original concept of PCMA (Perspective Control Microphone Array) (Lee 2011, 2012)
  - Perceived distance control by virtual microphones at each pick up point.
  - Combine blue and red microphones with a varying mixing ratio → Virtual microphone pointing towards a different direction → controls D/R ratio → changes listener's perspective.



Lee, H (2012) '[Subjective Evaluations of Perspective Control Microphone Array (PCMA)]'. *In: 132nd Audio Engineering Society Convention, 26-29 April 2012*, Budapest, Hungary

PCMA-3D Microphone Array

- Application of PCMA for 3D capture (Lee and Gribben 2014)



Separation between
Source and Environmental components !

- *d* depends on the desired diffuseness of the rear channels:

For maximum diffusenese, beyond critical distance recommended.

- The upper cardioids can be angled directly towards the ceiling:

this still allows enough suppression of the vertical interchnanel crosstalk.

Lee, H. and Gribben, C. (2014) '[Effect of Vertical Microphone Layer Spacing for a 3D Microphone Array]' *Journal of the Audio Engineering Society* , 62 (12), pp. 870-884. ISSN 15494950

Demo: Siglo De Oro Choir

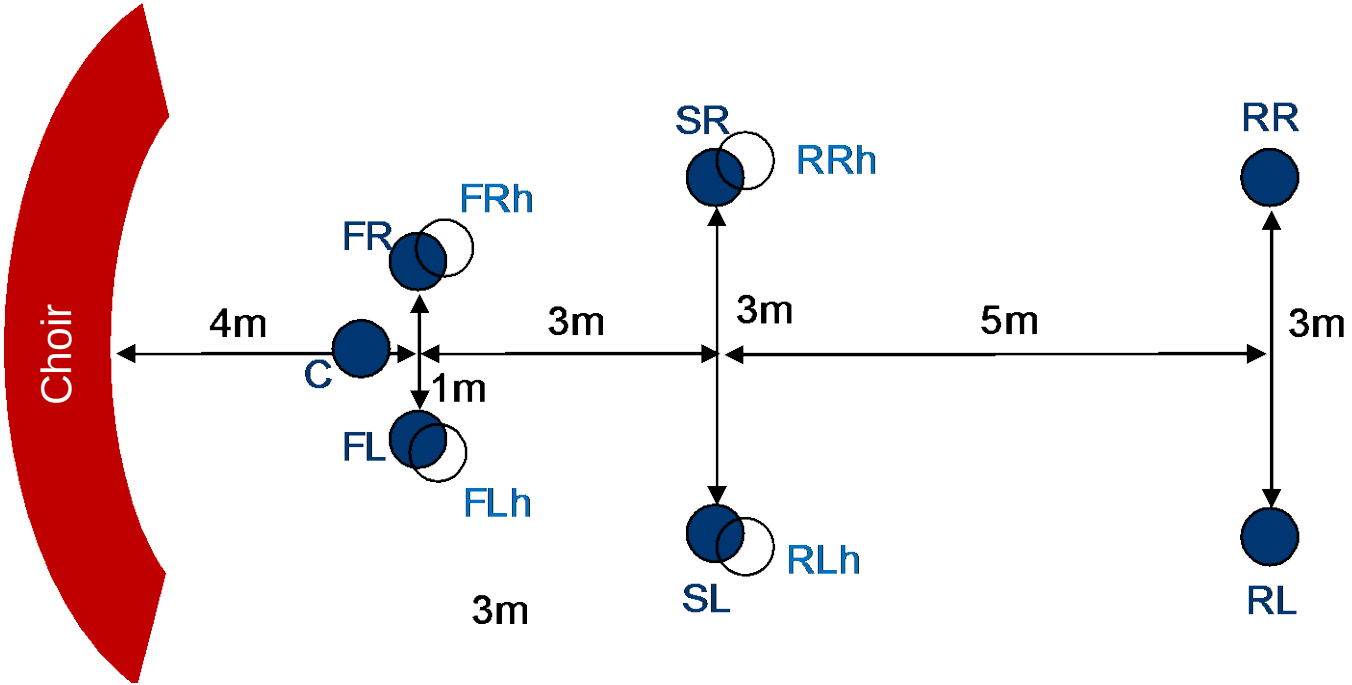
- Recorded in 11.0 using the PCMA-3D concept.
- Pure Audio Blu-ray
  - Auro-3D 9.0 96kHz
  - Dolby Atmos 48kHz
  - DTS 5.0 192kHz
  - LPCM 2.0 192kHz
- To be released by Delphian Records on 18 May.

Demo: Siglo De Oro Choir

- Recorded at Merton College Chapel in Oxford, UK.

Demo: Siglo De Oro Choir

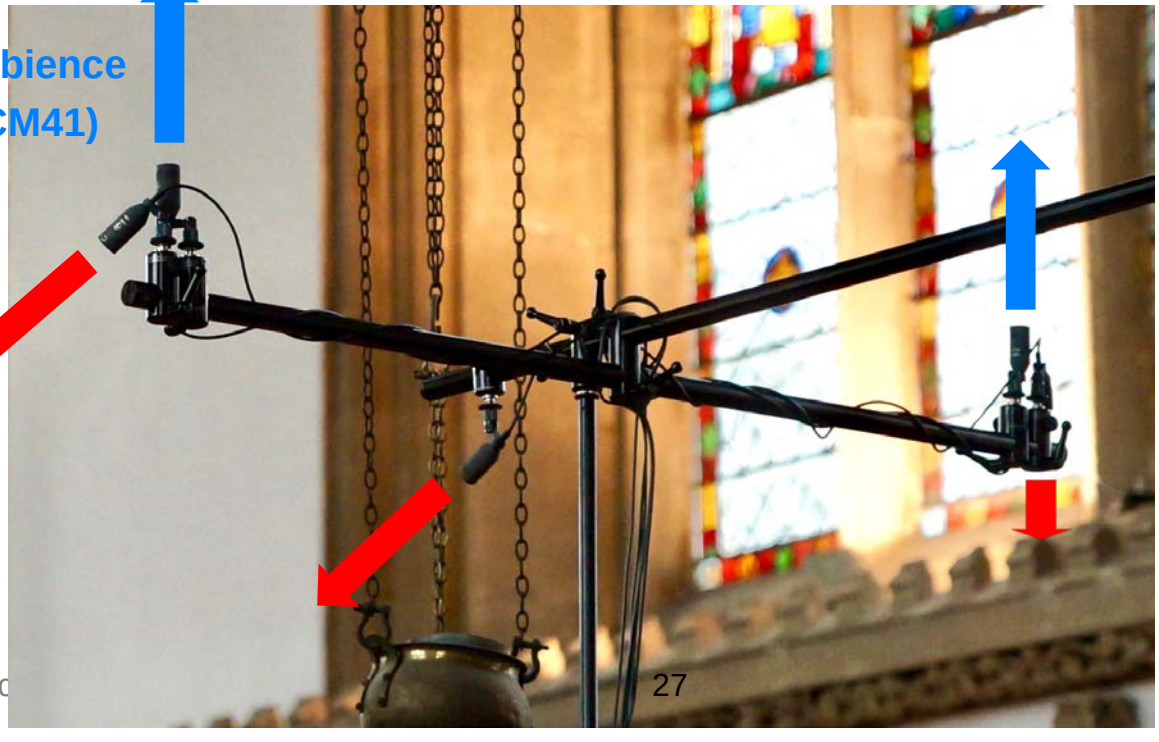
- PCMA-3D microphone arrangement for 11.0 (7+4)



Demo: Siglo De Oro Choir

- Microphones used: Schoeps CCM4 (main) and CCM41 (height).

Frontal array

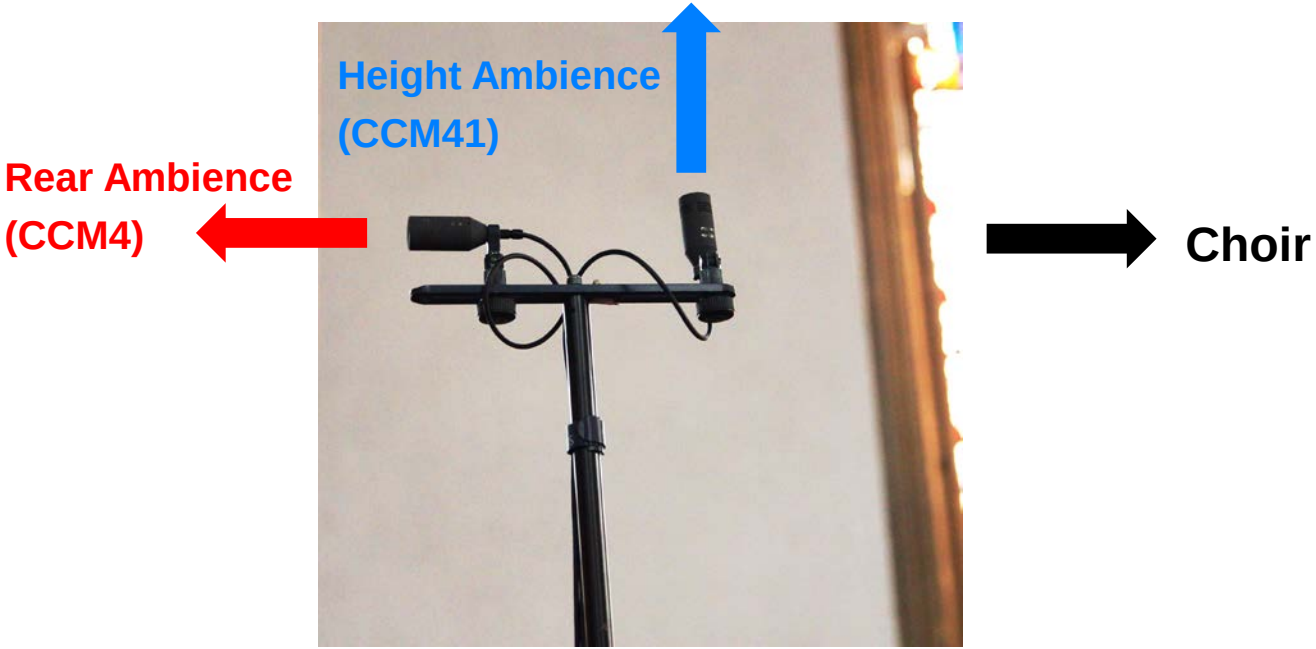


Demo: Siglo De Oro Choir

- Microphones used: Schoeps CCM4 and CCM41.

3D Recording of Siglo De Oro Choir

- Microphones used: Schoeps CCM4 and CCM41.

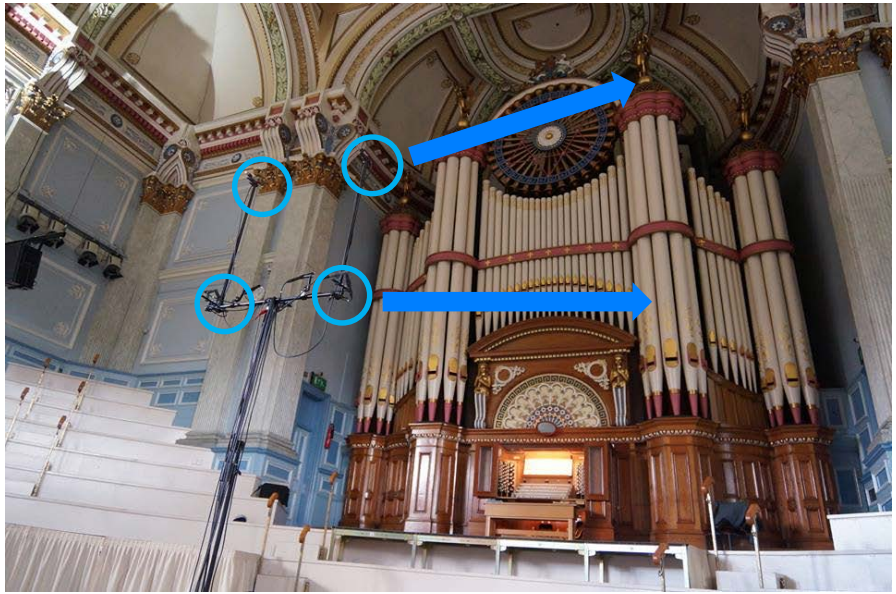


Demo: Zulu Ensemble in 9.0

- Recorded at St. Paul's at the University of Huddersfield.

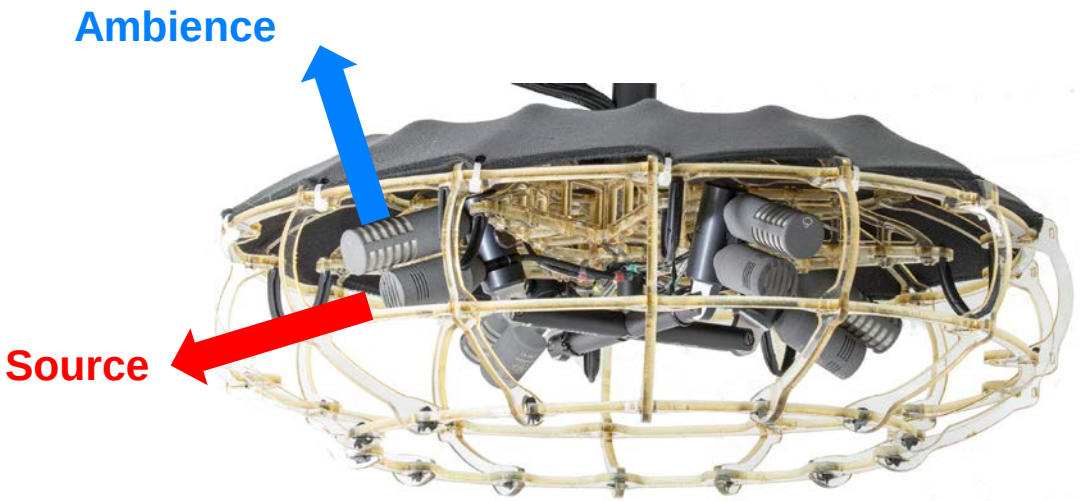
Demo: Organ

- Recorded at Huddersfield Town Hall.
- Capture direct sounds with both main and height microphones.
- Tall instrument e.g. organ; Elevated sources, e.g. Choir on platforms.



ORTF-3D by Schoeps

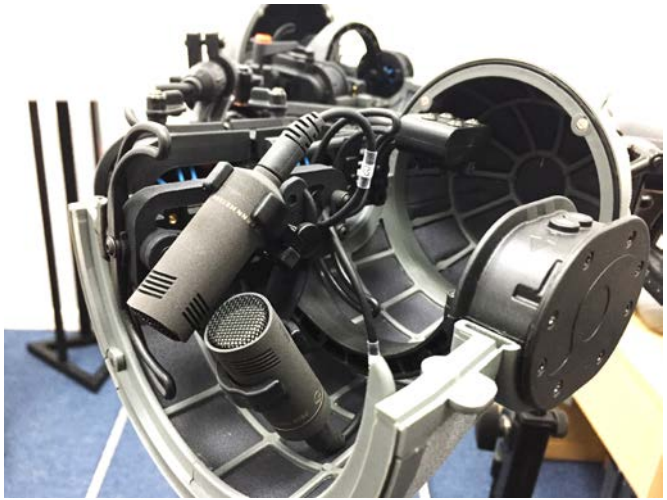
- Vertical concept based on a finding by Lee and Gribben (2014).
  - Vertically coincident, horizontally spaced.



Lee, H. and Gribben, C. (2014) 'Effect of Vertical Microphone Layer Spacing for a 3D Microphone Array' *Journal of the Audio Engineering Society* , 62 (12), pp. 870-884. ISSN 15494950

ESMA-3D

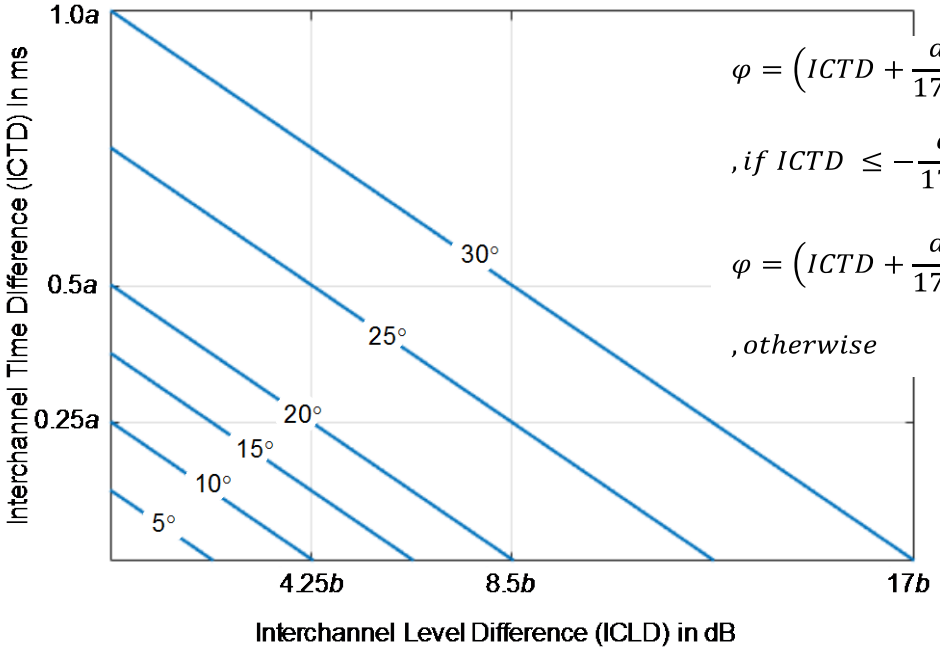
- Equal Segment Microphone Array for 360 audio capture.
- 50cm x 50cm square, ideal size for accurate localisation in a quadraphonic reproduction (Lee 2016).
- Vertically coincident (Cardioid main + supercardioid height.)



Lee, H (2016) 'Capturing and Rendering 360º VR Audio Using Cardioid Microphones'. *In: AES Conference on Audio for Augmented and Virtual Reality, 30 Sep - 1 Oct 2016*, Los Angeles, USA

Psychoacoustic model

- **New Time and Level Trade-off Functions**



$$\varphi = \left(ICTD + \frac{a}{17b} ICLD\right) \frac{4\theta}{3a}$$

$$, if\ ICTD \leq -\frac{a}{17b} ICLD + \frac{a}{2}\ \&\ ICLD \leq 17b\left(\frac{a}{2} - ICTD\right)$$

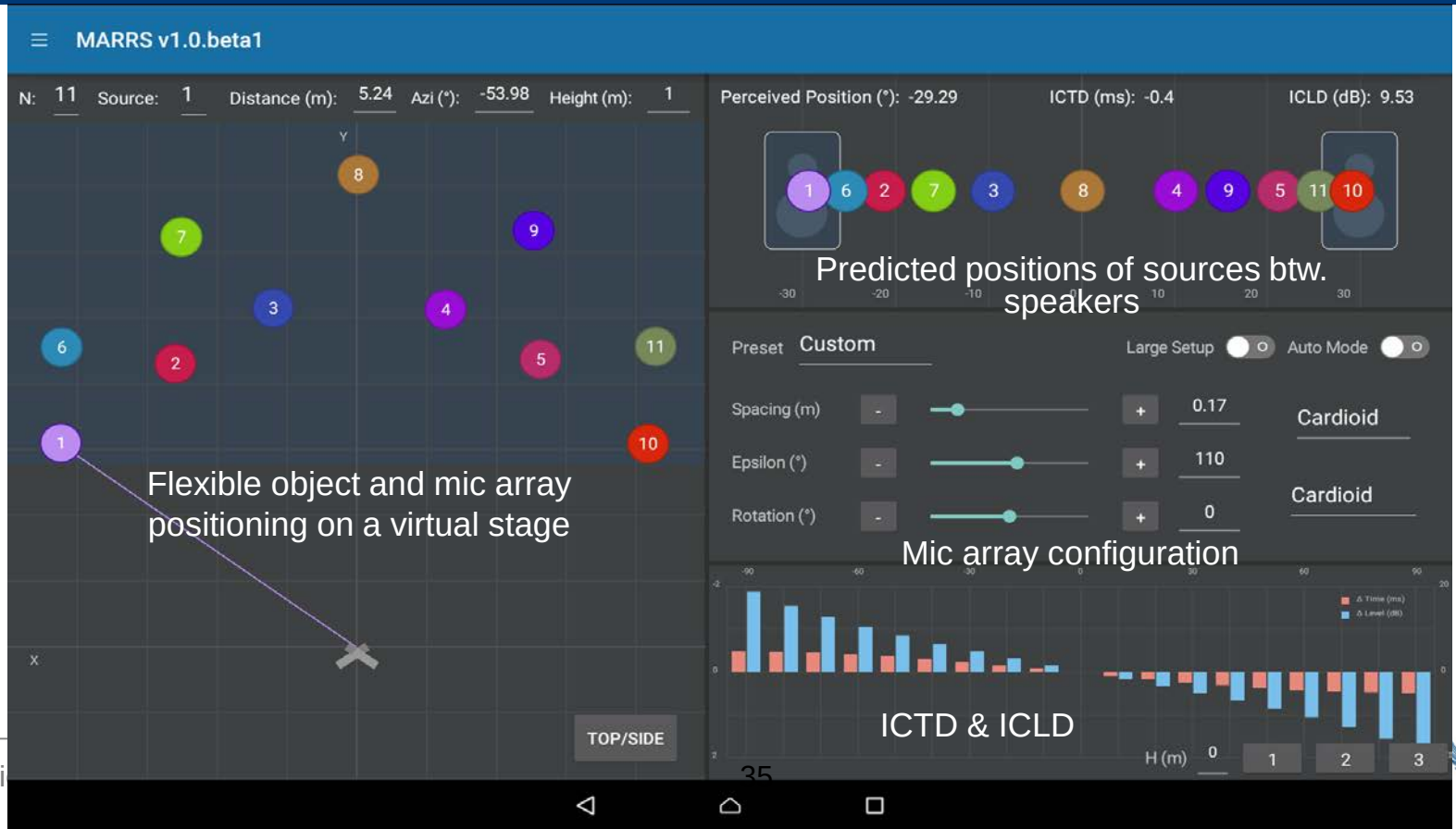
$$\varphi = \left(ICTD + \frac{a}{17b} ICLD + \frac{a}{2}\right) \frac{2\theta}{3a}$$

$$, otherwise$$

φ = predicted image angle
θ = half the loudspeaker base angle
a = ITD(θ)/ITD(30°)
b = ILD(θ)/ILD(30°)

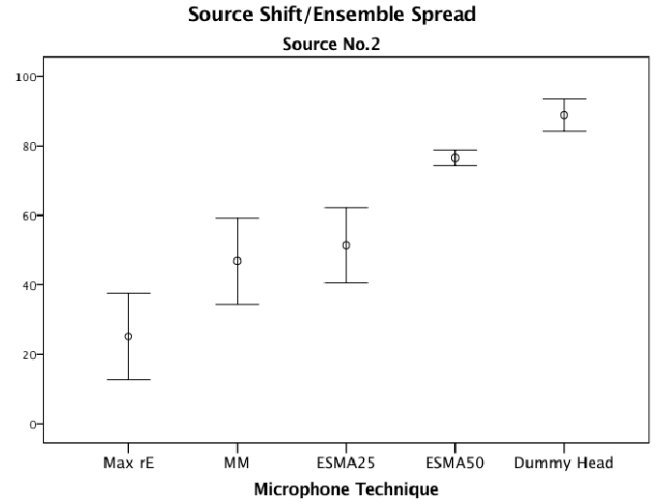
Developed based on H. Lee and F. Rumsey, “Level and time panning of phantom images for musical sources,” *J. Audio Eng. Soc.*, vol.61 (12), pp. 753-767 (2013 Dec.).

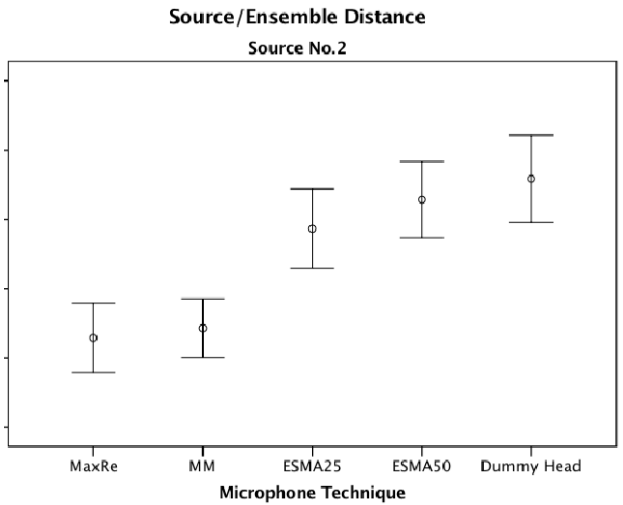
Psychoacoustic model

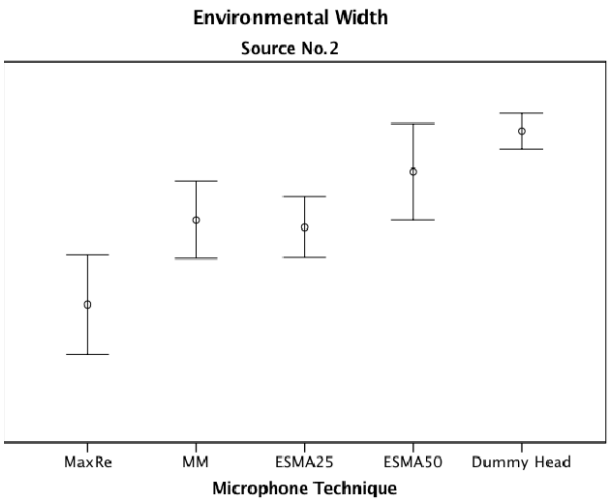


ESMA-3D

- Comparison against FOA and Dummy Head (Millns and Lee 2018).





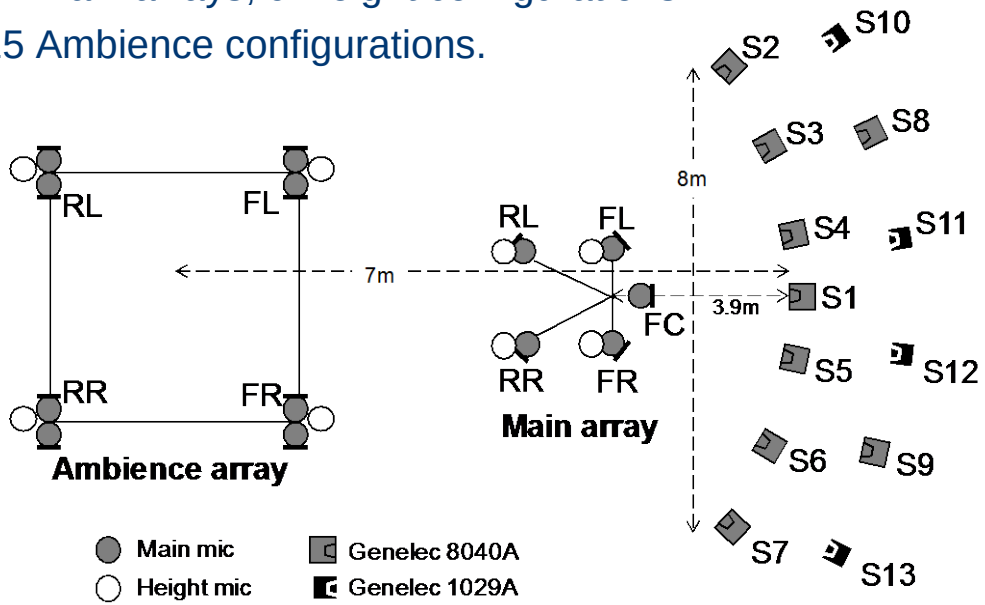


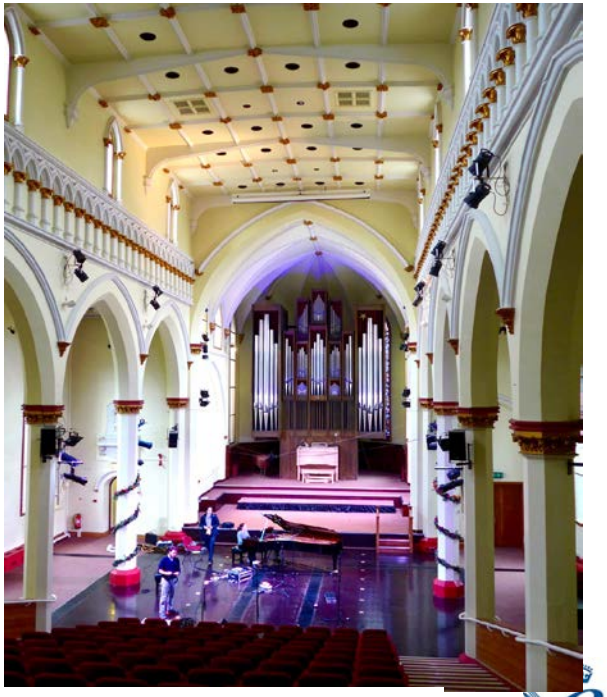
Millns, C. and Lee, H (2018) 'An Investigation into Spatial Attributes of 360° Microphone Techniques for Virtual Reality'. *In: AES the 144th International Convention, 23 – 26 May 2018*, Milan, Italy.

VR Soundscape Library

MAIR Library and Renderer

- Over 2000 Microphone Array Impulse Responses (MAIRs) captured for 13 source positions (Lee and Millns 2017).
- 12 Main arrays, 9 Height configurations.
- 15 Ambience configurations.



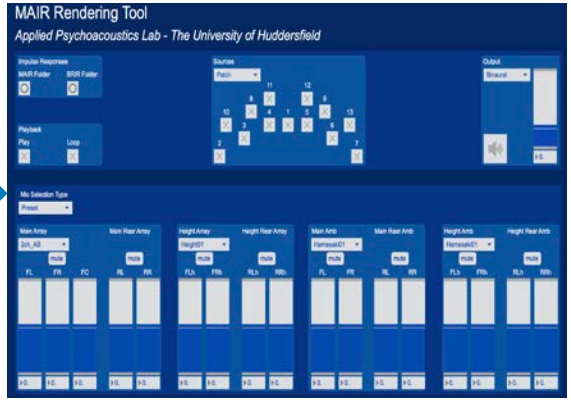


Lee, H. and Millns, C. (2017) '[Microphone Array Impulse Response (MAIR) Library for Spatial Audio Research]'. *In: Audio Engineering Society 143rd international convention, 18-21st October 2017*, New York

MAIR Library and Renderer

- Available from **www.github.com/APL-Huddersfield**
- Renderer allows mic array mixing and binaural/multichannel output.
- Takes outputs from a DAW session, or browse individual files.

DAW



MAIR Renderer

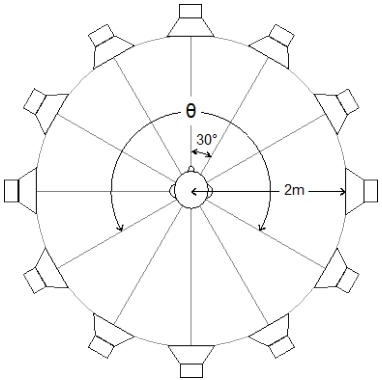
- Virtual mic array comparison
- Binaural & multichannel playback

Lee, H. and Millns, C. (2017) '[Microphone Array Impulse Response (MAIR) Library for Spatial Audio Research]'. *In: Audio Engineering Society 143rd international convention, 18-21st October 2017*, New York

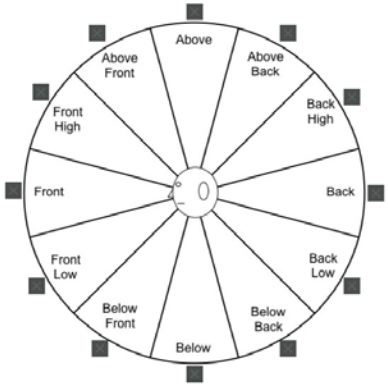
Phantom Image Elevation Effect

Phantom Image Elevation

- Phantom centre image tends to be perceived to be elevated in the median plane, and the effect is stronger with a larger speaker angle (first found by de Boer 1939).
- Investigation into source dependency (Lee 2017)
  - 11 different source types; speaker angle from 0° to 360° with 30° intervals.



Loudspeaker arrangement

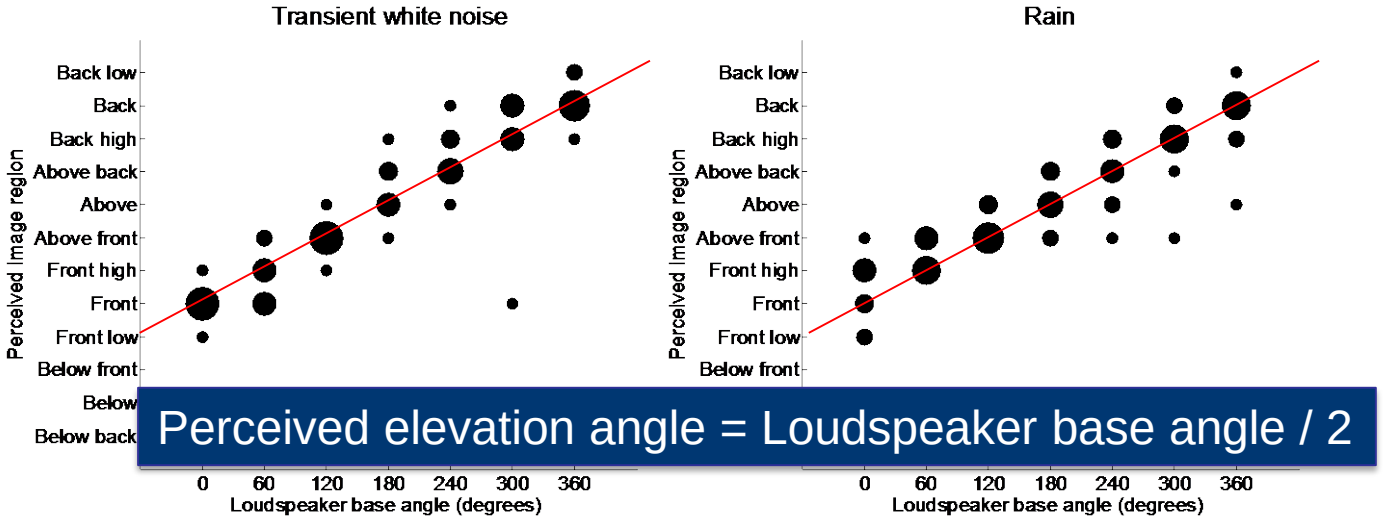


Response method

Lee, H (2017) '[Sound Source and Loudspeaker Base Angle Dependency of the Phantom Image Elevation Effect]' *Journal of the Audio Engineering Society* , 65 (9), pp. 733-748. ISSN 1549-4950

Phantom Image Elevation

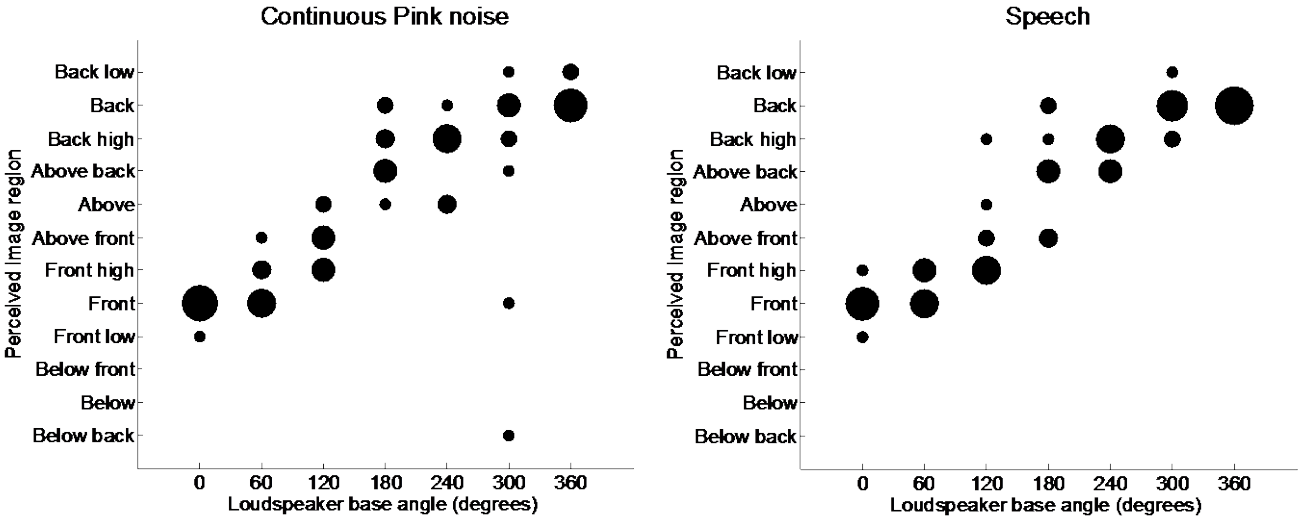
- Sound source dependency (25 subjects)
  - Responses are most linear and consistent for source with a broad and flat spectrum.



Lee, H (2017) '[Sound Source and Loudspeaker Base Angle Dependency of the Phantom Image Elevation Effect]' *Journal of the Audio Engineering Society* , 65 (9), pp. 733-748. ISSN 1549-4950

Phantom Image Elevation

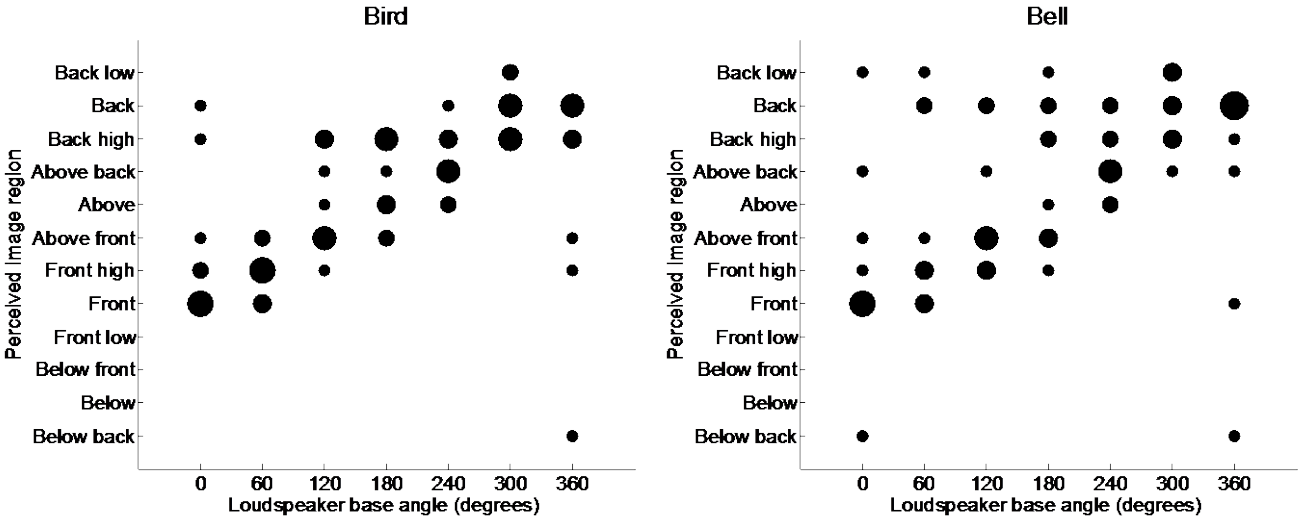
- Sound source dependency (25 subjects)
  - The above perception is weaker for sources with more low frequency energy. (no strong “aboveness”)



Lee, H (2017) ‘Sound Source and Loudspeaker Base Angle Dependency of the Phantom Image Elevation Effect’ *Journal of the Audio Engineering Society* , 65 (9), pp. 733-748. ISSN 1549-4950

Phantom Image Elevation

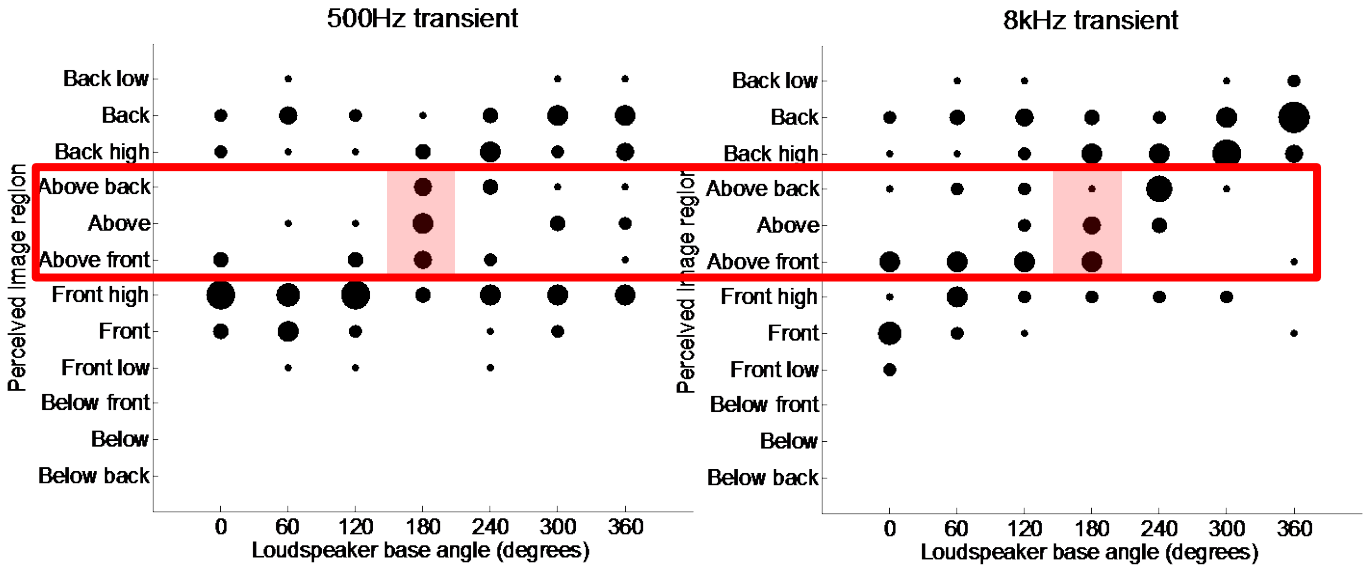
- Sound source dependency (25 subjects)
  - Responses are most inconsistent for sources with narrow spectrum or steady-state nature.



Lee, H (2017) '[Sound Source and Loudspeaker Base Angle Dependency of the Phantom Image Elevation Effect]' *Journal of the Audio Engineering Society* , 65 (9), pp. 733-748. ISSN 1549-4950

Phantom Image Elevation

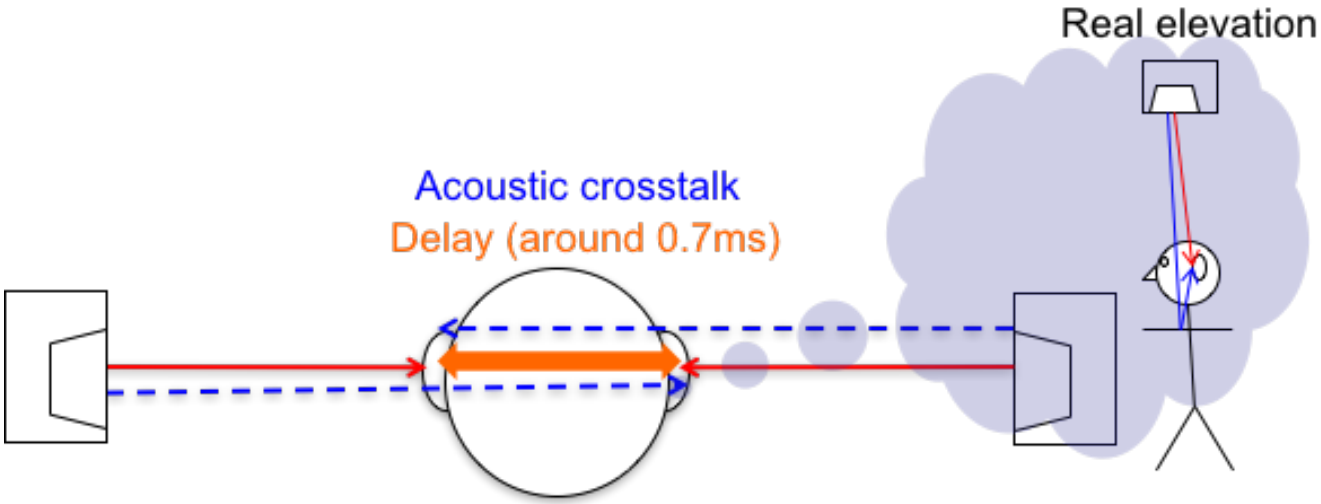
- Frequency dependency (20 subjects) (Lee 2016)
  - 500Hz and 8kHz: the most effective bands for the ‘above’ perception among all octave bands.



Lee, H (2016) ‘Phantom Image Elevation Explained’. *In: Audio Engineering Society the 141st International Convention, 29 Sep - 2 Oct*, Los Angeles, USA

Phantom Image Elevation

- A new theory (Lee 2017)
  - At low frequencies, the brain interprets the spectral notch caused by acoustic crosstalk as that caused by the shoulder reflection by a real source elevated in the median plane.



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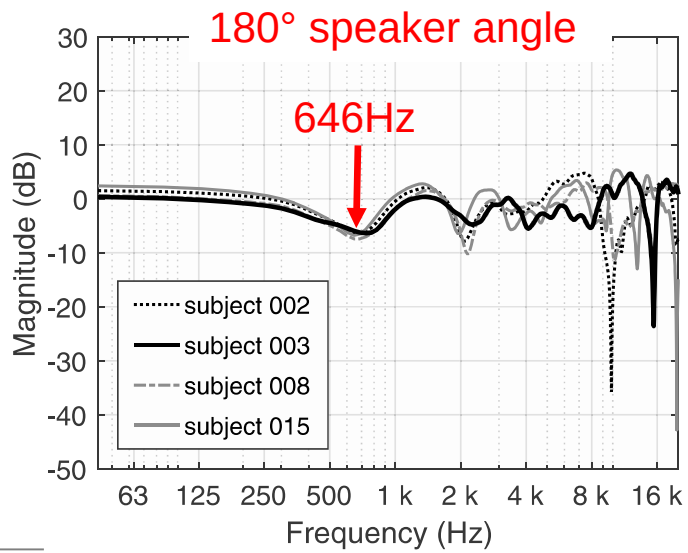
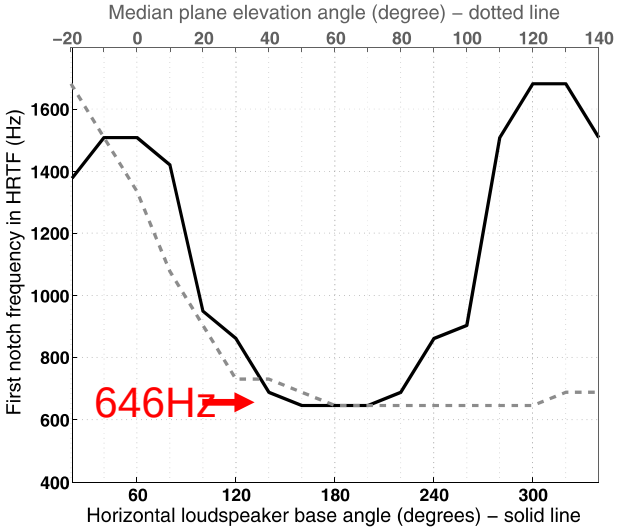
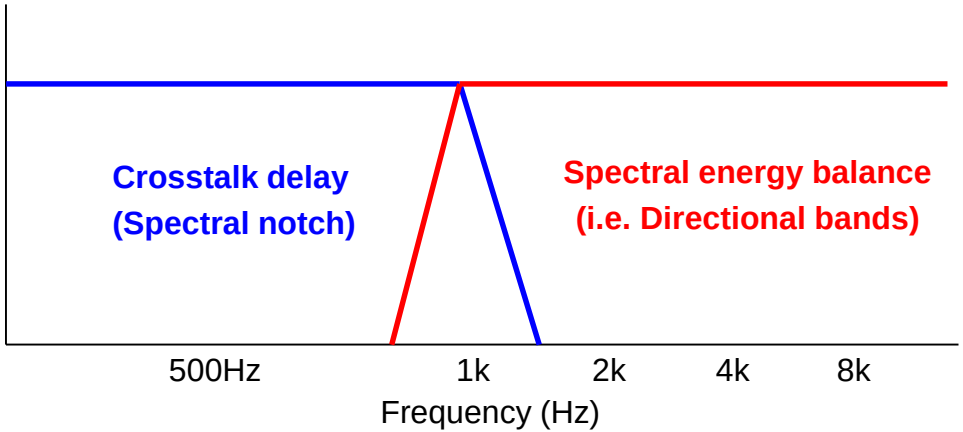




Lee, H (2017) '[Sound Source and Loudspeaker Base Angle Dependency of the Phantom Image Elevation Effect]' *Journal of the Audio Engineering Society* , 65 (9), pp. 733-748. ISSN 1549-4950

Phantom Image Elevation

- A new theory (Lee 2017)
  - Low frequencies: spectral notch due to acoustic crosstalk.
  - High frequencies: spectral energy balance (i.e. boosted bands).



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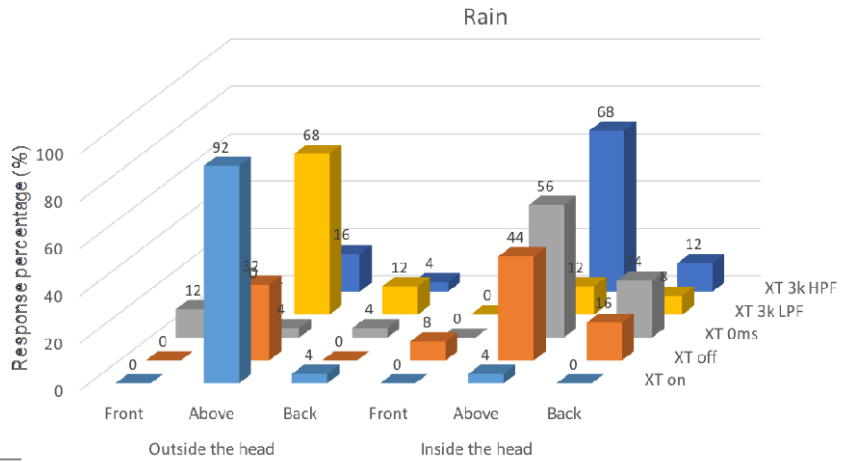
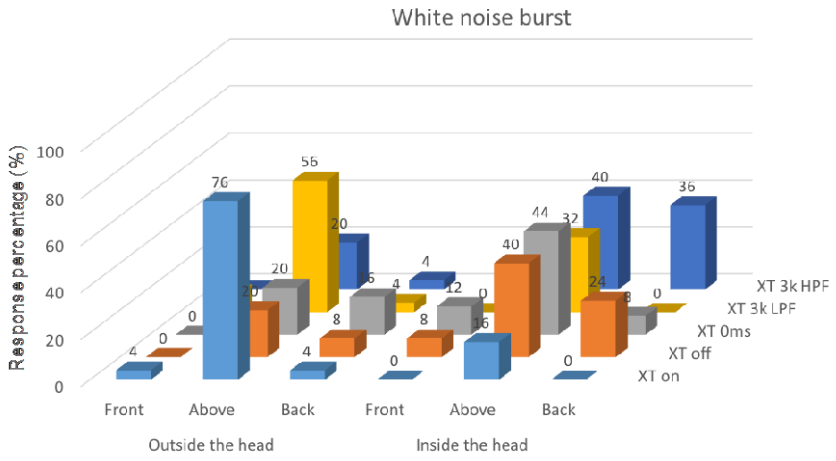
Phantom Image Elevation

- Verification (Lee 2016)
  - Individualised binaural simulation with 5 subjects (5 repetitions).
  - Crosstalk on and off / high-passed and low-passed.
  - LF crosstalk → Above localisation **outside** the head.
  - HF crosstalk → Above localisation **inside** the head.

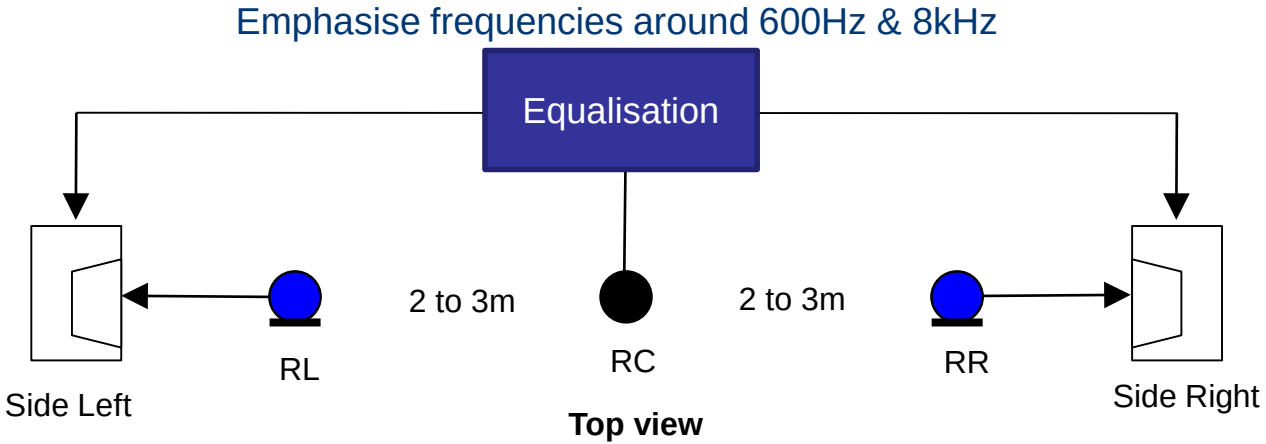




Lee, H (2016) '[Phantom Image Elevation Explained]'. *In: Audio Engineering Society the 141st International Convention, 29 Sep - 2 Oct*, Los Angeles, USA

Phantom Image Elevation

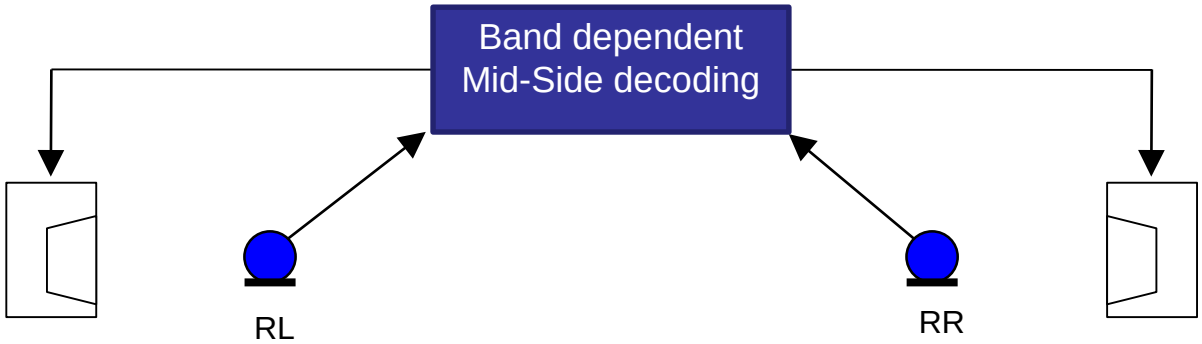
- Exploiting the effect for surround ambience recording (Lee 2017)
- A centre ambience microphone fed into both side (rear) L and R speakers adds “aboveness” to the ambient image, while the wide microphones provide horizontal spread of the image.



Lee, H (2017) ‘Sound Source and Loudspeaker Base Angle Dependency of the Phantom Image Elevation Effect’ *Journal of the Audio Engineering Society* , 65 (9), pp. 733-748. ISSN 1549-4950

Phantom Image Elevation

- Band-dependent MS decoding for side or rear channels (Lee 2016).
- Use mid signals for 500Hz and 8kHz bands for the elevation effect.

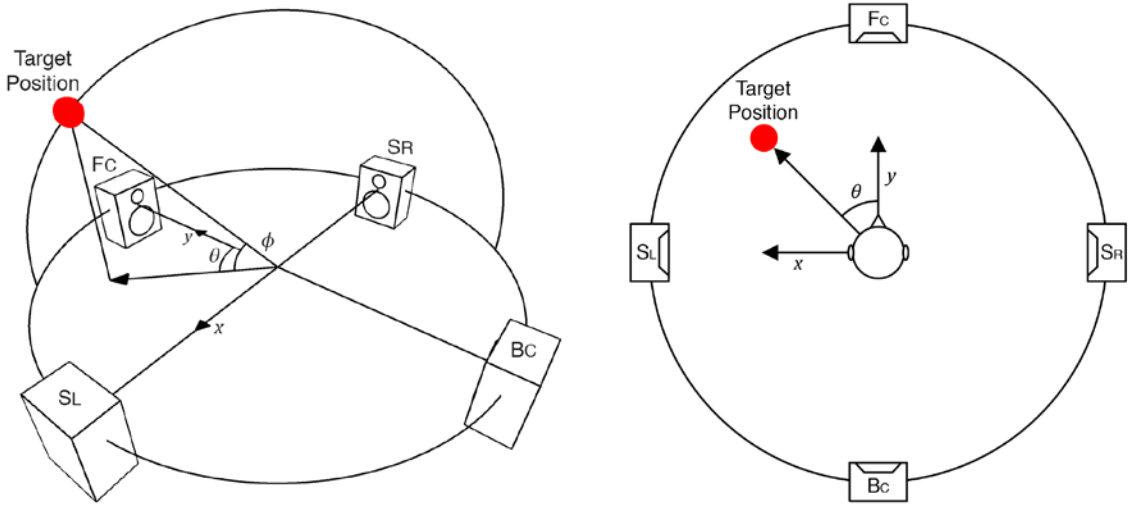


Top view

Lee, H (2016) 'Perceptually Motivated 3D Diffuse Field Upmixing'. *In: 2016 AES International Conference on Sound Field Control, 18th - 20th July 2016*, Guildford, UK

Virtual Hemispherical Amplitude Panning (VHAP)

- Virtual 3D panning method exploiting the phantom image elevation effect (Lee, Johnson and Mironovs 2018).
- 4 ear-height loudspeakers (SL, SR, FC, BC) with a constant power relationship.
- Use 3 active loudspeakers (e.g. SL, SR, FC for a target image in the front half; SL, SR, BC for the rear half).

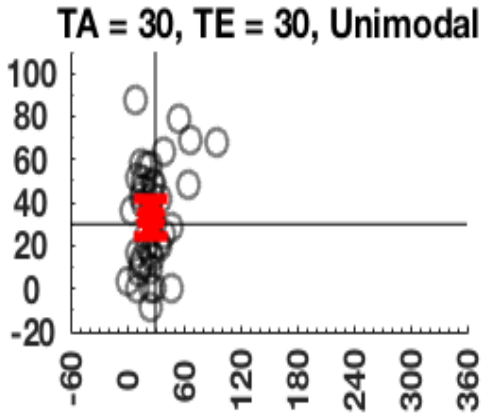


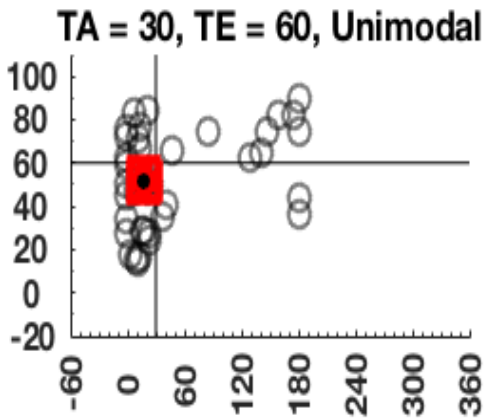
Lee, H., Johnson, D. and Mironovs, M. (2018) 'Virtual Hemispherical Amplitude Panning (VHAP): A Method for 3D Panning without Elevated Loudspeakers' *In: Audio Engineering Society 144st international convention, 23-26 May 2018*, Milan, Italy.

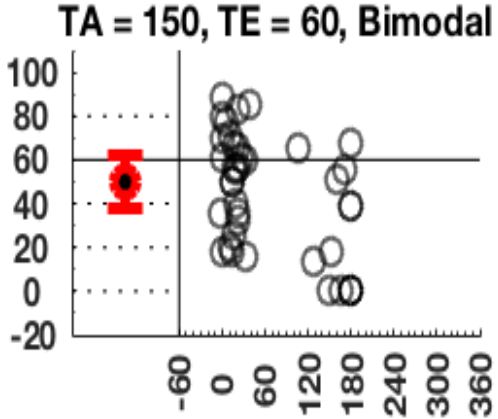
Virtual Hemispherical Amplitude Panning (VHAP)

- Virtual 3D panning method exploiting the phantom image elevation effect (Lee, Johnson and Mironovs 2018)
- Works with some limitations in consistency.

TA = Target Azimuth (deg); TE = Target Elevation (deg)







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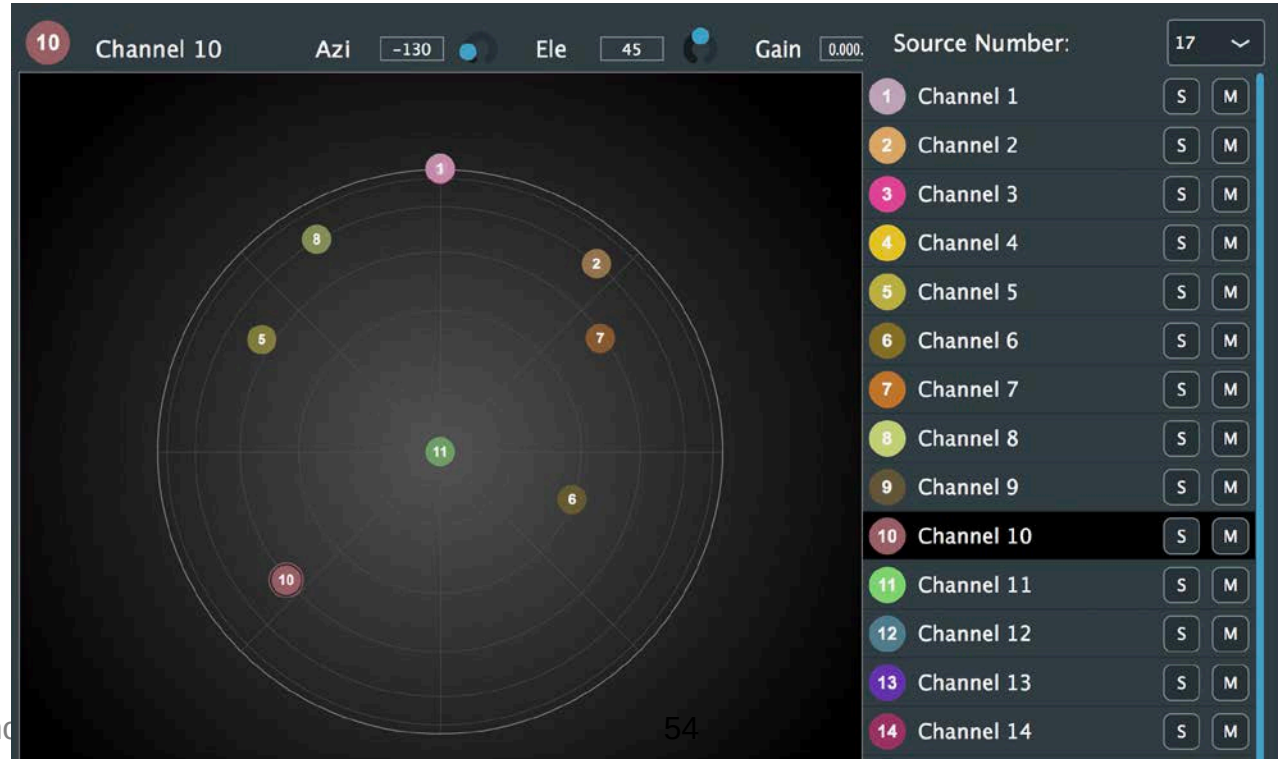
VHAP vst plug-in

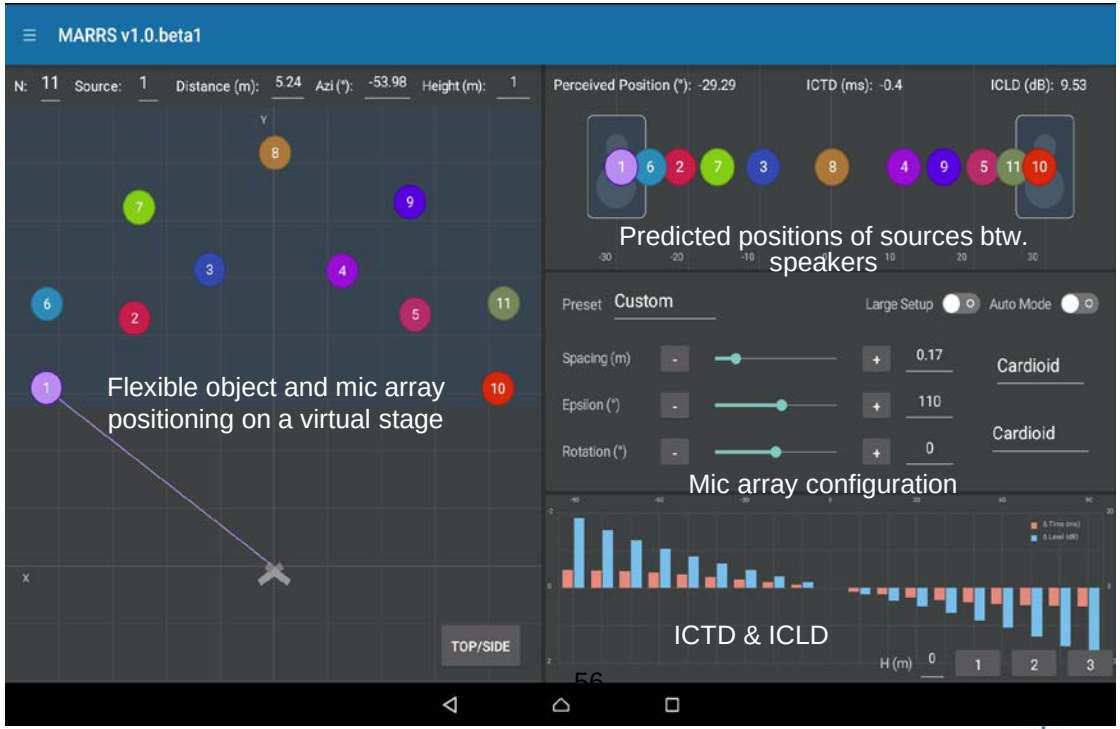
- To be released soon.



APL Software
for Researchers and Sound Engineers

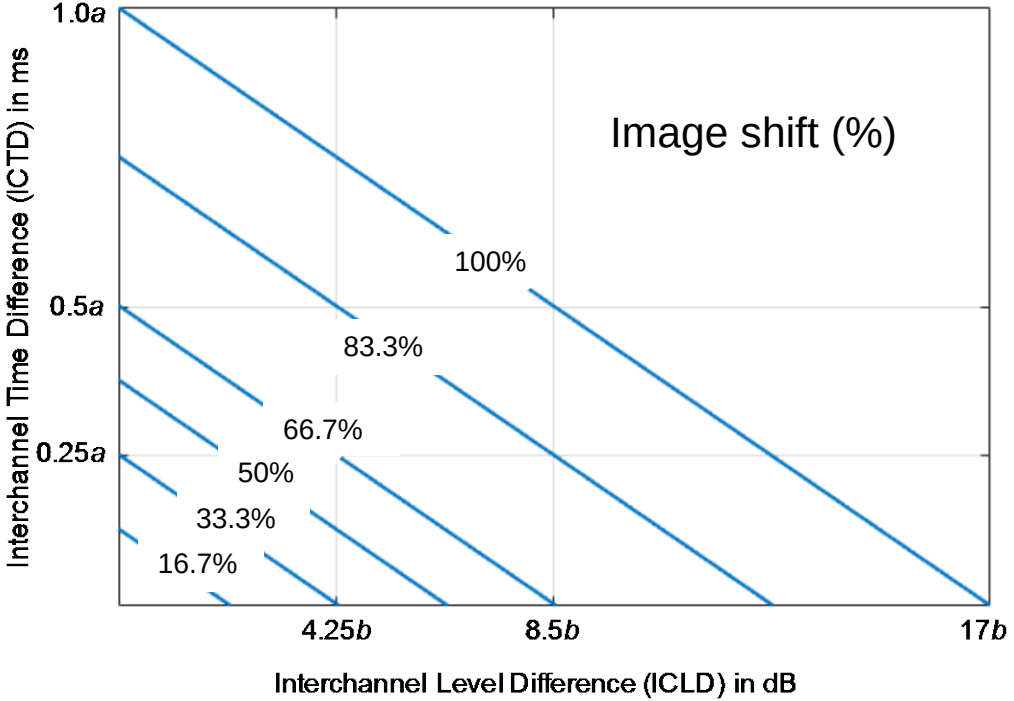
MARRS app for mic technique simulation

- Object-oriented mic technique design tool (Lee, Johnson and Mironovs 2017).
- Based on the time-level trade-off functions
- Free download from iOS and Android app stores.



A New Time and Level Trade-off Model

- Prediction of image localisation depending on loudspeaker base angle (Lee, Johnson and Mironovs 2017)



$$\varphi = \left(ICTD + \frac{a}{17b}ICLD\right)\frac{4\theta}{3a}$$

$$, if\ ICTD \leq -\frac{a}{17b}ICLD + \frac{a}{2}\ \&\ ICLD \leq 17b\left(\frac{a}{2} - ICTD\right)$$

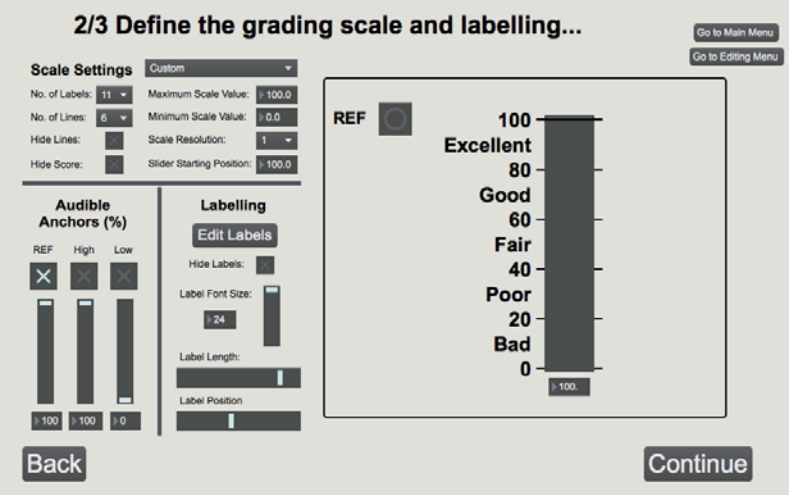
$$\varphi = \left(ICTD + \frac{a}{17b}ICLD + \frac{a}{2}\right)\frac{2\theta}{3a}$$

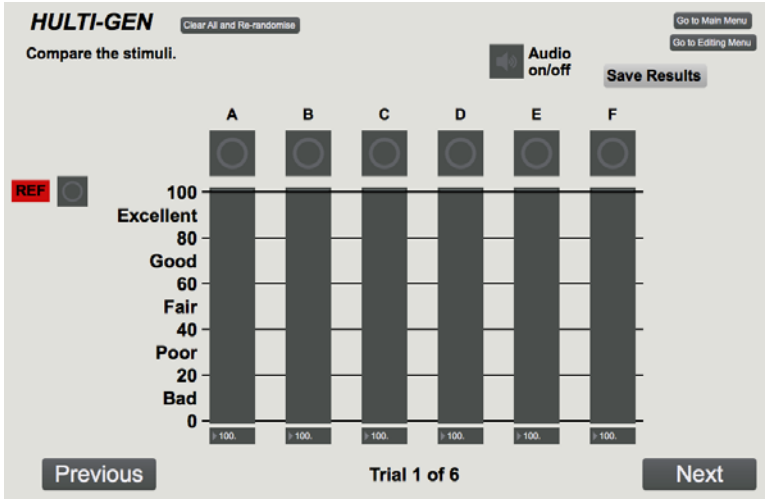
$$, otherwise$$

φ = predicted image angle
θ = half the loudspeaker base angle
a = ITD(θ)/ITD(30°)
b = ILD(θ)/ILD(30°)

HULTI-GEN (universal listening test interface generator)

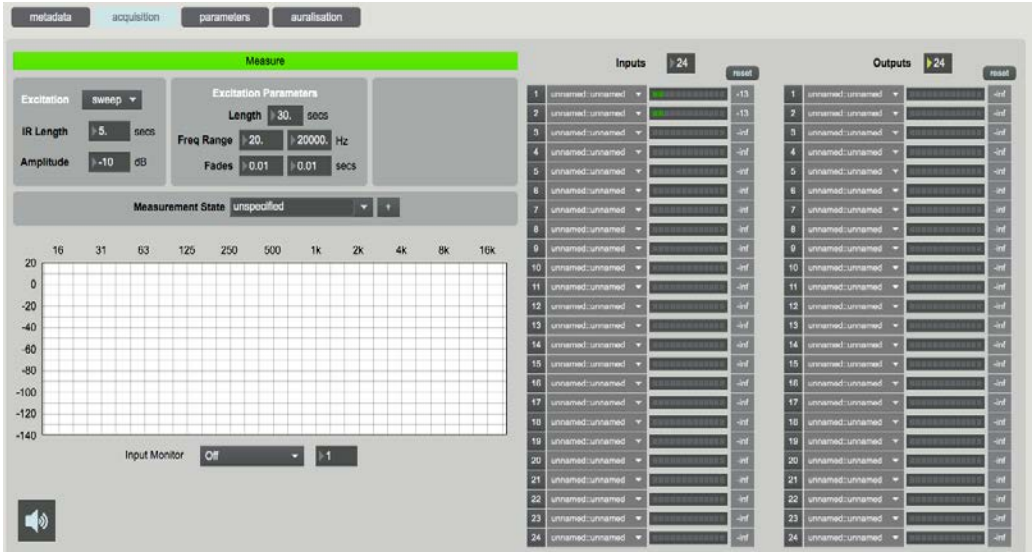
- Fully customisable listening test GUI generator.
- Standalone Max application (no license required.)
- Download: http://eprints.hud.ac.uk/id/eprint/24809/





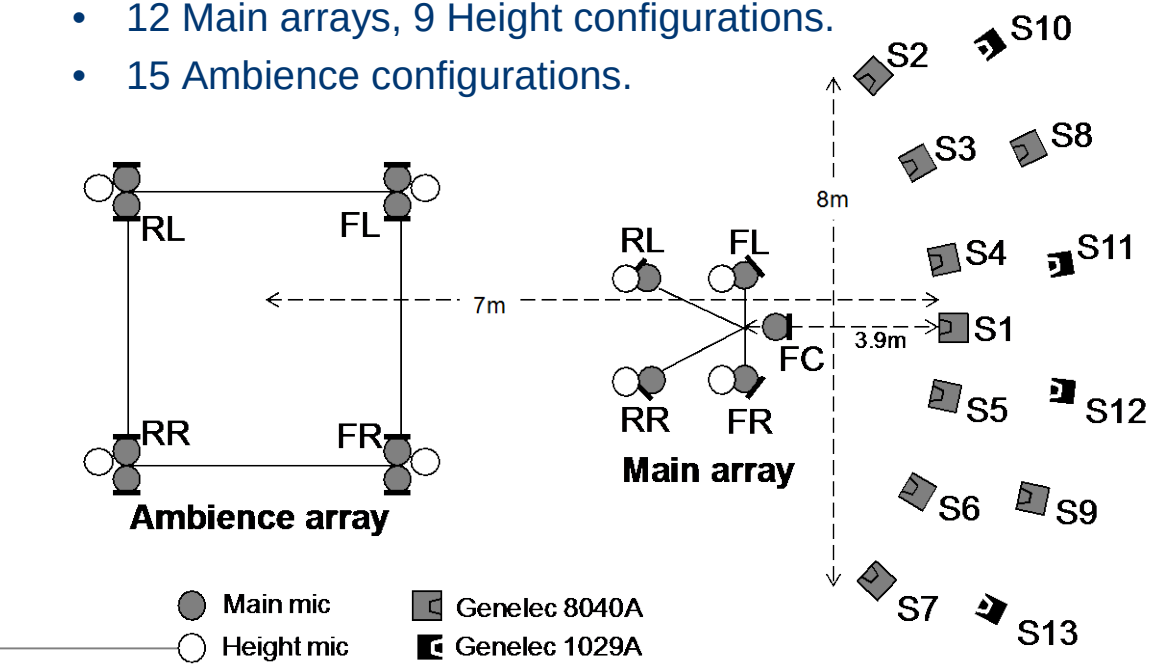
HAART (multichannel impulse response toolbox)

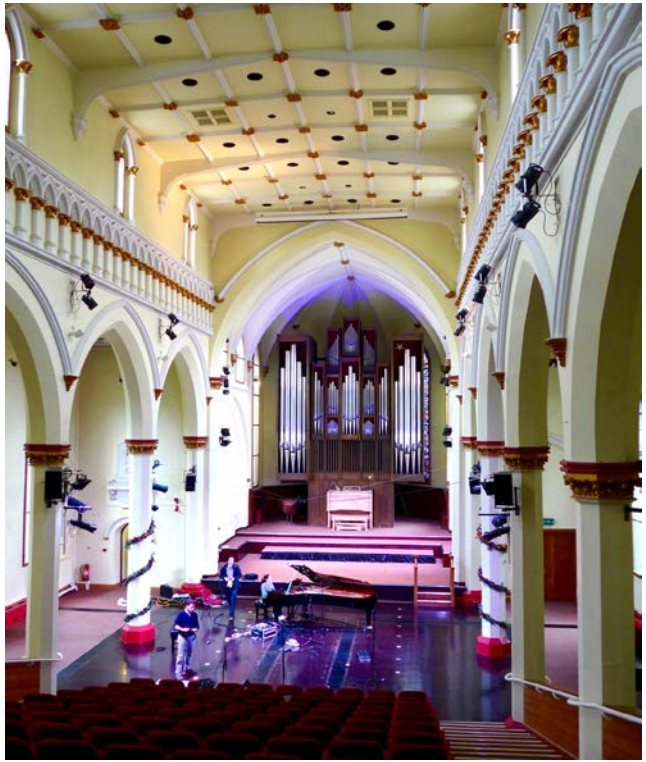
- Impulse response measurement with 24 mics and 24 loudspeakers on one click → Parameter analysis → Binaural auralisation.
- Download: http://eprints.hud.ac.uk/id/eprint/24579/



MAIR Library and Renderer

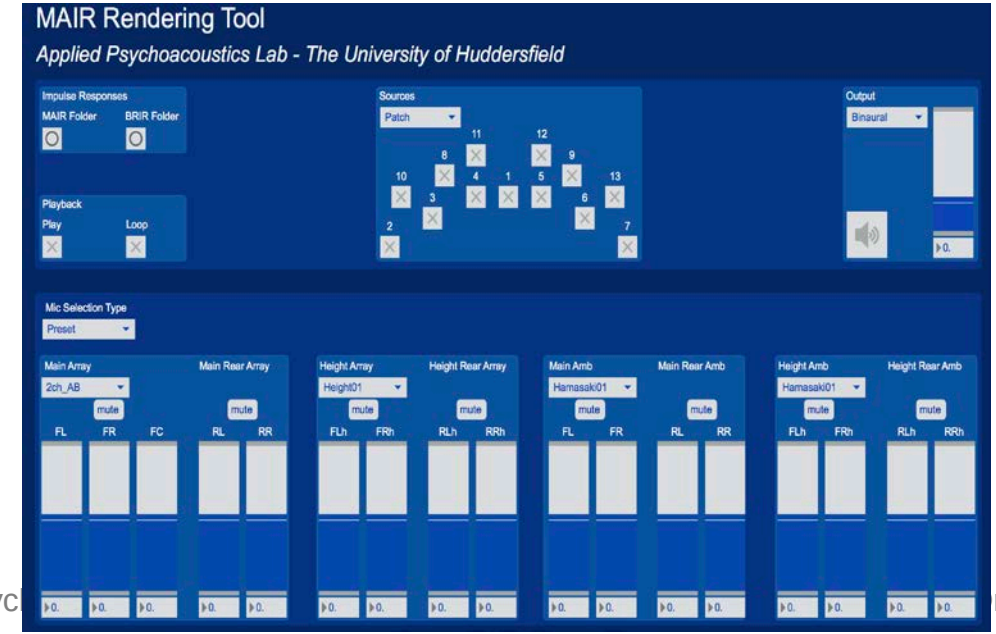
- Over 2000 Microphone Array Impulse Responses (MAIRs) captured for 13 source positions (Lee and Millns 2017). www.github.com/APL-Huddersfield
- 12 Main arrays, 9 Height configurations.
- 15 Ambience configurations.





MAIR Library and Renderer

- www.github.com/APL-Huddersfield
- Renderer allows mic array mixing and binaural/multichannel output.
- Takes outputs from a DAW session, or browse individual files.



- Virtual mic array comparison
- Binaural & 9ch 3D playback

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