University of HUDDERSFIELD

Psychoacoustics of 3D Sound Recording: Research and Practice

Dr Hyunkook Lee

Applied Psychoacoustics Lab (APL)

University of Huddersfield, UK

h.lee@hud.ac.uk

www.hyunkooklee.com

www.hud.ac.uk/apl

THE QUEEN'S AWARDS FOR ENTERPRISE

About me

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- 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).

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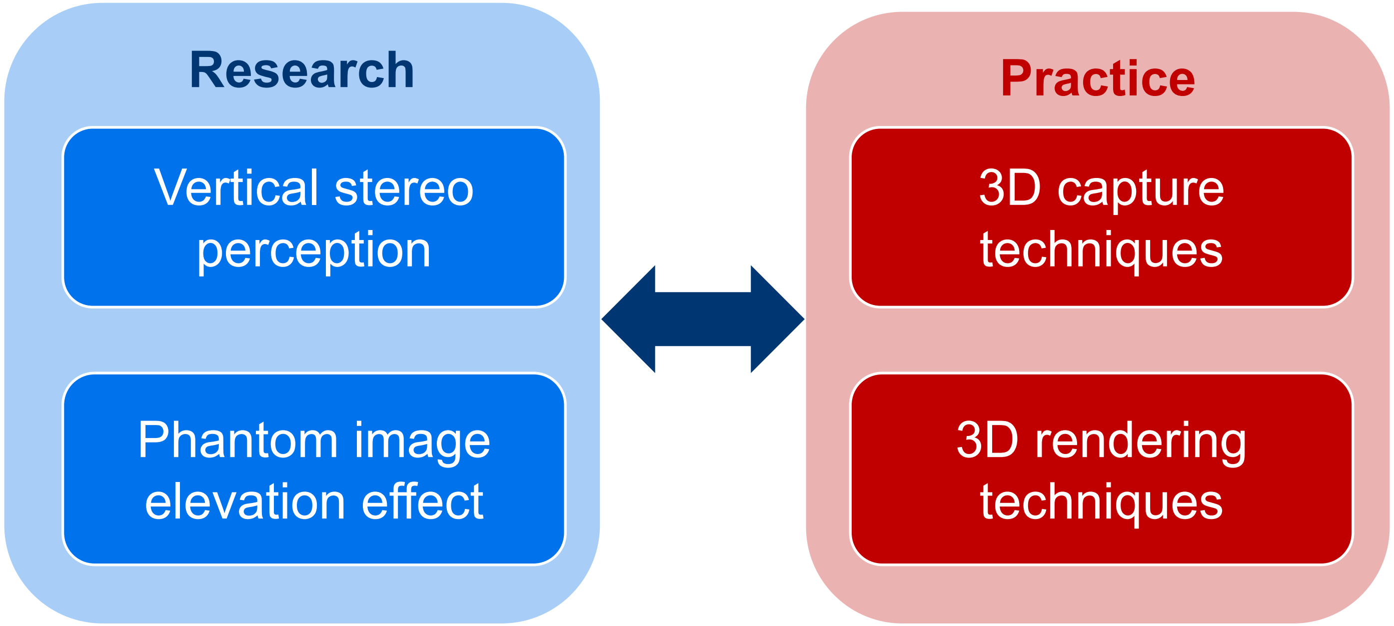
Applied Psychoacoustics Lab (APL)

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

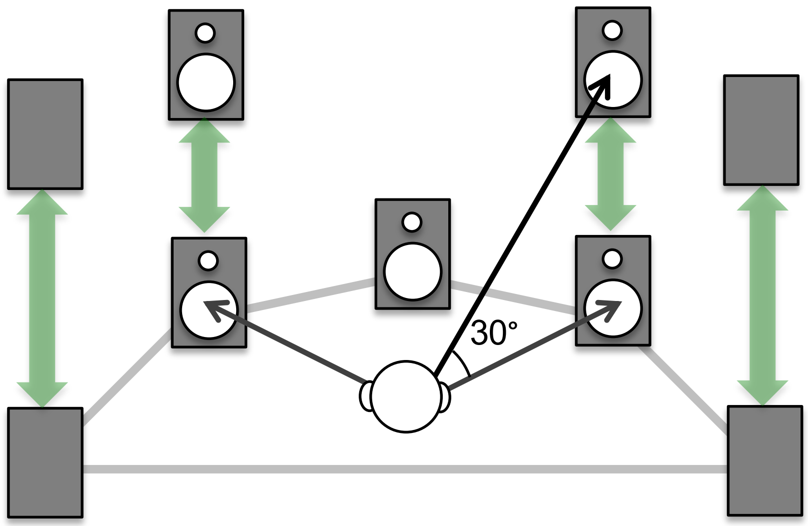
Today's talk and demo



With 9-channel 3D demos

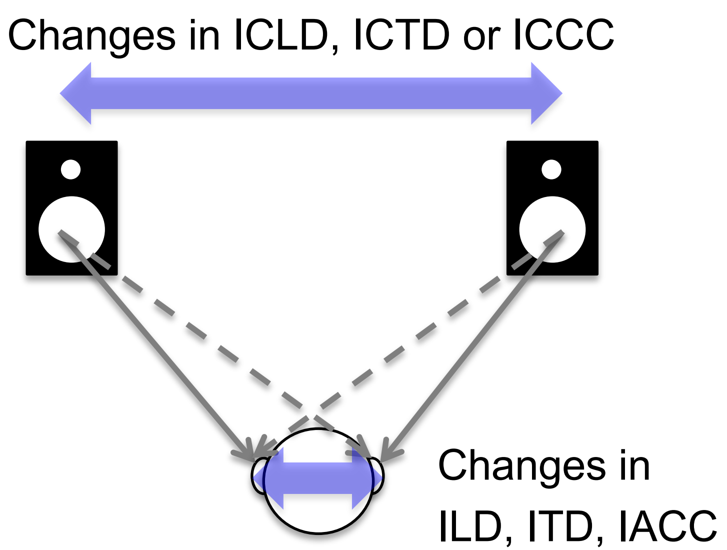
Background

- What's the optimal way of recording for 3D formats?
- How do we perceive sounds with vertical stereophony?



Background

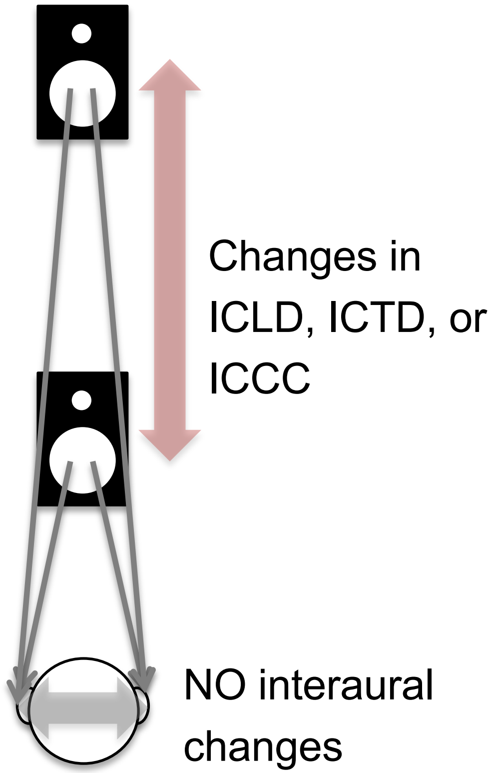
- Horizontal spatial perception
  - Inter-Channel cues translated into Inter-Aural cues



Background

- Vertical spatial perception in the median plane.

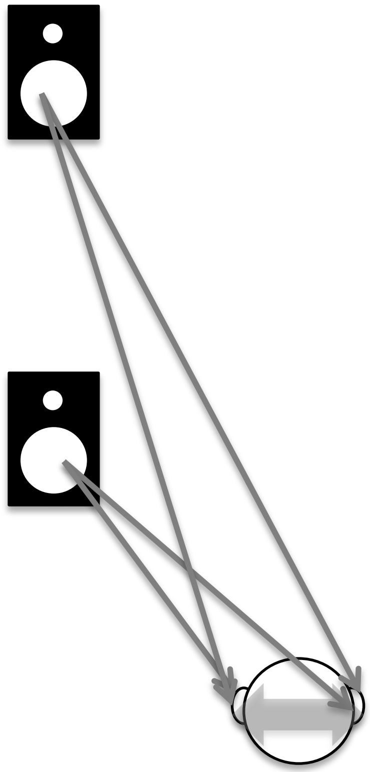
Vertical localisation solely relies on **spectral** cues.



Background

- Vertical spatial perception at an off-centre azimuth.

Vertical localisation mainly relies on **spectral** cues & some **interarual** cues.



Background

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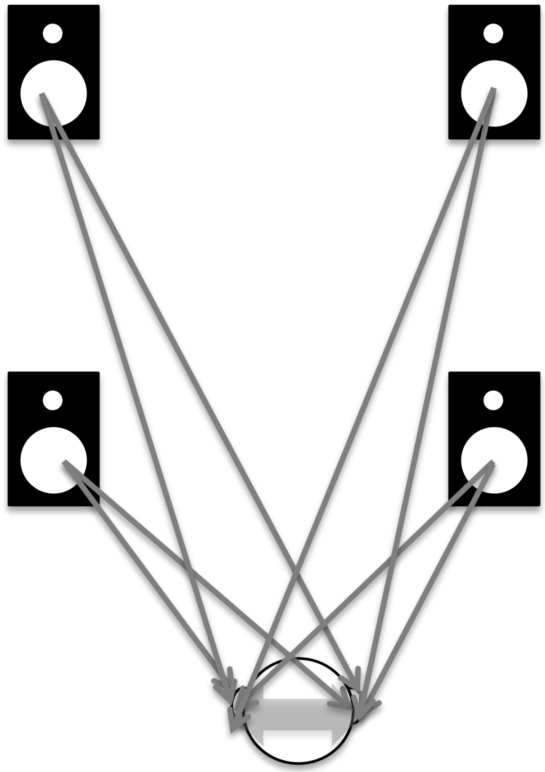
- Vertical spatial perception with two vertical stereophonic layers.

  Localisation is affected by **spectral** cues, **interaural** cues and the **phantom image elevation** effect.



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Vertical localization of octave band phantom sources

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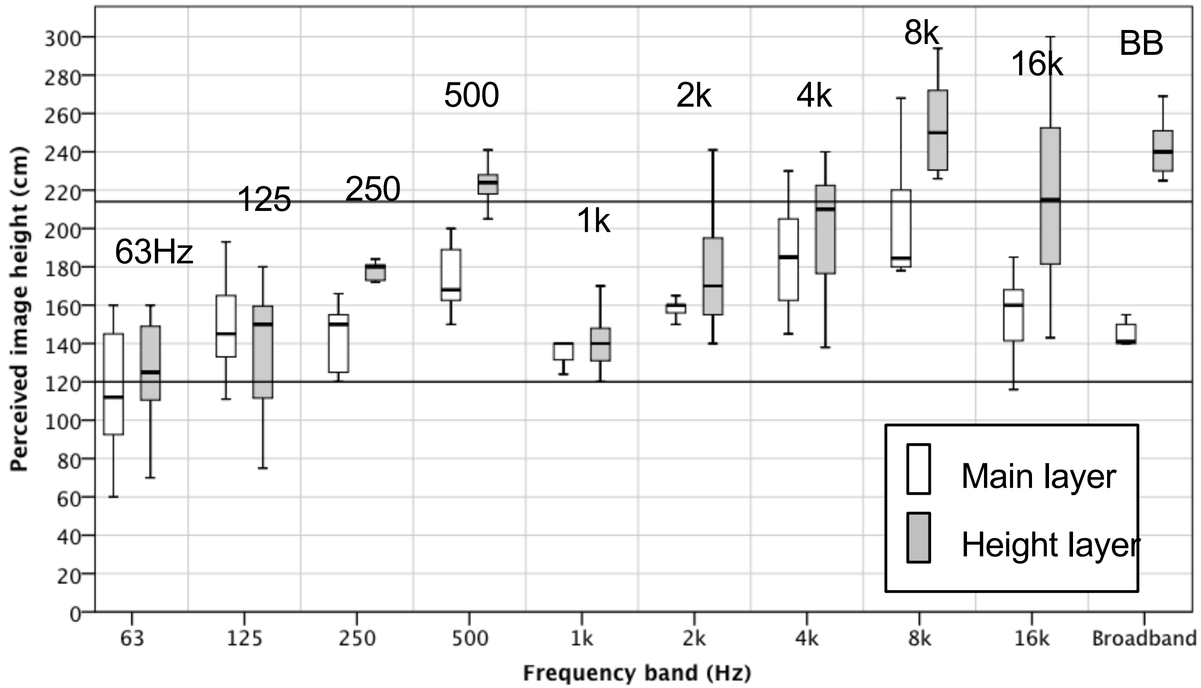
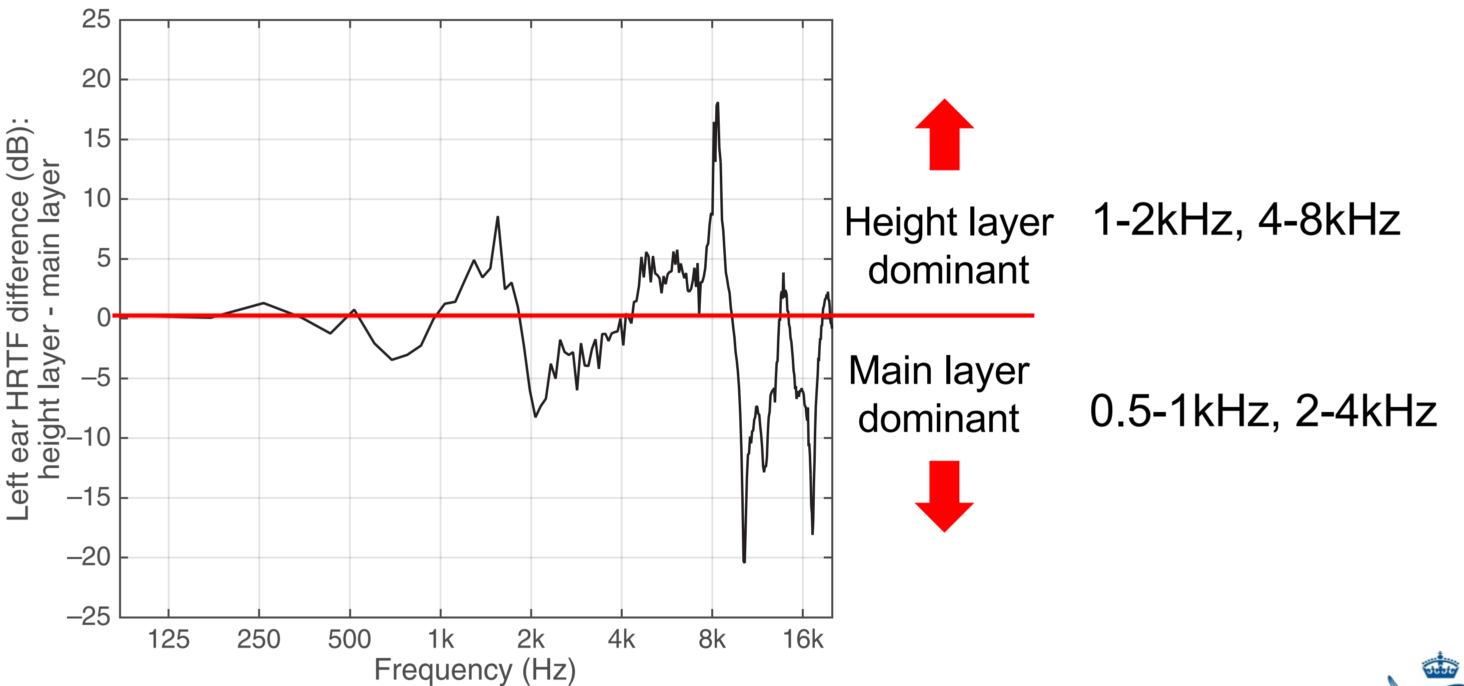
- Each frequency band has its inherent vertical image position (Lee 2016).



Lee, H (2016) 'Perceptual Band Allocation (PBA) for the Rendering of Vertical Image Spread with a Vertical 2D Loudspeaker Array' *Journal of the Audio Engineering Society* , 64 (12), pp. 1003-1013. ISSN 1549-4950

Main layer vs. Height layer in HRTF

- Delta HRTF (Height layer – Main layer) for the left ear (Lee 2016).
  - From MIT's KEMAR HRIR database



Lee, H (2016) 'Perceptual Band Allocation (PBA) for the Rendering of Vertical Image Spread with a Vertical 2D Loudspeaker Array' *Journal of the Audio Engineering Society* , 64 (12), pp. 1003-1013. ISSN 1549-4950

Vertical Stereo Perception

&

3D Microphone Techniques

Vertical interchannel crosstalk

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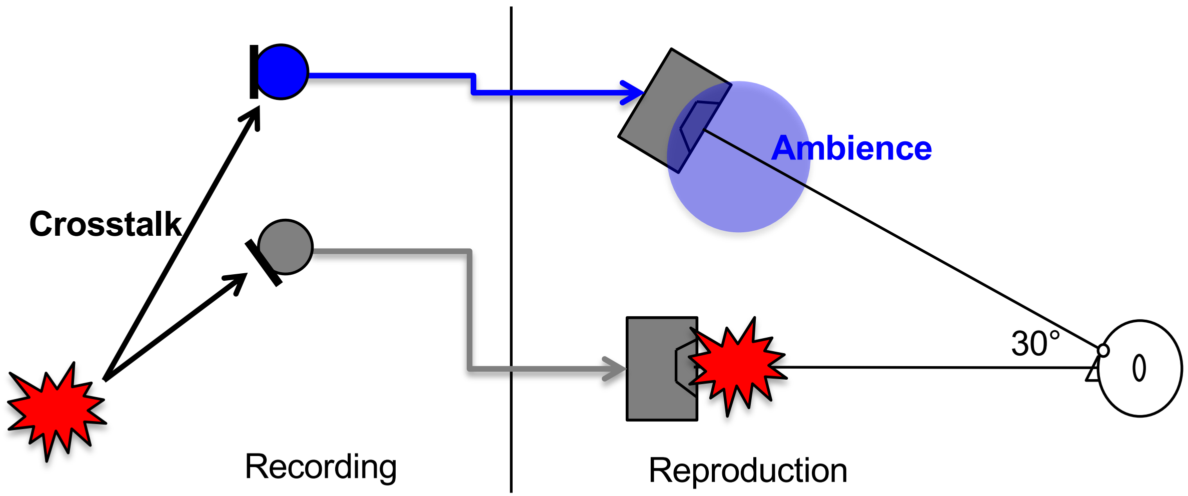
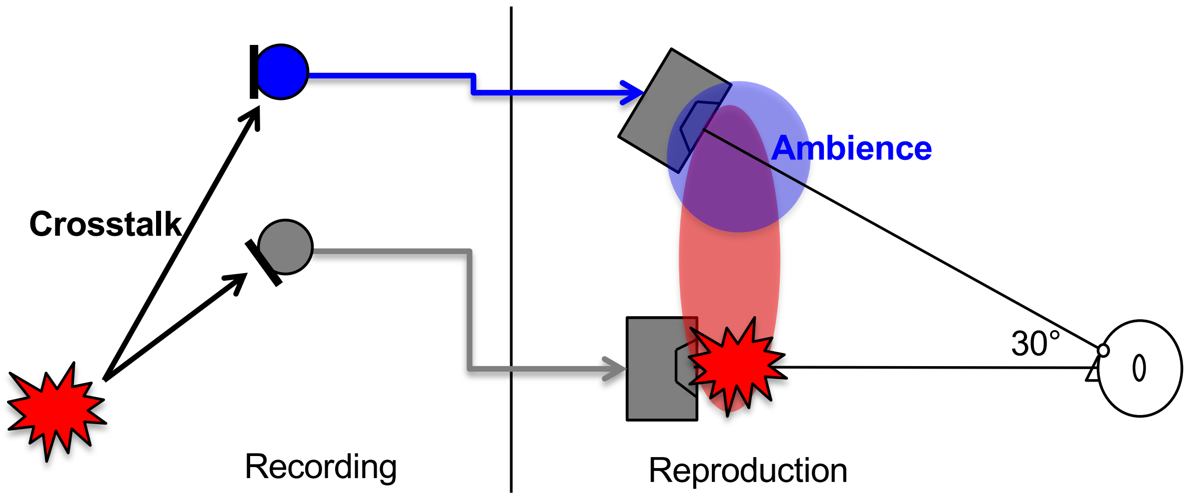
- What is vertical interchannel crosstalk?
  - A (delayed) direct sound captured by a height microphone that aims to capture ambience.



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

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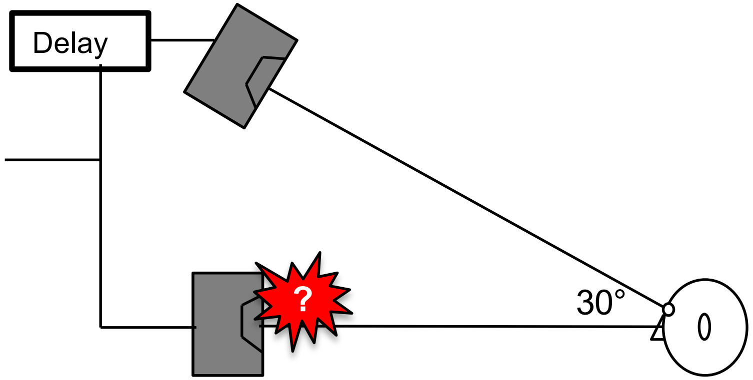
- Question 1: Can the image be localised at the ear-height by applying time delay between the vertically arranged microphones?

e.g. Omni mic for height
(no level diff but only time diff)



Vertical Interchannel Time Difference

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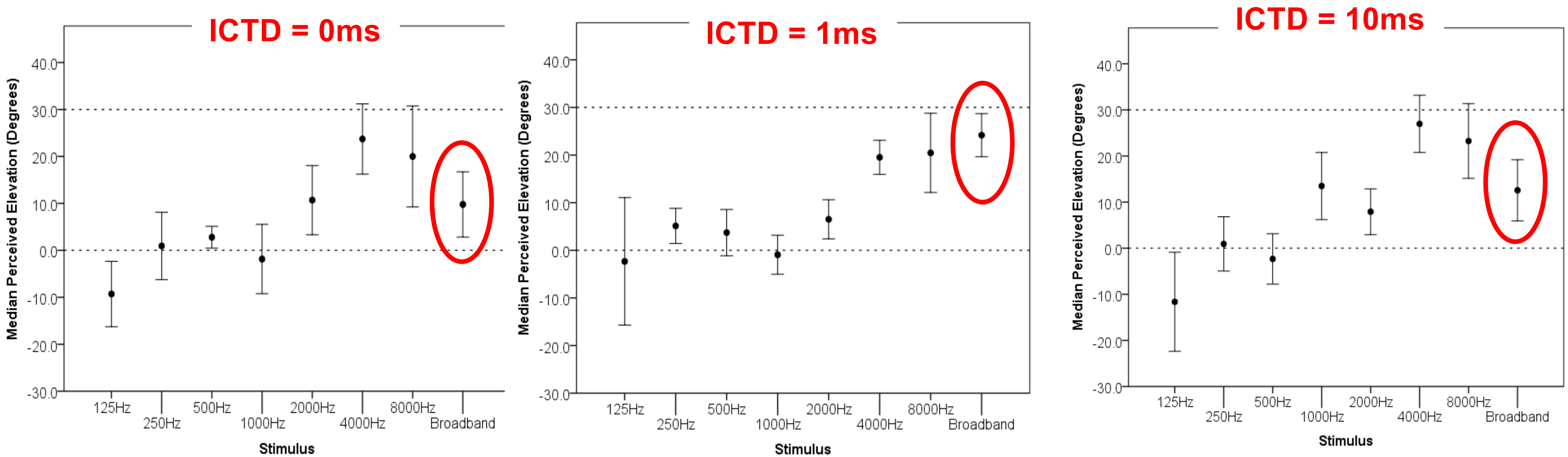
- Interchannel time difference (ICTD) is a very unstable cue for vertical localisation (Wallis and Lee 2015).
- The precedence effect does NOT operate vertically.



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

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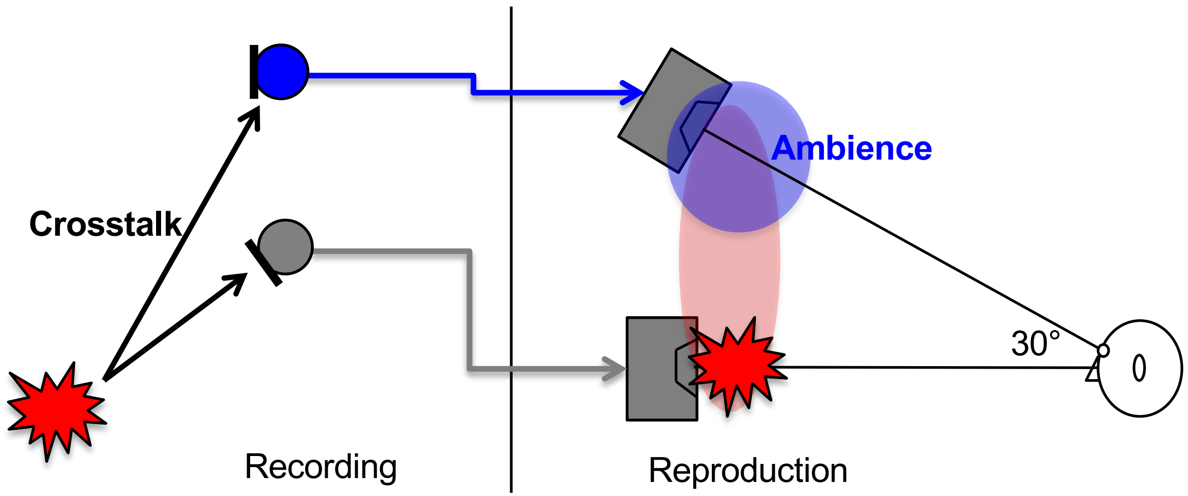
- Question 2: How much level attenuation of vertical crosstalk is required for the image to be “*localised*” around the ear-height?



Vertical Localisation Threshold

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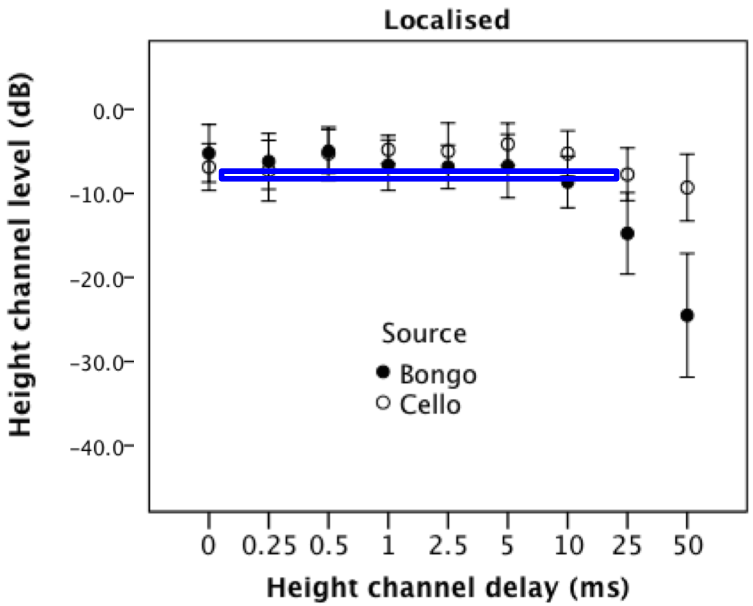
- Localised threshold (Lee 2011, Wallis and Lee 2017)
  - **Up to ICTD of 10ms**, the height channel level should be attenuated by at least **7dB** compared to the main channel level.



-7dB

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

Vertical Localisation Threshold

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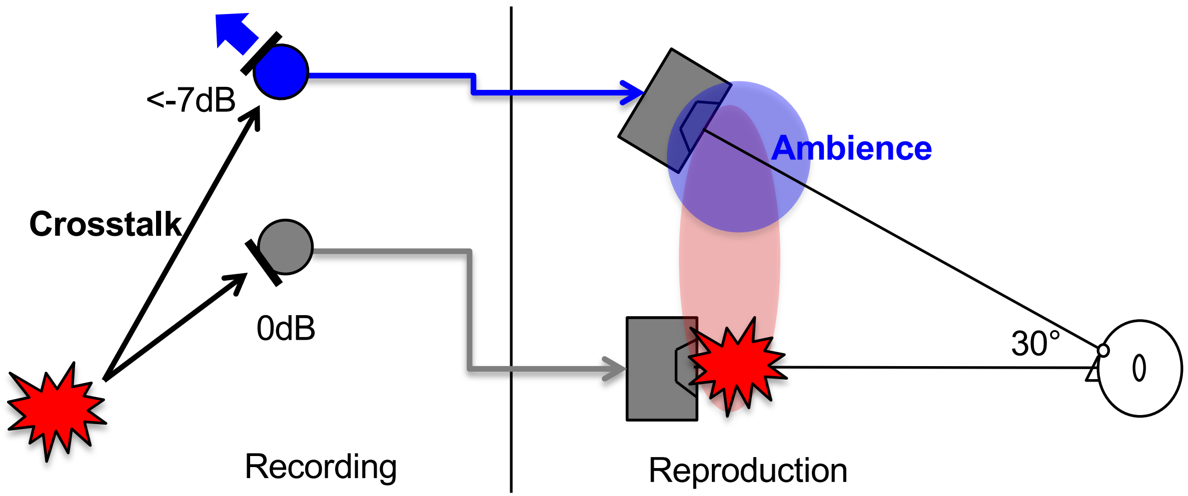
- Localised threshold (Lee 2011, Wallis and Lee 2017)
  - The height microphone should be angled so that its ICLD to the main microphone becomes at least **-7dB**.



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

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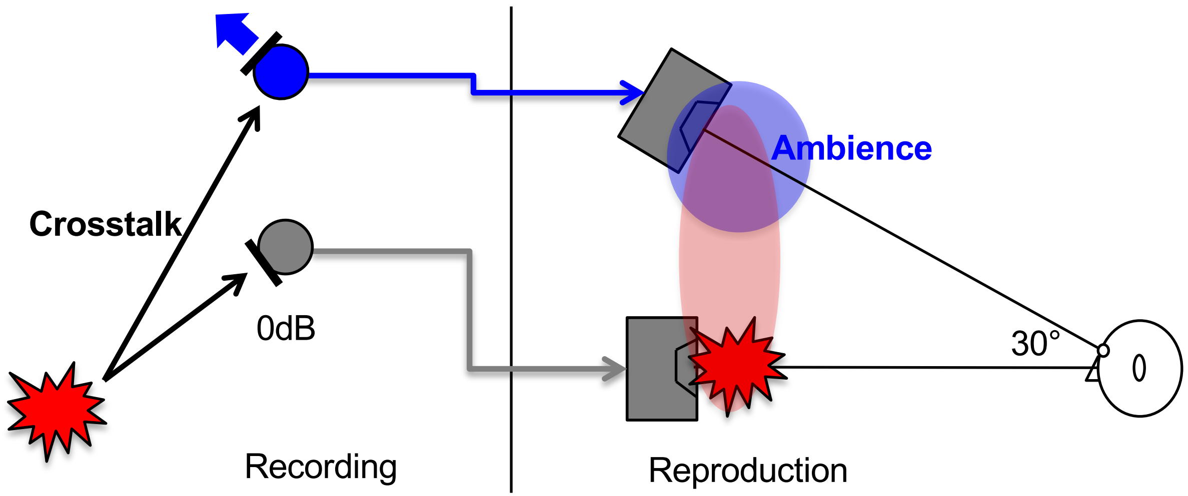
- Question 3: How much level attenuation of direct sound is required for the perceptual effects of vertical crosstalk to be "*completely inaudible*"?



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

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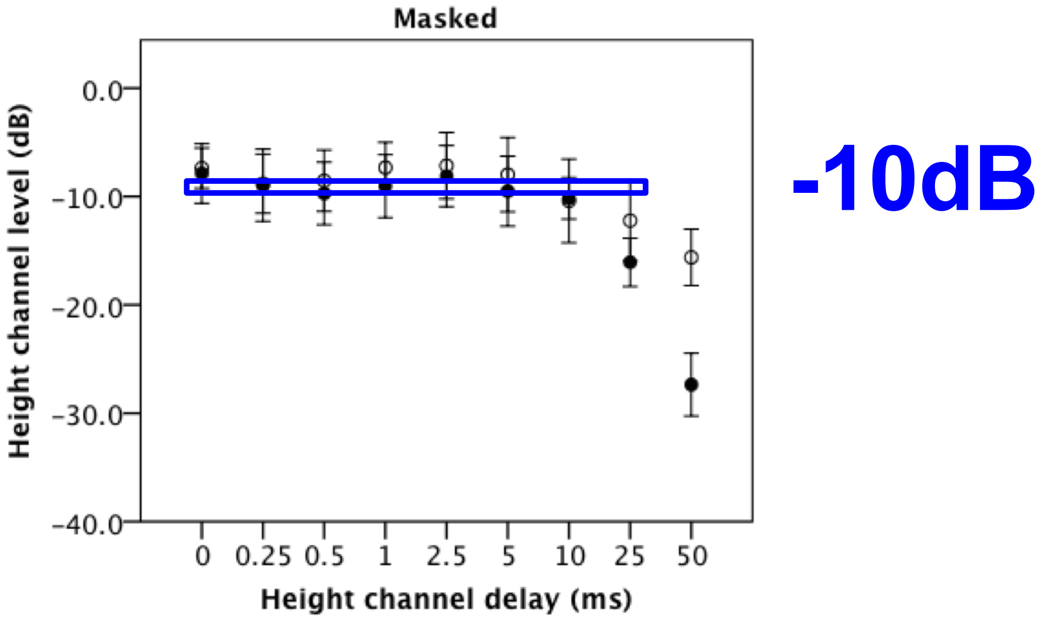
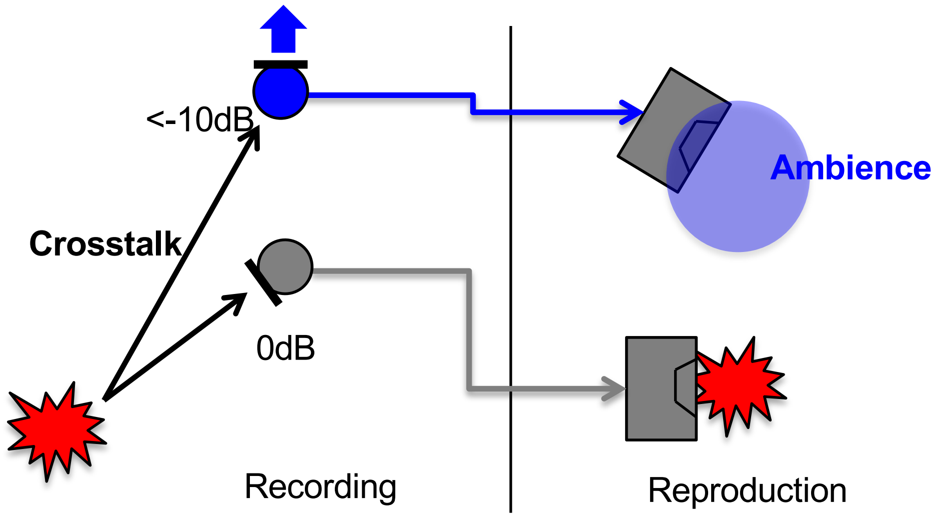
- Masked threshold (Lee 2011)
  - **Up to ICTD of 10ms**, the height channel level should be attenuated by at least **10dB** to make the crosstalk inaudible.



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

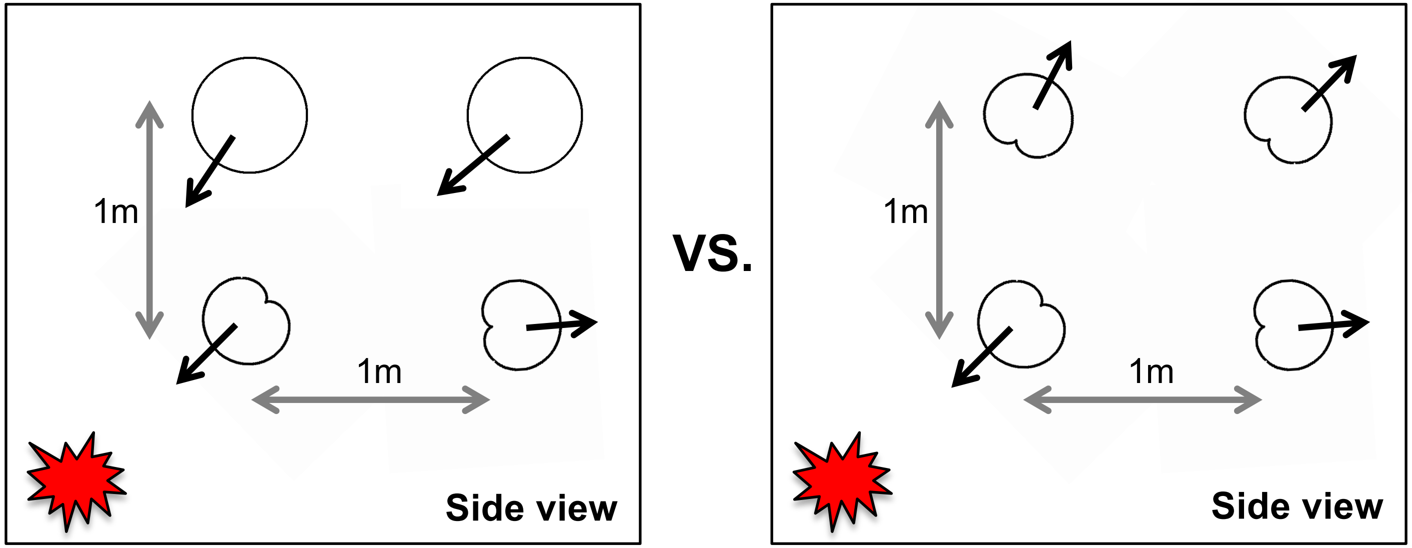
- Masked threshold (Lee 2011)
  - The height microphone should be angled so that its ICLD to the main microphone becomes at least **-10dB**.



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

Omni vs. Cardioid for height

- Height mic polar pattern: **Omni vs. Cardioid**
- Multichannel 3D RIR recorded using a 9-channel Main Mic Array
- Convolved with various mono sources
- Venue: St.Paul's concert hall (RT=2.1sec) in Huddersfield, UK

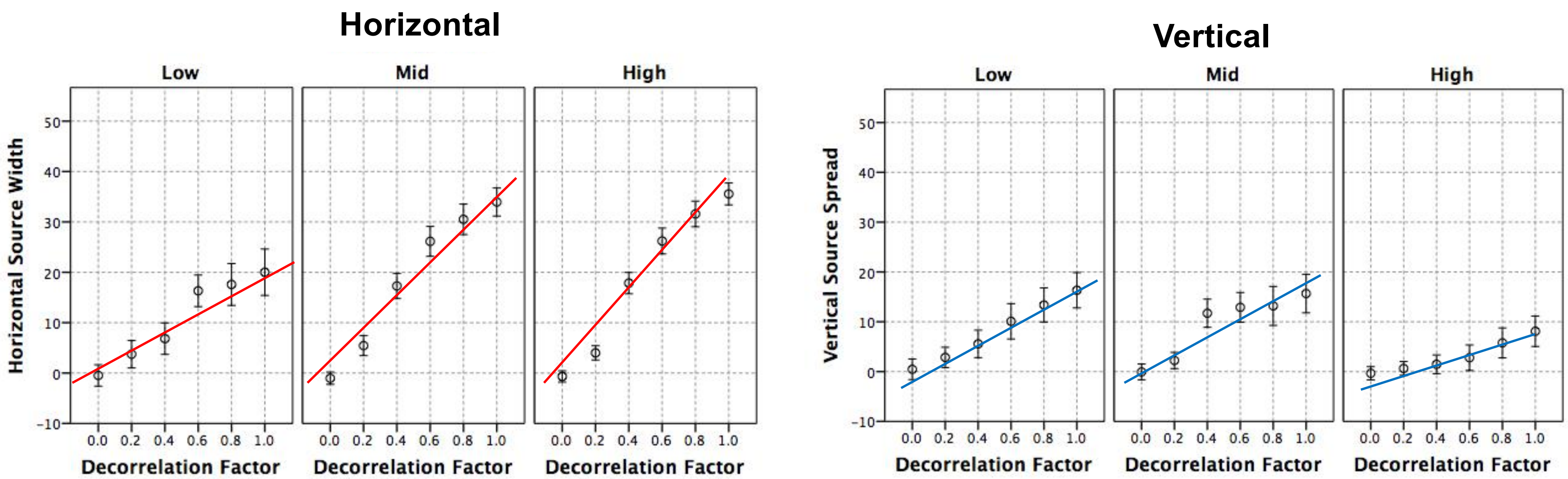


Demo: Omni vs. Cardioid for height

- Omni height: source-related effect (upwards localisation shift, loudness increase & colouration due to comb-filtering).
- Backward cardioid: environment-related effect (perceived source distance, vertical image spread, engulfment).
- Backward cardioid has more headroom to increase height ambience level without affecting localisation, loudness and tone colour.

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

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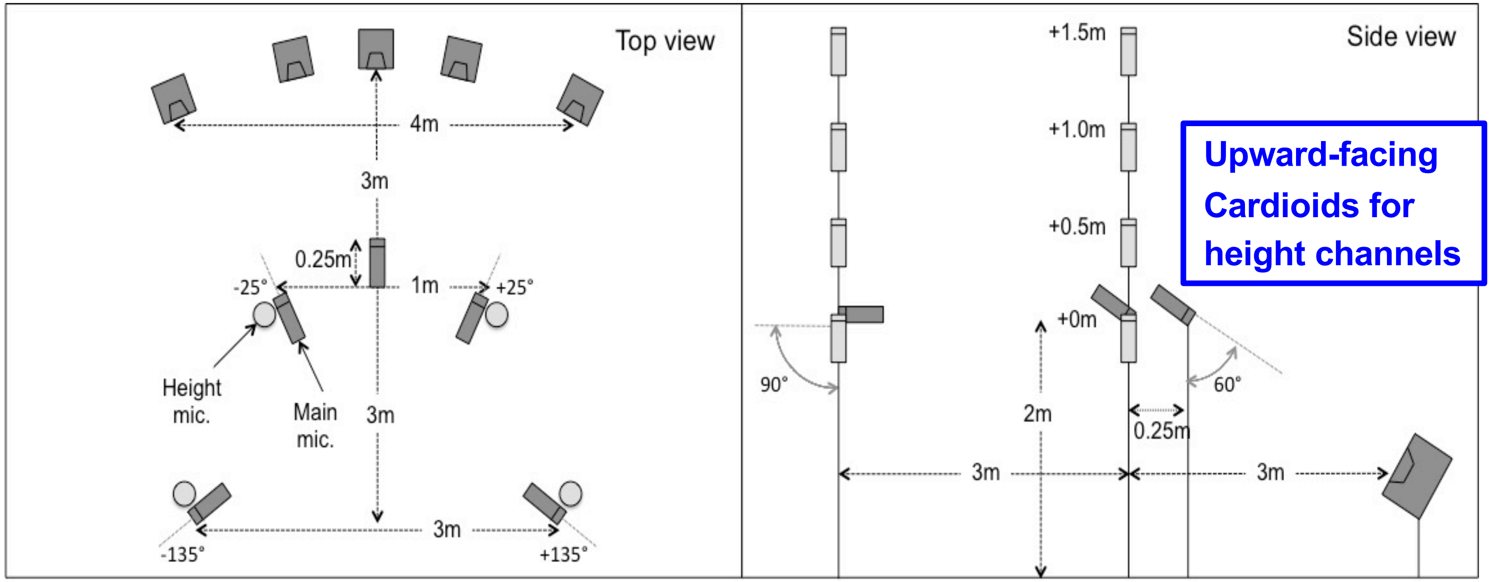
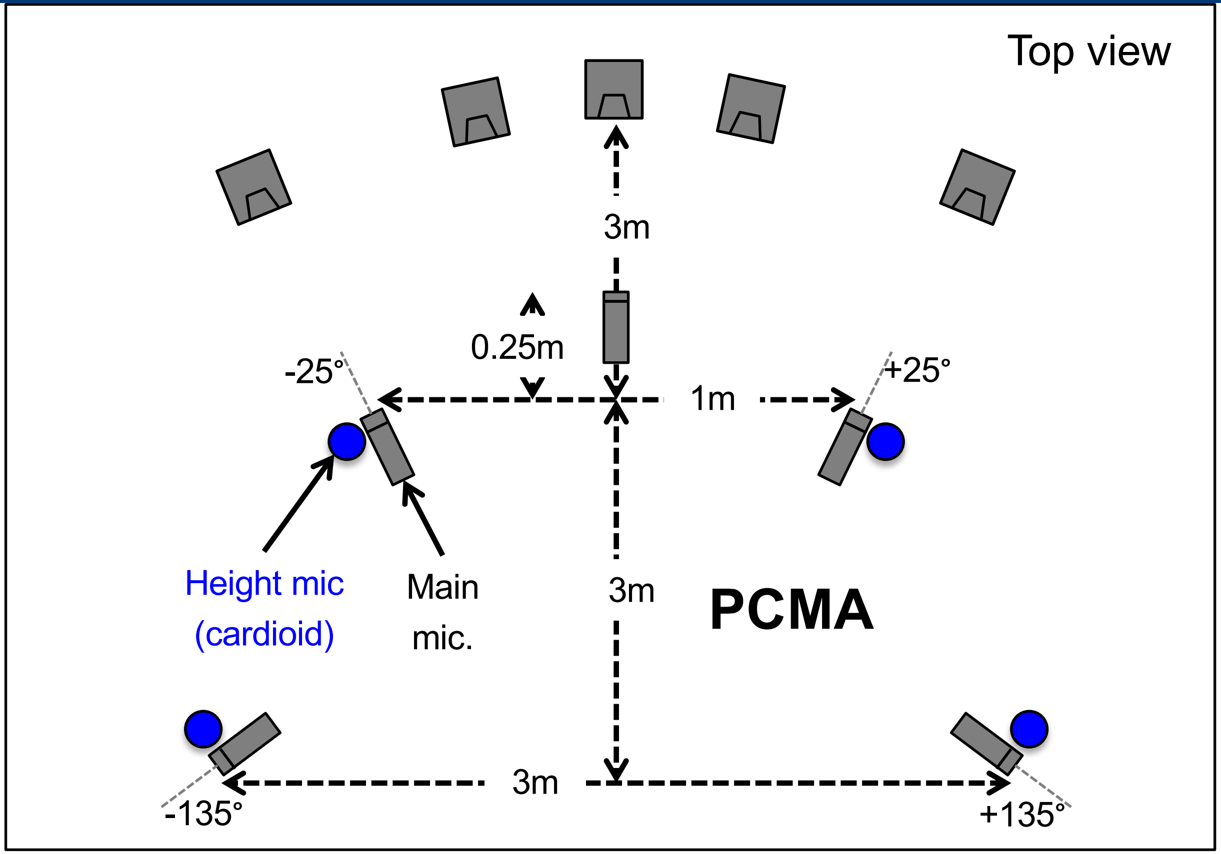
- The effect of vertical microphone spacing on spatial impression (Lee and Gribben 2014)



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



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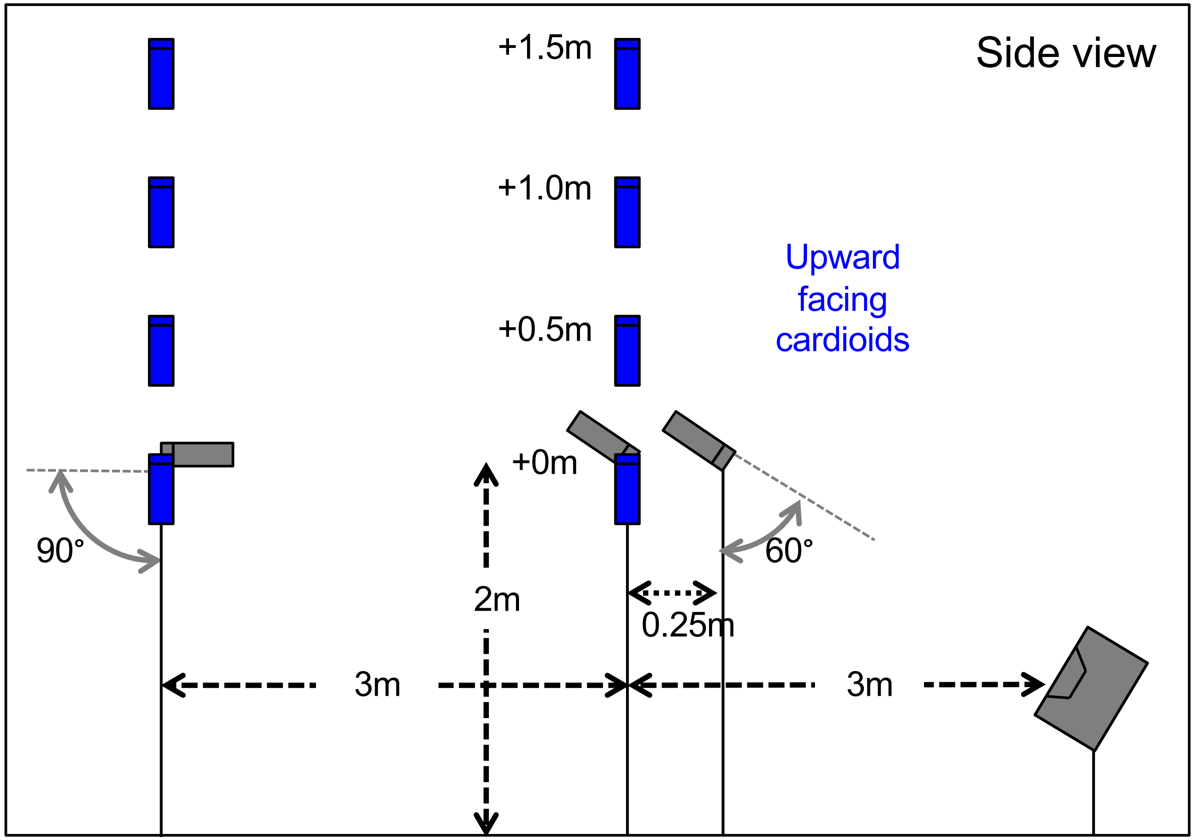
Recording Setup



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

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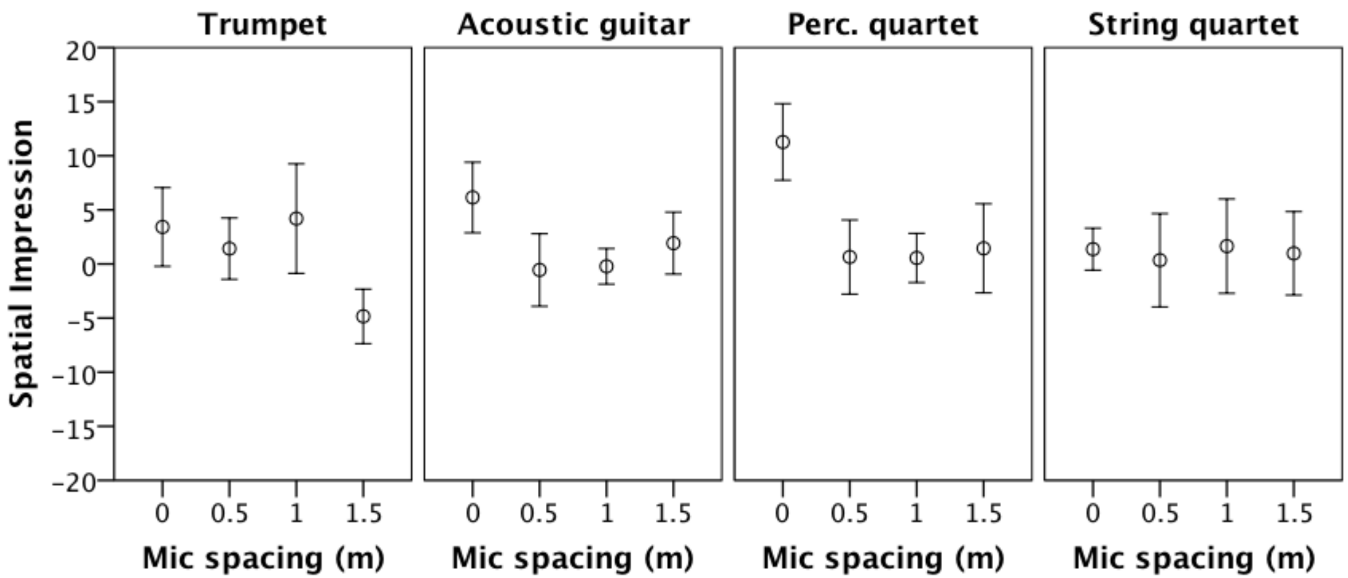
- Vertical microphone spacing does not have a significant effect on perceived spatial impression.
- 0m spacing (vertically coincident) produced greater spatial impression for percussive sources.



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

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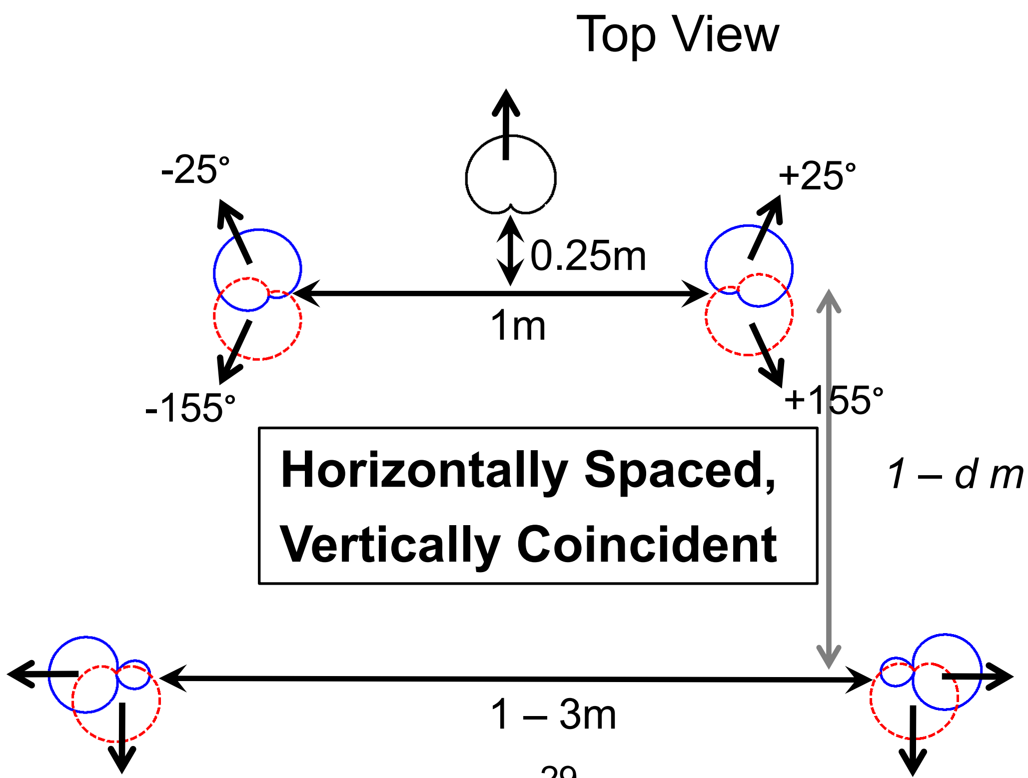
- Original concept of PCMA (Perspective Control Microphone Array) (Lee 2011, 2012)
  - Perceived distance control by virtual microphones at each pick up point.
  - Combine blue and red microphones with a varying mixing ratio → Virtual microphone pointing towards a different direction → controls D/R ratio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

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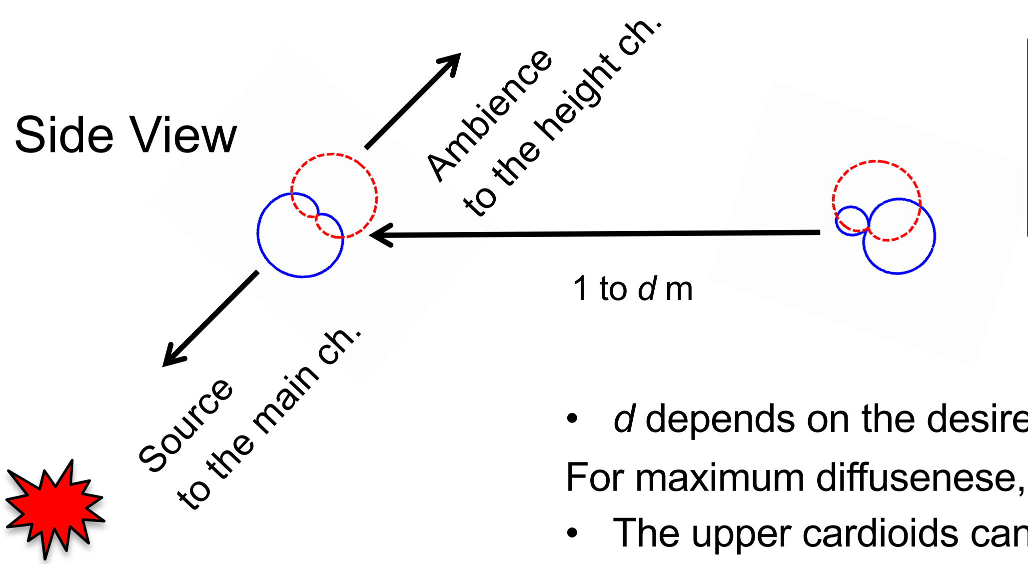
- Application of PCMA for 3D capture (Lee and Gribben 2014)



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

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- 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.

SCHOEPS Mikrofone | pure audio | DOLBY ATMOS | AURO 3D AUDIO | dts-HD Master Audio | msm studio group ltd.

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Demo: Siglo De Oro Choir

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- Recorded at Merton College Chapel in Oxford, UK.

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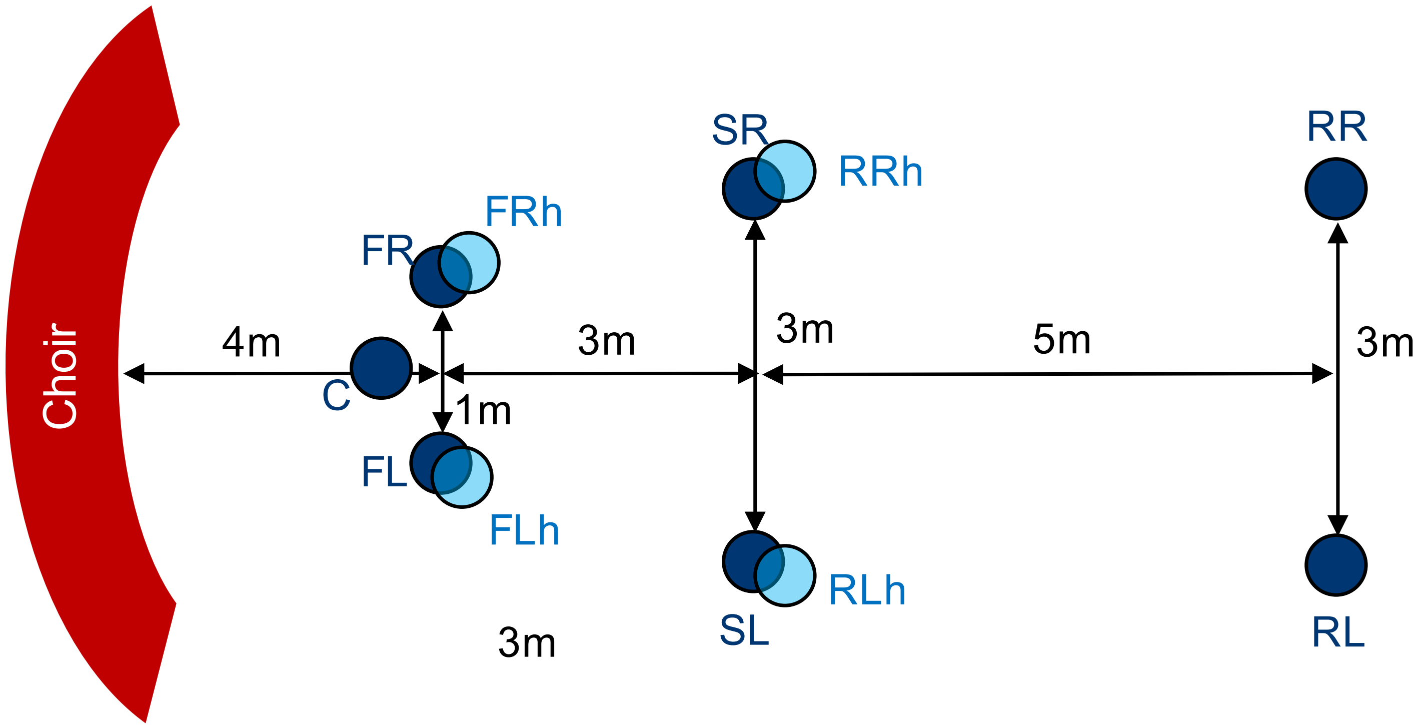
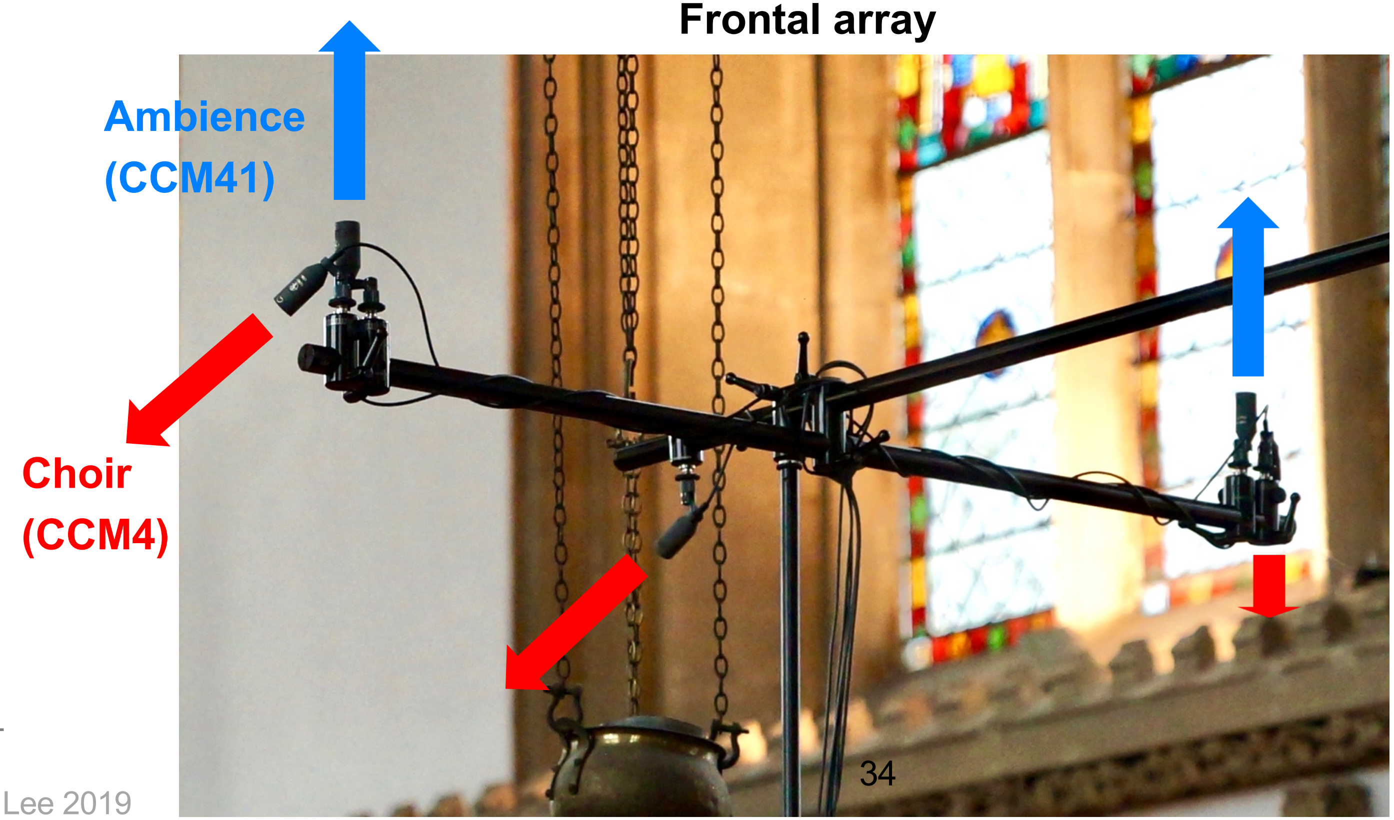
- PCMA-3D microphone arrangement for 11.0 (7+4)



Demo: Siglo De Oro Choir

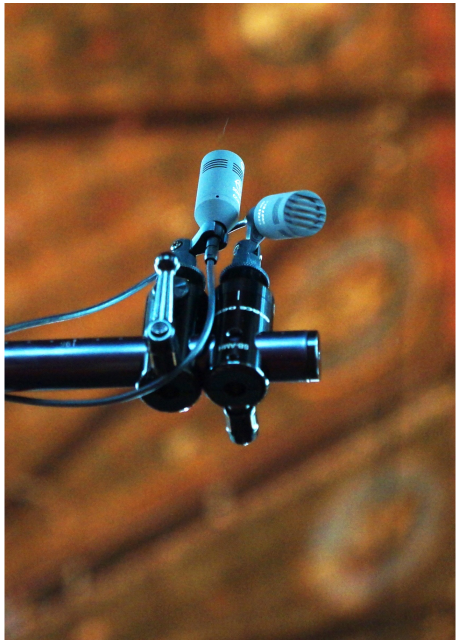
- Microphones used: Schoeps CCM4 (main) and CCM41 (height).

Frontal array



Demo: Siglo De Oro Choir

- Microphones used: Schoeps CCM4 and CCM41.



3D Recording of Siglo De Oro Choir

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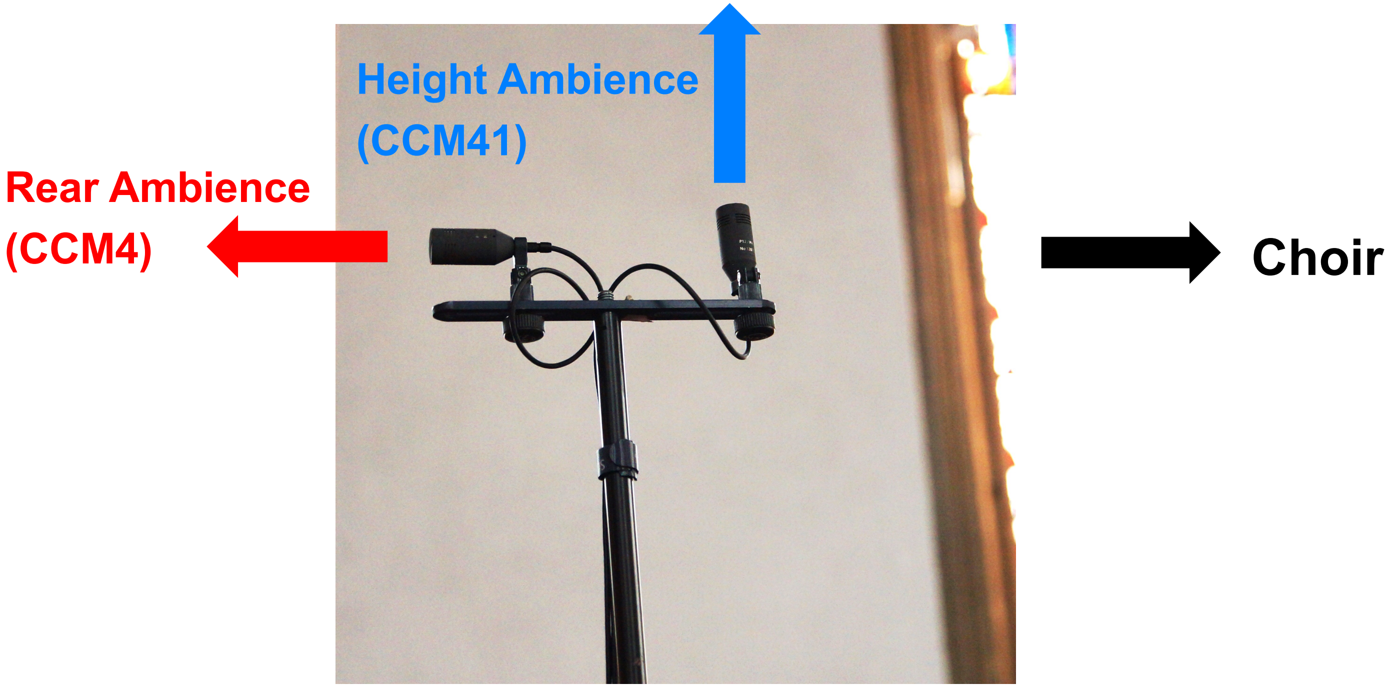
- Microphones used: Schoeps CCM4 and CCM41.



Demo: Zulu Ensemble in 9.0

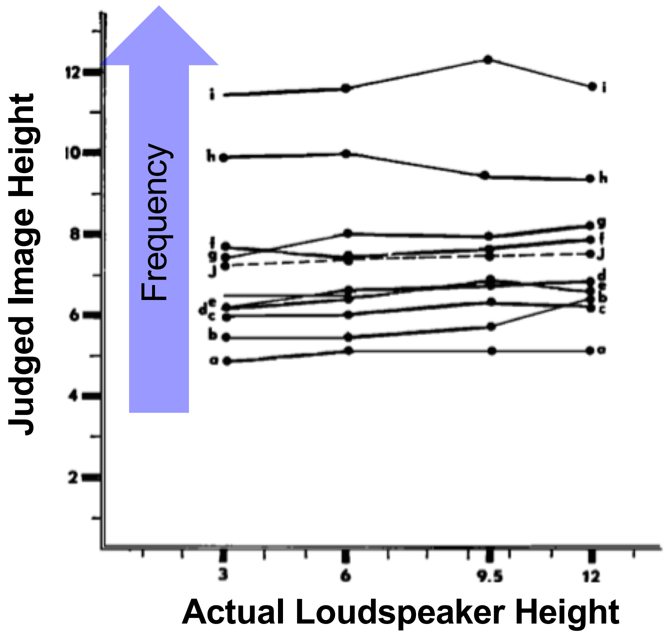
- Recorded at St. Paul's at the University of Huddersfield.

Benefit of Height Channels

- For typical ambience signals, there is little sense of localisation from the physical height speaker positions.

- Pitch-Height Effect
  - – Lower frequencies tend to be localised lower regardless of the physical height of the source.

Roffler and Butler (1968)



Benefit of Height Channels

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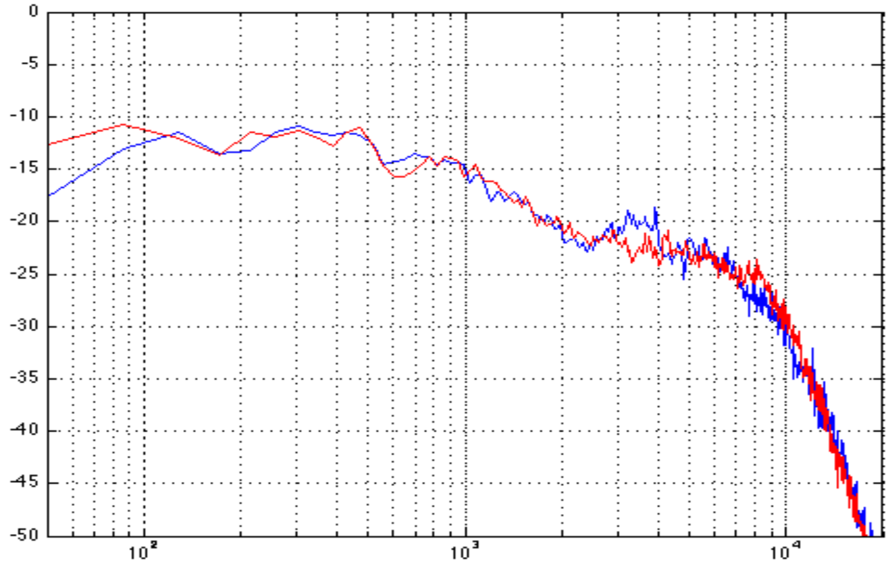
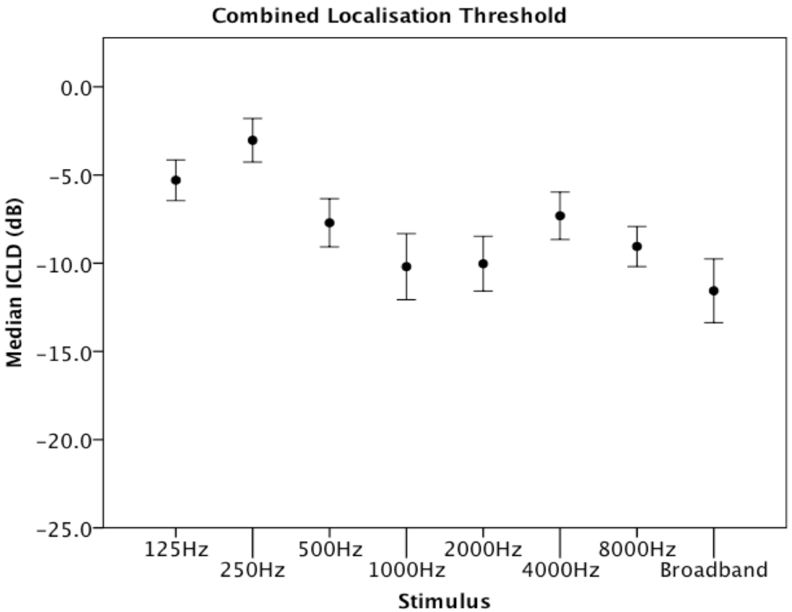
- Spectrum of typical acoustic reverberation
  - High frequency roll-off.
  - Pitch-height effect!
  - Not localised at the physical height speaker position.

- Main benefits of height channels for ambience
  - Perceived depth
  - Vertical image spread
  - Openness



Frequency Dependency of Localisation Threshold

- Localised threshold depends on frequency.
- Results for octave-band pink noises (Wallis and Lee 2016)



Pitch-height effect!

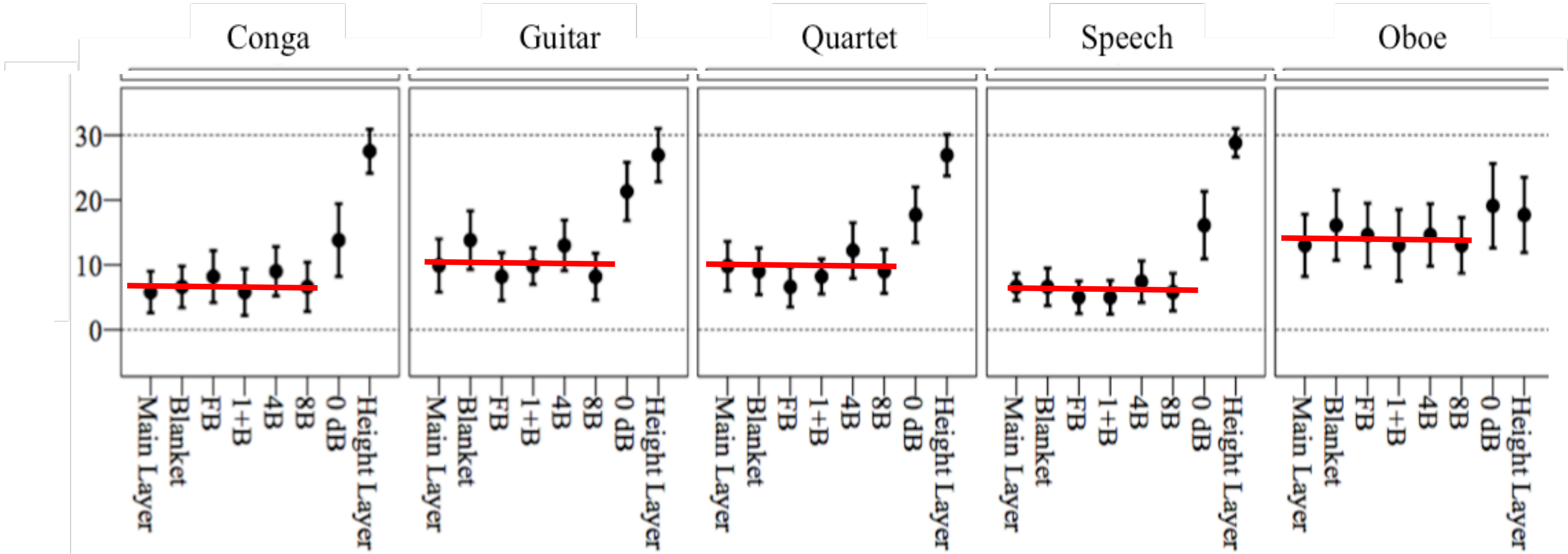
- LF bands from height channels are localised low inherently.

→ requires less level reduction.

Wallis, R. and Lee, H. (2016) '[Vertical Stereophonic Localisation in the Presence of Interchannel Crosstalk: the Analysis of Frequency- Dependent Localisation Thresholds](#)' *Journal of the Audio Engineering Society* , 64 (10), pp. 762-770.

Frequency Dependency of Localisation Threshold

- Band-dependent application of localisation threshold for musical sources (Wallis and Lee 2017).
  – Reducing only high frequencies (e.g. 8kHz band) can still localise the image at the same perceived height of the main layer.



Wallis, R. and Lee, H. (2017) 'The Reduction of Vertical Interchannel Crosstalk: The Analysis of Localisation Thresholds for Natural Sound Sources' *Applied Sciences* , 7 (3). ISSN 2076-3417

ORTF-3D by Schoeps

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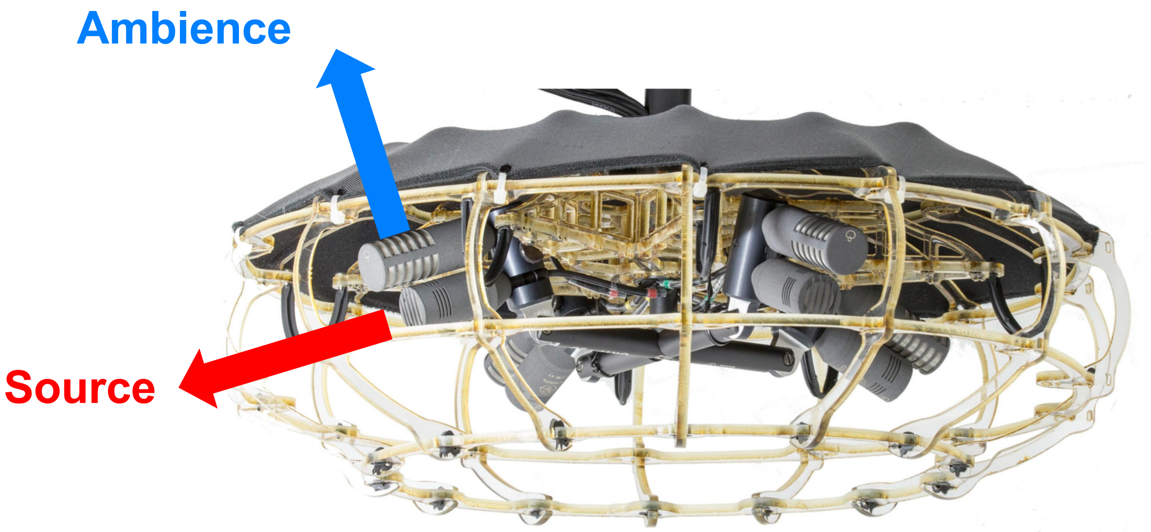
- Vertical concept based on a finding by Lee and Gribben (2014).
  - Vertically coincident, horizontally spaced.



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

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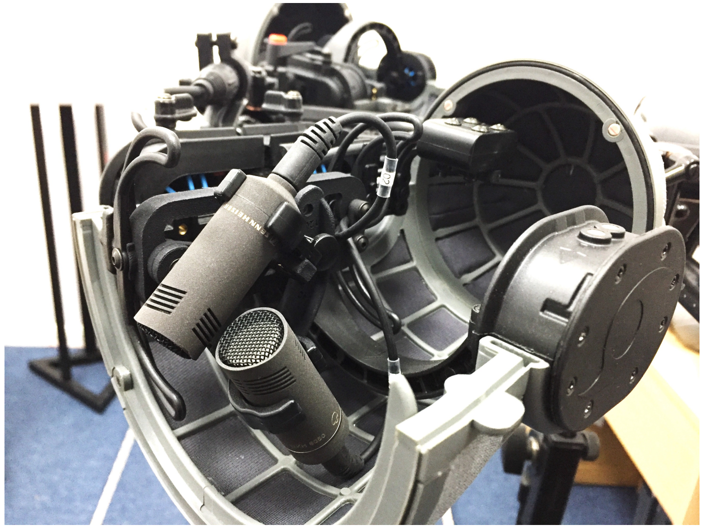
- Equal Segment Microphone Array for 360-deg recording (for VR).
- **50cm x 50cm** square, ideal size for accurate localisation in a quadraphonic reproduction (Lee 2016).
- Vertically coincident (Cardioid main + supercardioid height.)



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

MARRS app for mic technique simulation

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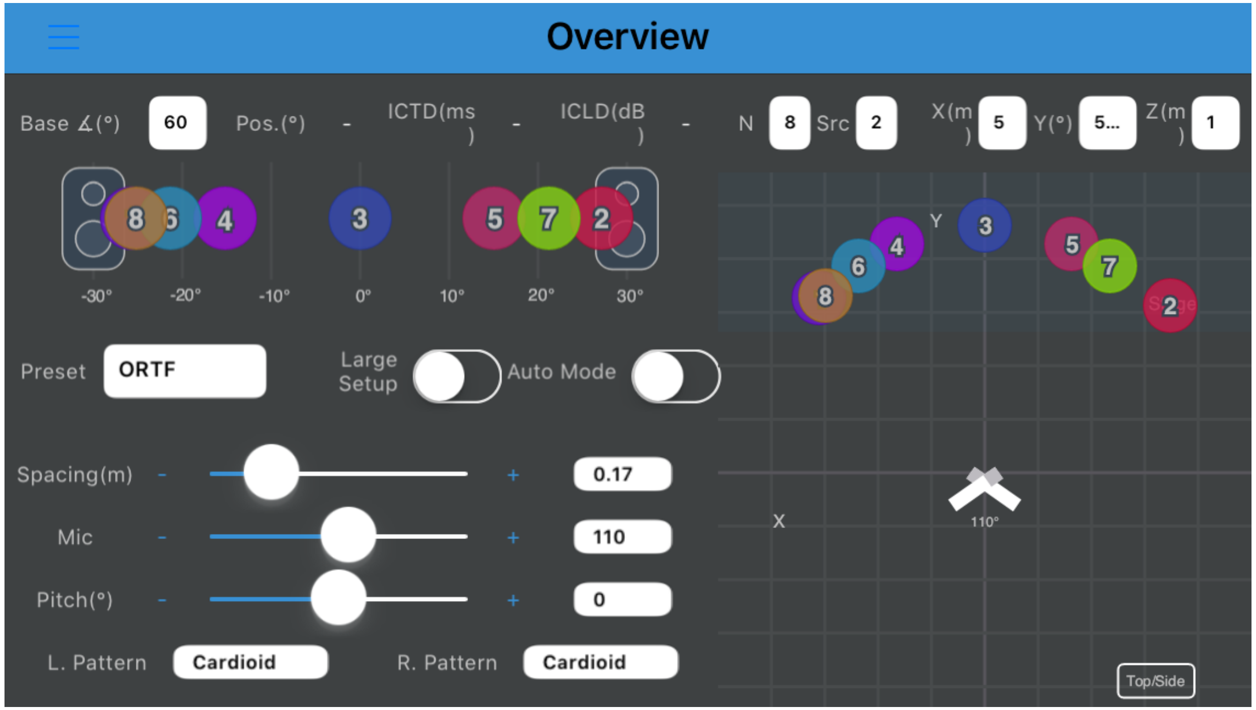
- Object-oriented mic technique simulation tool (Lee, Johnson and Mironovs 2017).
- Free download from iOS and Android app stores (Search **MARRS**).

iOS android

- Web version:
  marrsweb.hud.ac.uk



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ESMA-3D

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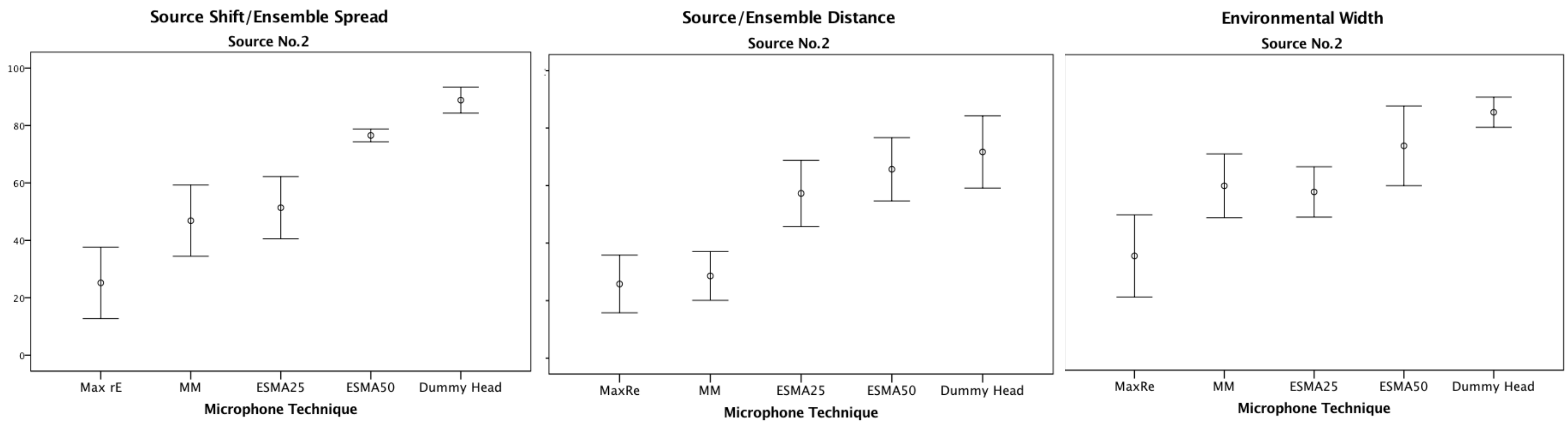
- Comparison against FOA and Dummy Head (Millns and Lee 2018).



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.

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VR Soundscape Library

Demo: Organ

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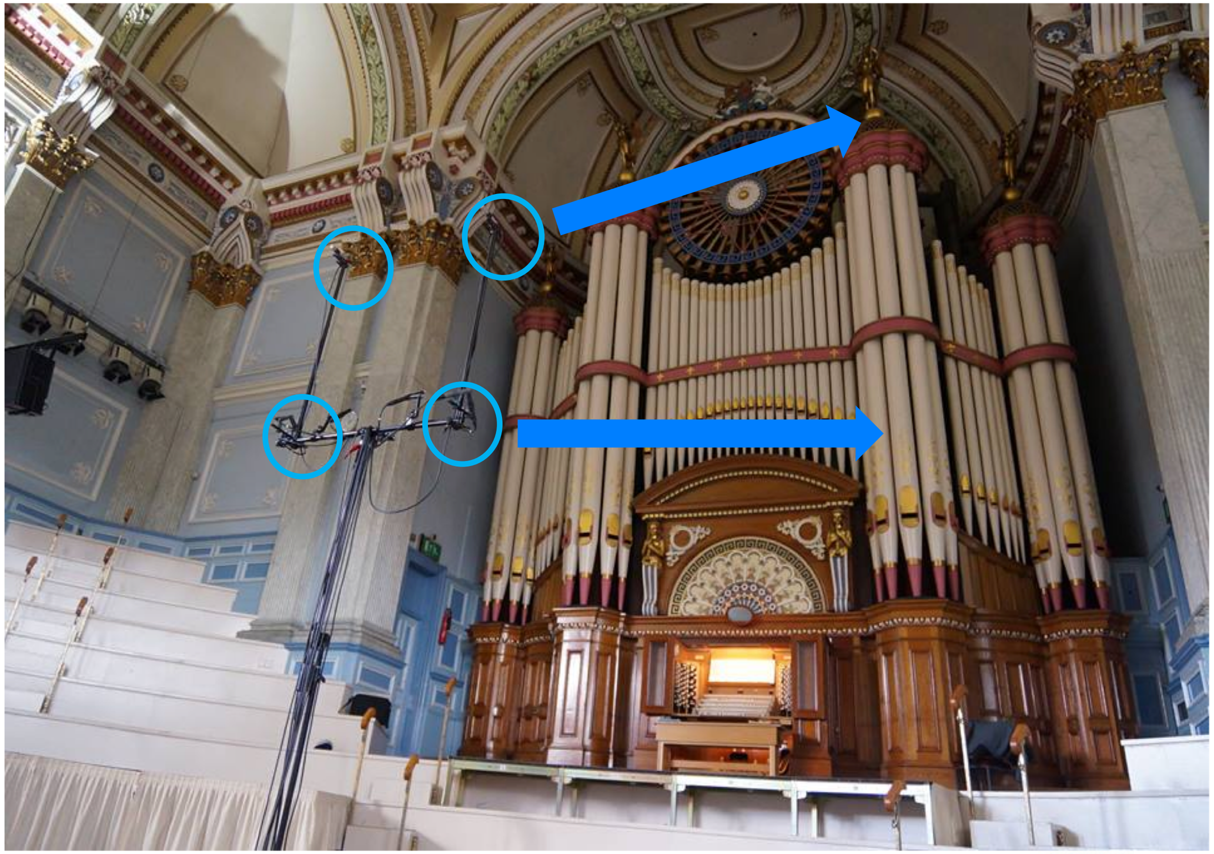
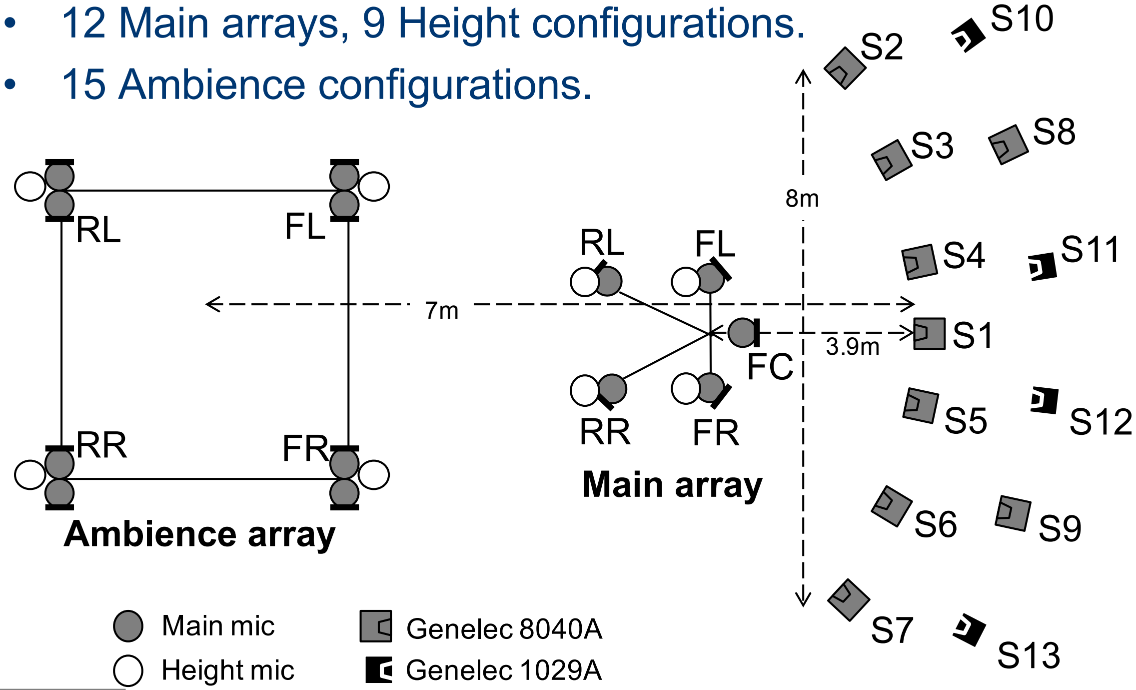
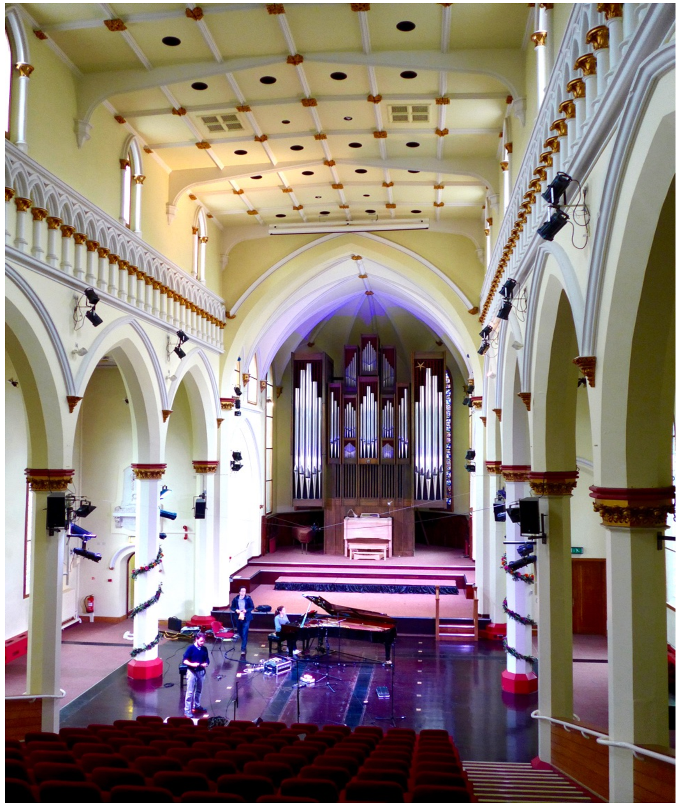
- Recorded at Huddersfield Town Hall.
- Capture direct sounds with both main and height microphones.
- Tall instrument e.g. organ; Elevated sources, e.g. Choir on platforms.



MAIR Library and Renderer

- Over 2000 Microphone Array Impulse Responses (MAIRs) captured for 13 source positions (Lee and Millns 2017). **www.hud.ac.uk/apl/resources**
- 12 Main arrays, 9 Height configurations.
- 15 Ambience configurations.





MAIR Library and Renderer

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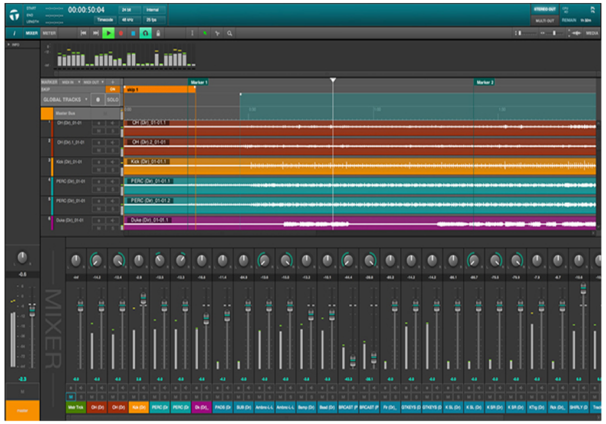
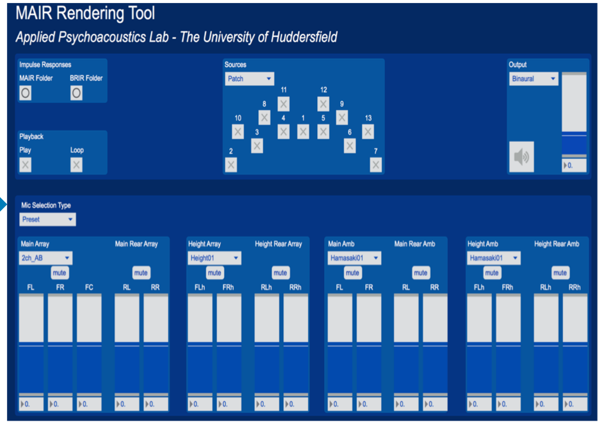
- Renderer allows mic array mixing and binaural/multichannel output.
- Takes outputs from a DAW session, or browse individual files.



DAW



MAIR Renderer

- Virtual mic array comparison
- Binaural & multichannel playback

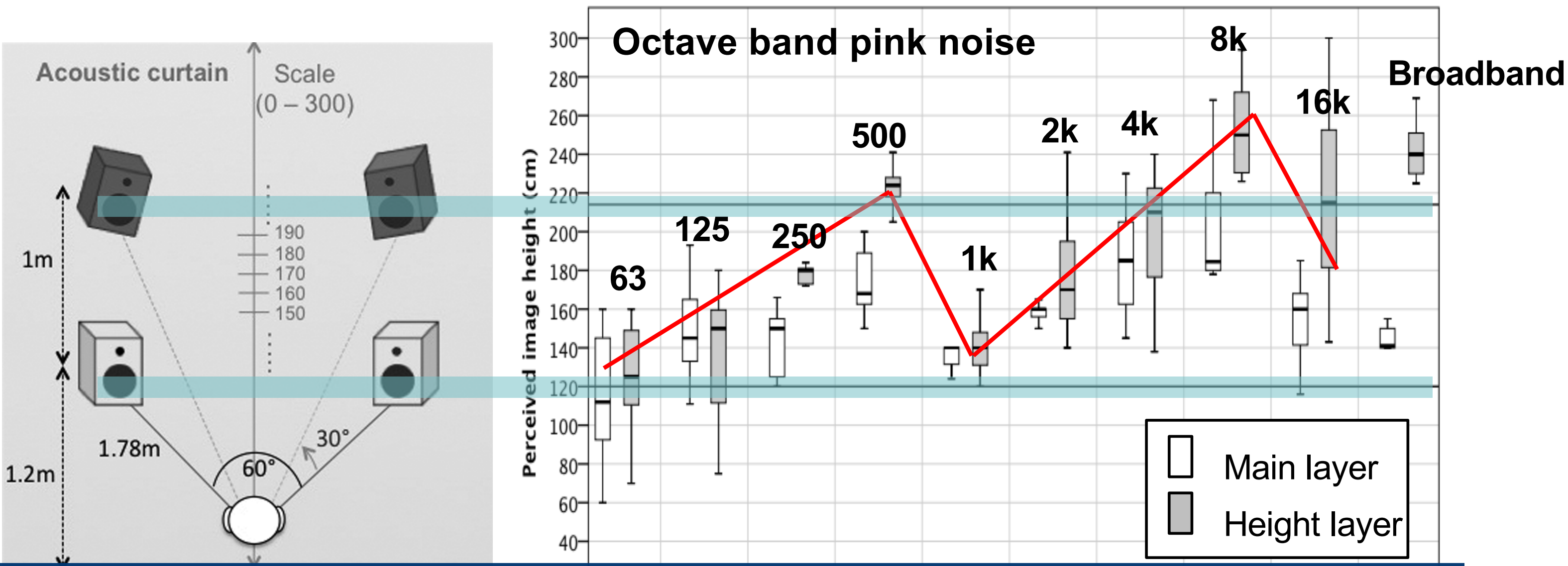
Lee, H. and Millns, C. (2017) '[Microphone Array Impulse Response (MAIR) Library for Spatial Audio Research](#)'. *In: Audio Engineering Society 143rd international convention, 18-21st October 2017*, New York

THE QUEEN'S AWARDS FOR ENTERPRISE

Phantom Image Elevation Effect

Pitch-Height Effect for Phantom Source

- Pitch-height effect for horizontal **phantom** image (Lee 2016)



- Overall, the pitch-height effect operates in two separate regions.
- Reset at 1kHz → Back localisation (Blauert's Directional bands)

Lee, H (2016) 'Perceptual Band Allocation (PBA) for the Rendering of Vertical Image Spread with a Vertical 2D Loudspeaker Array' *Journal of the Audio Engineering Society* , 64 (12), pp. 1003-1013. ISSN 1549-4950

Phantom Image Elevation

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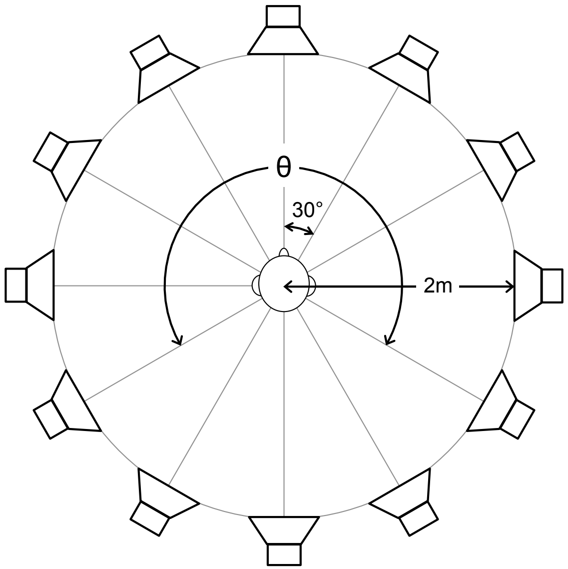
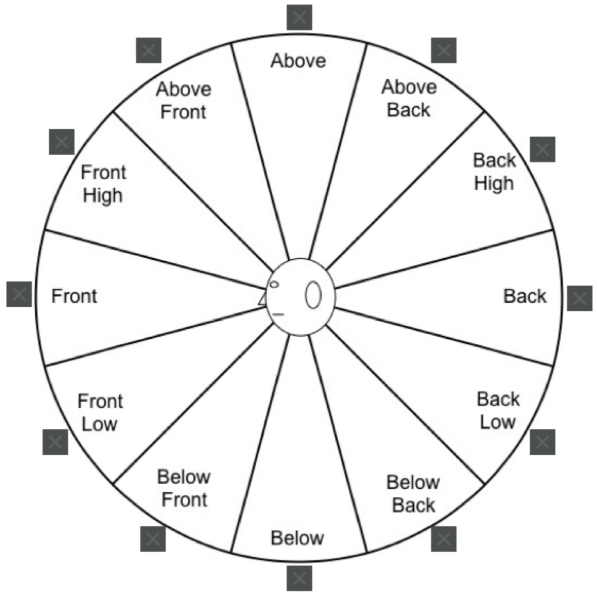
- Investigation into source dependency (Lee 2017)
  – 11 different source types; speaker angle from 0° to 360° with 30° intervals.



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

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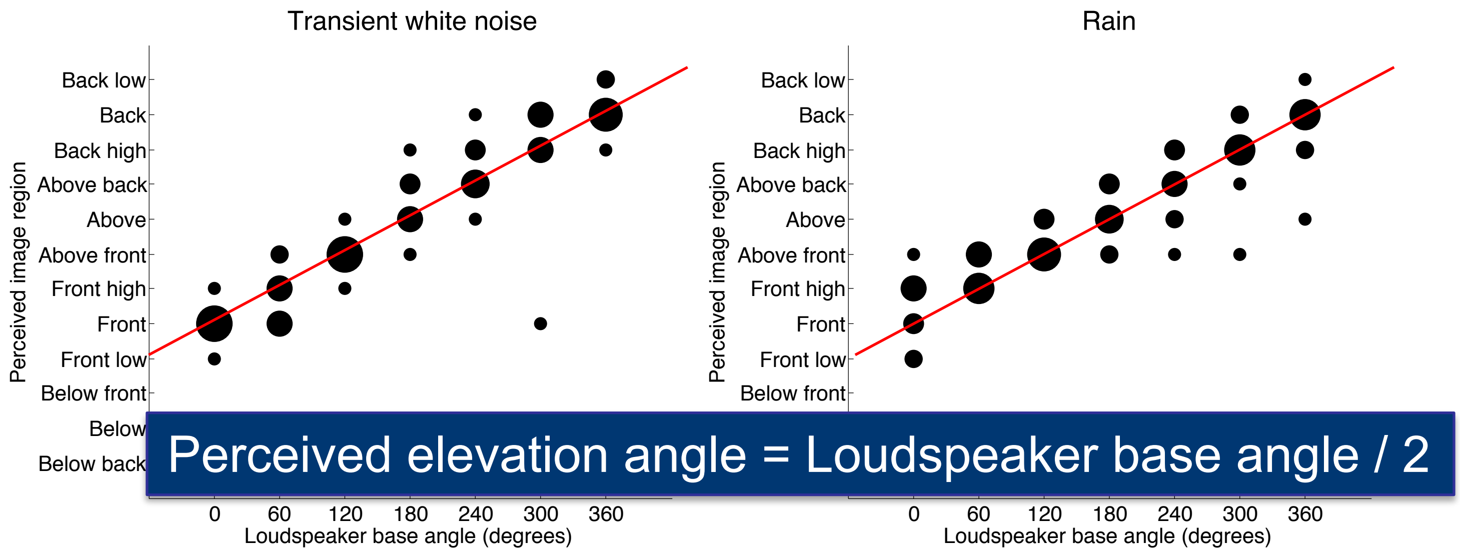
- Sound source dependency
  - Responses are most linear and consistent for source with a broad and flat spectrum.



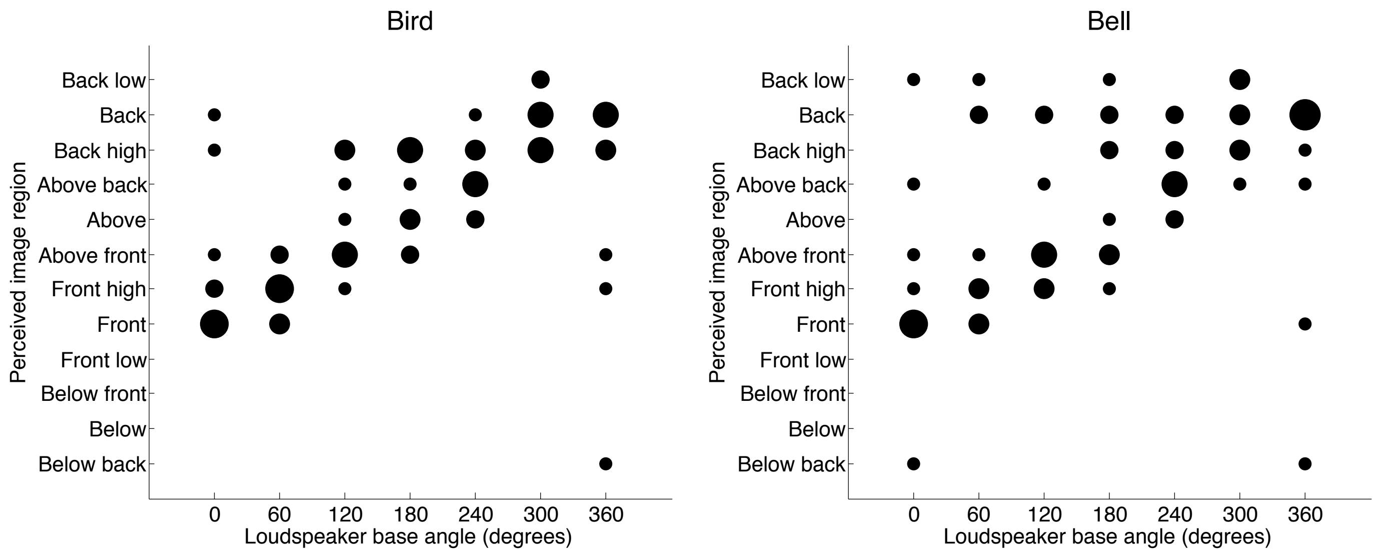
Perceived elevation angle = Loudspeaker base angle / 2

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

University of Huddersfield

- Sound source dependency
  - 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

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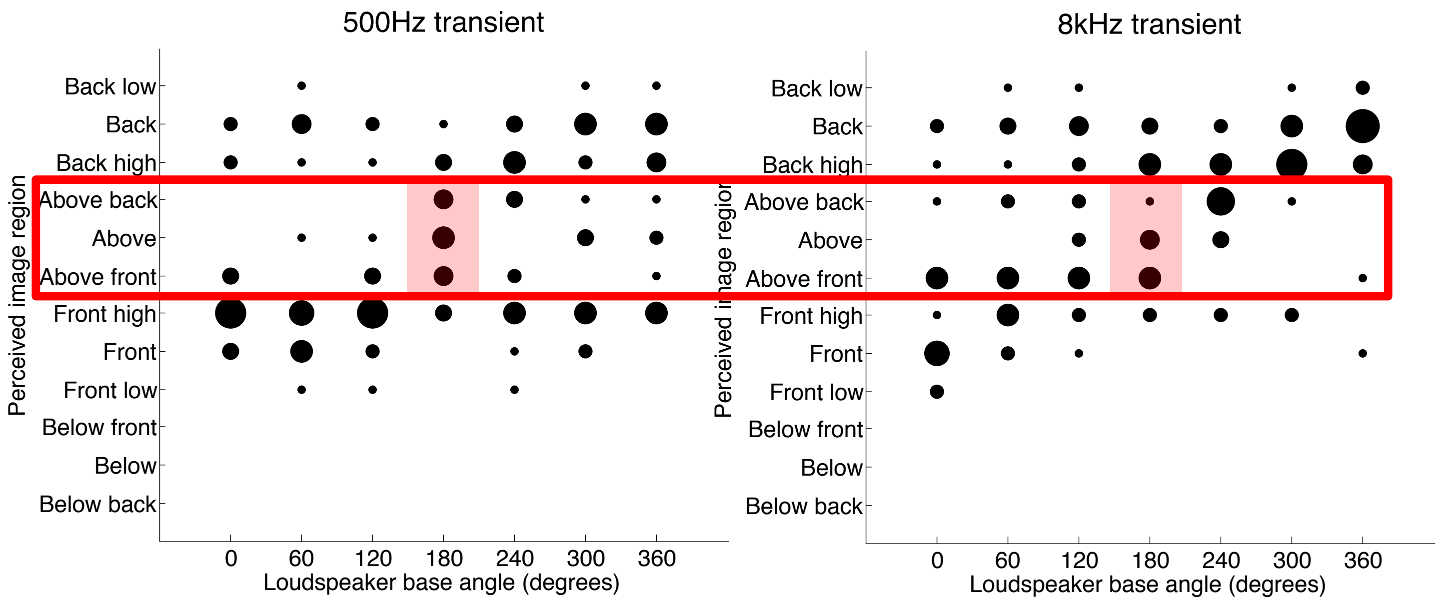
- Frequency dependency (Lee 2016)
  - 500Hz and 8kHz: the most effective bands for the ‘above’ perception among all octave bands.



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

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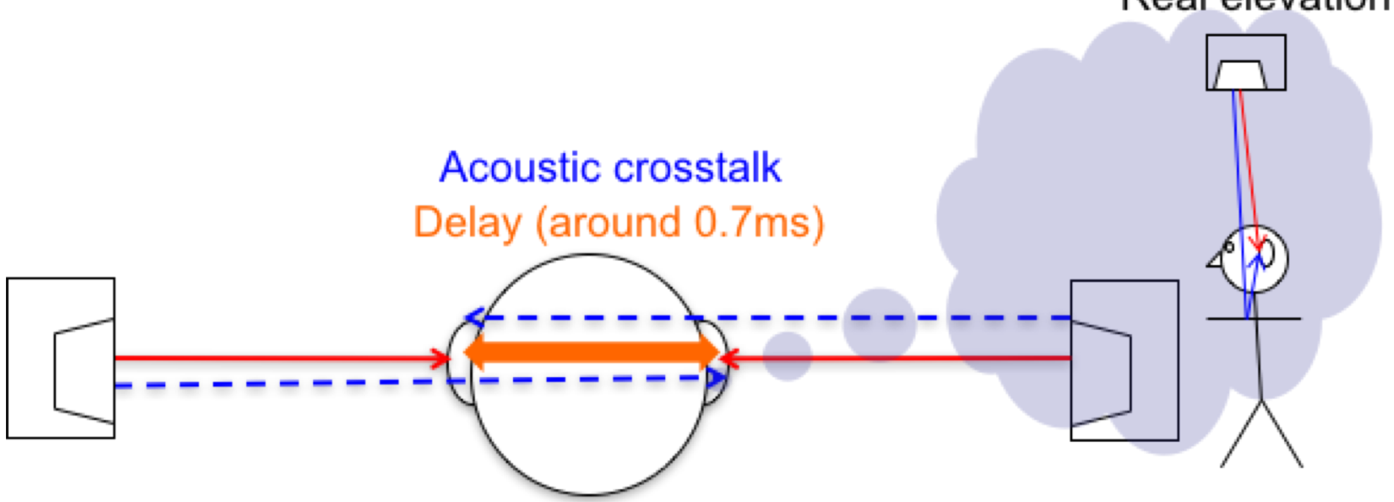
- A new theory (Lee 2017)
  - At low frequencies, the brain interprets the spectral notch caused by acoustic crosstalk as that caused by the shoulder reflection by a real source elevated in the median plane.



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

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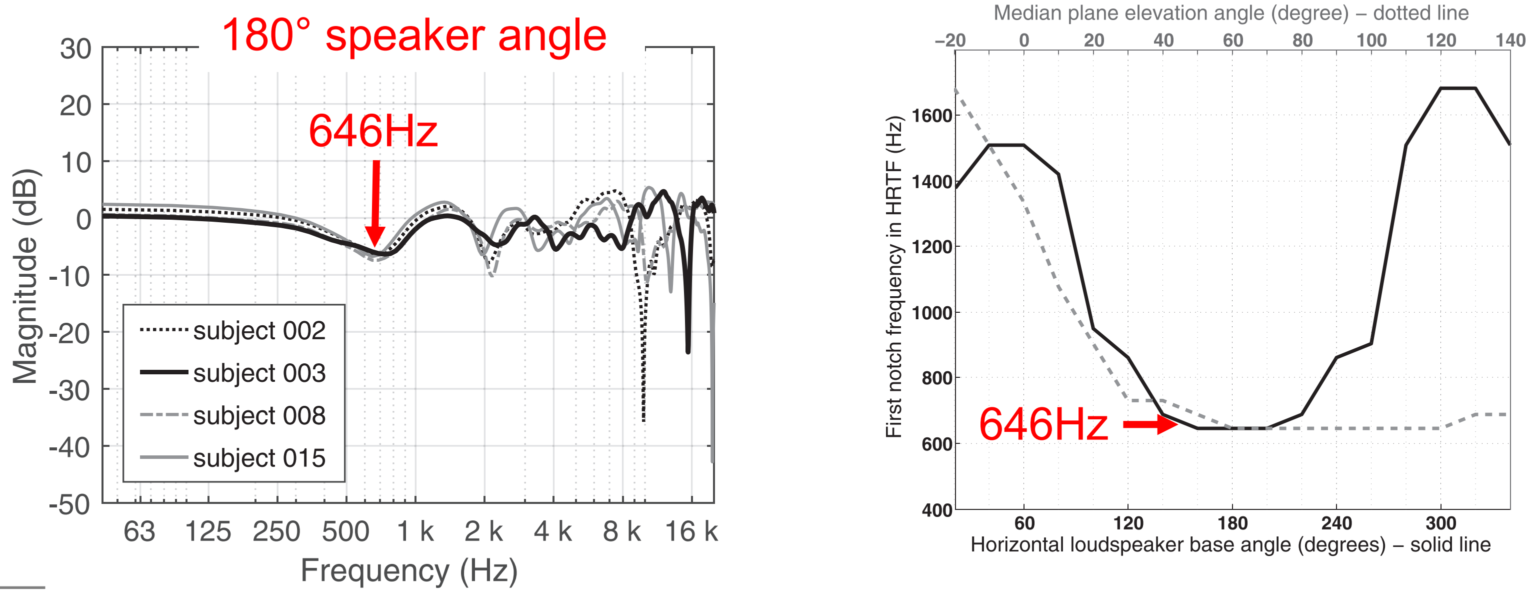
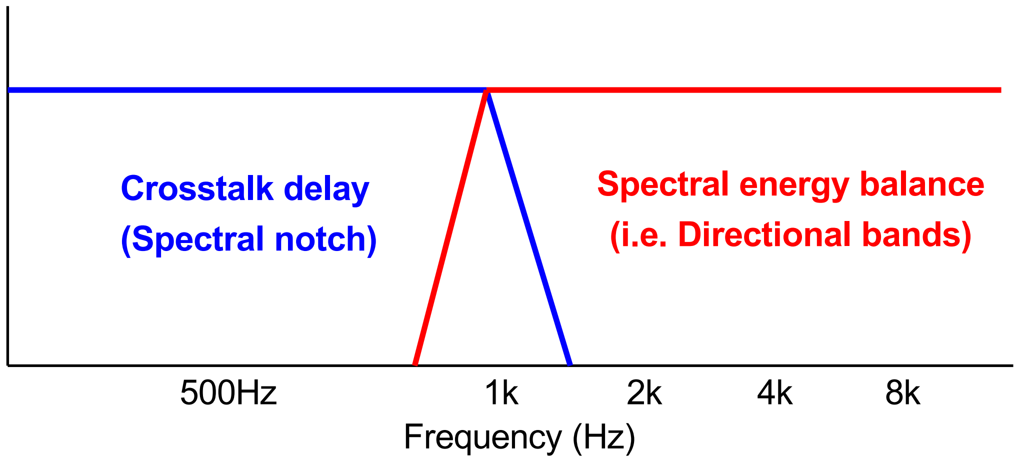


Lee, H (2017) '[Sound Source and Loudspeaker Base Angle Dependency of the Phantom Image Elevation Effect]' *Journal of the Audio Engineering Society* , 65 (9), pp. 733-748. ISSN 1549-4950

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).



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

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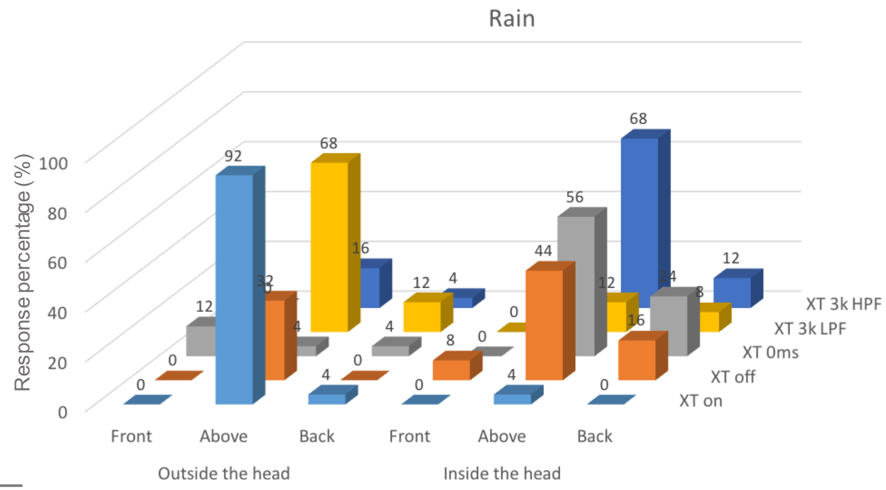
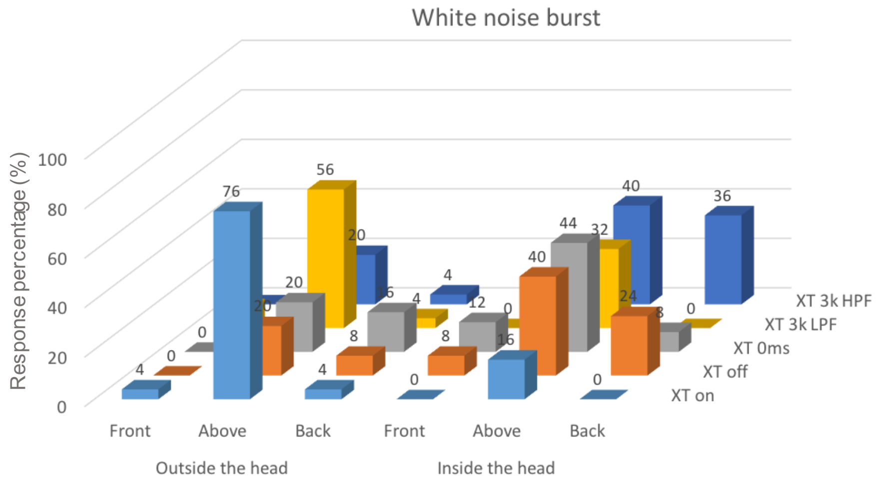
- Verification (Lee 2016)
  - Individualised binaural simulation with 5 subjects (5 repetitions).
  - Crosstalk on and off / high-passed and low-passed.
  - LF crosstalk → Above localisation **outside** the head.
  - HF crosstalk → Above localisation **inside** the head.

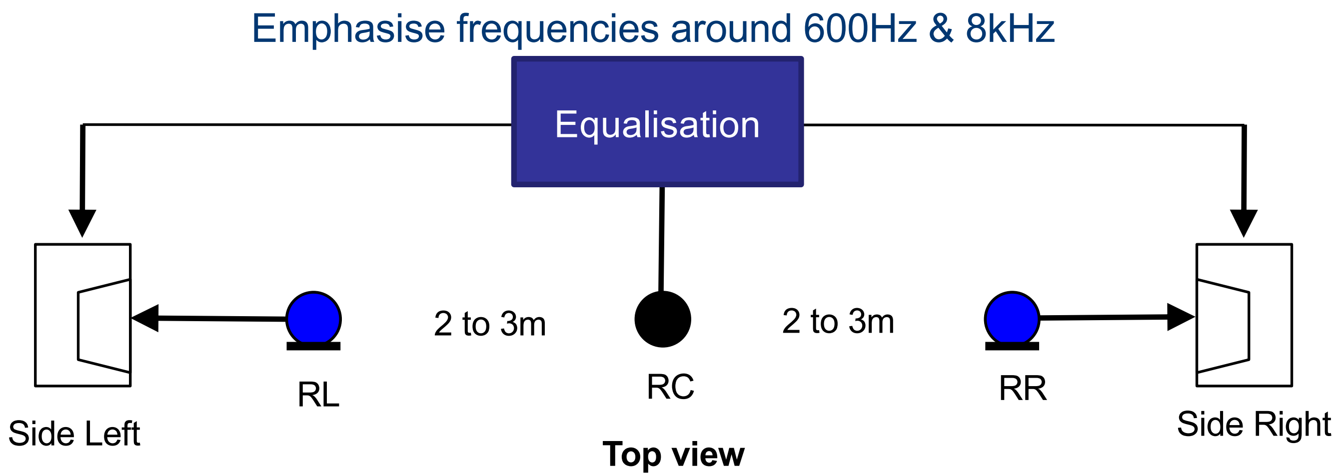




Lee, H (2016) '[Phantom Image Elevation Explained](#)'. *In: Audio Engineering Society the 141st International Convention, 29 Sep - 2 Oct*, Los Angeles, USA

Ambience microphone technique

- Exploiting the phantom image elevation effect (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

Ambience microphone technique

- 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)

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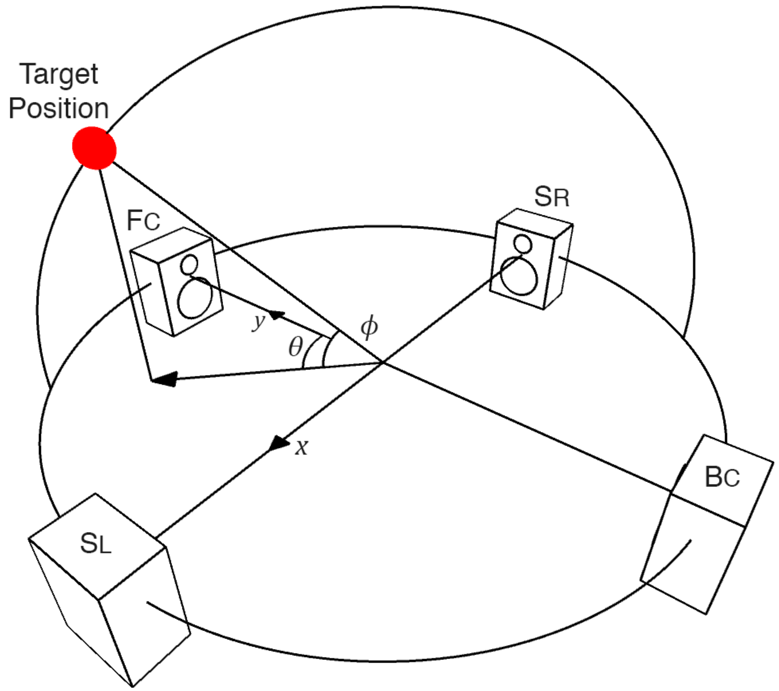
- An efficient 3D panning method exploiting the phantom image elevation effect.
- Requires only 4 ear-height loudspeakers at 0°, 90°, 180° and 270°.
- Trade-off between the phantom elevation effect and interaural differences.



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.

VHAP VST plugin

- Freely available from **www.hud.ac.uk/apl/resources**

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Frequency-based Vertical Processing

Perceptual Band Allocation (PBA)

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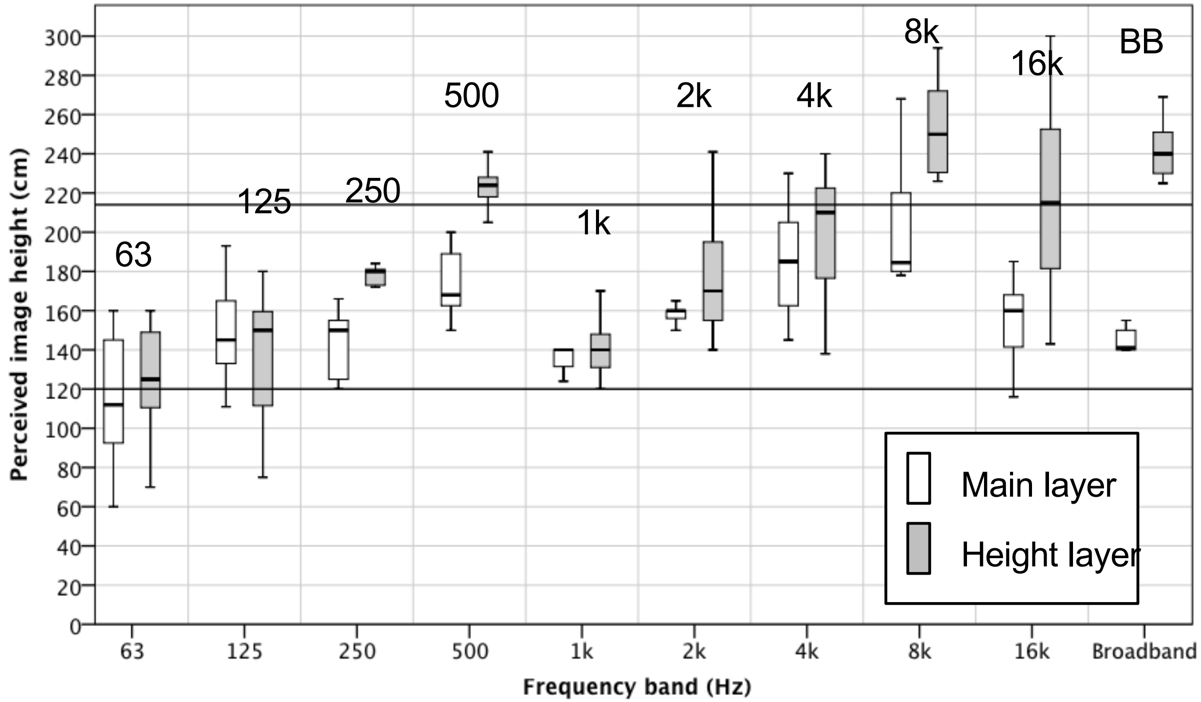
- Each frequency band has its inherent vertical image position (Lee 2016).



Lee, H (2016) '[Perceptual Band Allocation (PBA) for the Rendering of Vertical Image Spread with a Vertical 2D Loudspeaker Array]' *Journal of the Audio Engineering Society* , 64 (12), pp. 1003-1013. ISSN 1549-4950

THE QUEEN'S AWARDS FOR ENTERPRISE

Perceptual Band Allocation (PBA)

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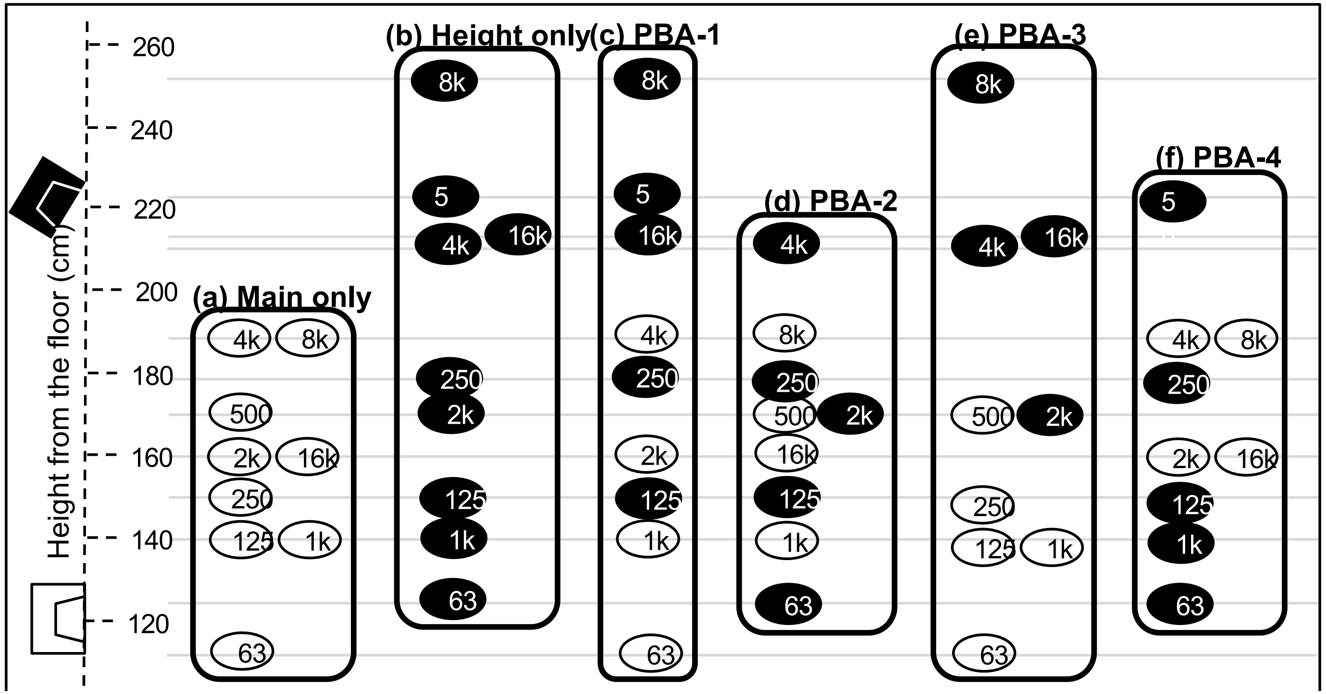
- It is possible to produce different degrees of vertical image spread by allocating each band to a different loudspeaker layer (Lee 2016).



Lee, H (2016) ‘Perceptual Band Allocation (PBA) for the Rendering of Vertical Image Spread with a Vertical 2D Loudspeaker Array’ *Journal of the Audio Engineering Society* , 64 (12), pp. 1003-1013. ISSN 1549-4950

2-Band PBA

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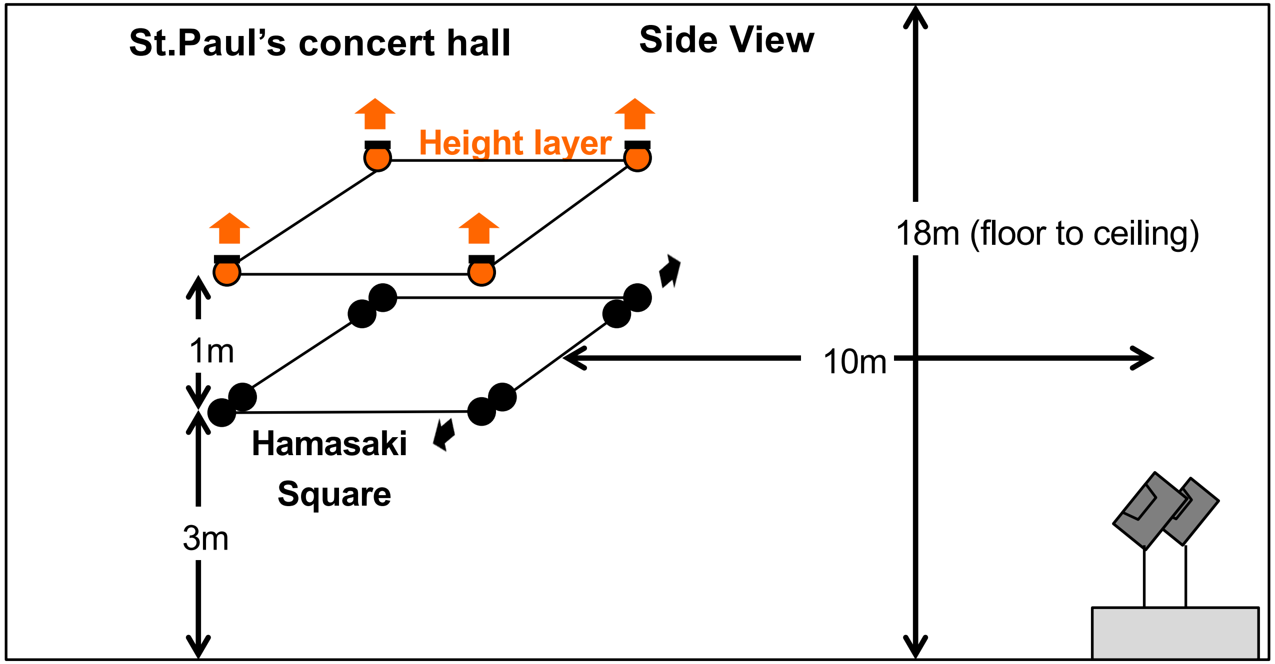
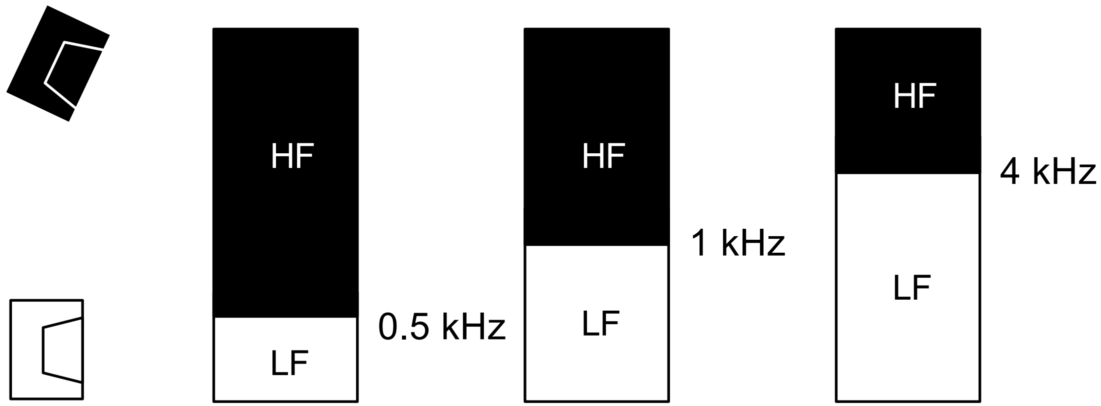
- Simple PBA with 2 band split (low and high bands) (Lee 2015).



Lee, H (2015) '2D to 3D ambience upmixing based on perceptual band allocation' *Journal of the Audio Engineering Society* , 63 (10), pp. 811-821. ISSN 1549-4950\

2-Band PBA process

- Low and high pass filtering
  - 4ch ambient signals captured by the Hamasaki Square
  - At three different crossover frequencies: 0.5, 1 and 4kHz
- LF signals to main channels, HF signals to height channels



Lee, H (2015) '2D to 3D ambience upmixing based on perceptual band allocation' *Journal of the Audio Engineering Society* , 63 (10), pp. 811-821. ISSN 1549-4950\

3D LEV – Overall plots

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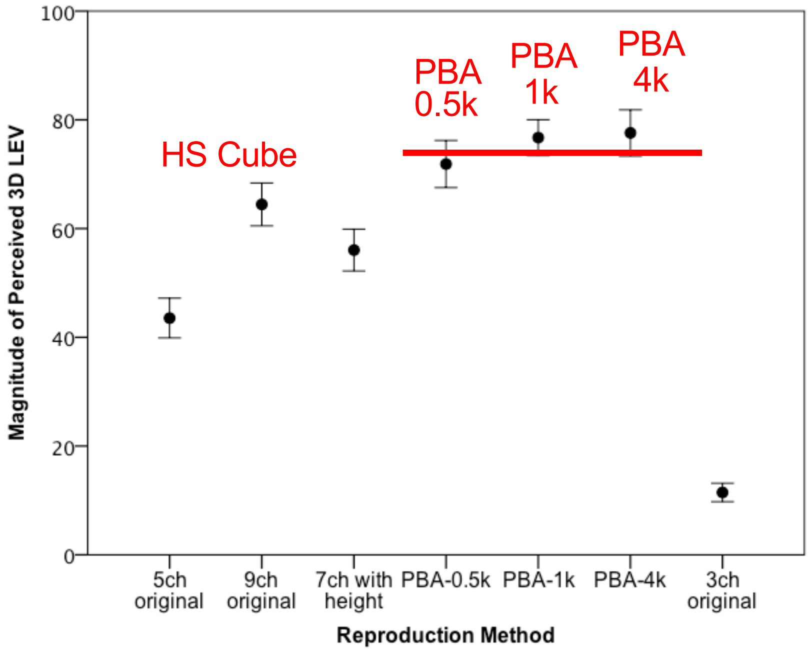
- PBA upmixing sounded more enveloping than 9-channel original Hamasaki-Cube (within the experimental condition).



Lee, H (2015) '2D to 3D ambience upmixing based on perceptual band allocation' *Journal of the Audio Engineering Society* , 63 (10), pp. 811-821. ISSN 1549-4950\

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- For questions or more information, please email me and visit the websites below.
- Free software and databases are available from the APL website.

h.lee@hud.ac.uk

www.hyunkooklee.com

www.hud.ac.uk/apl

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