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Capturing and Rendering 360° VR Audio using Cardioid Microphones

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Motivation

• Near-coincident mic arrays
  – ORTF, NOS, etc.
  – Arguably, preferred to pure coincident or pure spaced techniques by most professional recording engineers.
  – Rely on the trade-off between Time and Level differences.
  – Best of both worlds (Localisability & Spaciousness).

• Cardioid microphones
  – Most popular.
  – Most widely available.

• Record for VR using favourite cardioid mics arranged in a near-coincident fashion?
Contents

• Research background
• Localisation test in loudspeaker reproduction
• Localisation test in binaural reproduction
• Discussion
• Summary
Research Background
Existing methods for VR audio capture

- **First Order Ambisonics (FOA)**

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Very good “localisability” due to the coincident nature (But not necessarily good localisation “accuracy”).&lt;br&gt;• Virtual microphones from flexible decoding.&lt;br&gt;• Compact.</td>
<td>• High interchannel correlation.&lt;br&gt;• Lack of spaciousness.&lt;br&gt;• Comb-filtering and rapid change in image position even with a small head movement.</td>
</tr>
</tbody>
</table>
### Existing methods for VR audio capture

- **Higher Order Ambisonics (HOA)**

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Higher spatial resolution.</td>
<td>• Requires a large number of channels for a proper decoding. ( N = (M + 1)^2 )</td>
</tr>
<tr>
<td>• More accurate localisation.</td>
<td>• Very expensive.</td>
</tr>
<tr>
<td></td>
<td>• Tonal quality.</td>
</tr>
<tr>
<td></td>
<td>• Spaciousness?</td>
</tr>
</tbody>
</table>
## Existing methods for VR audio capture

- **Quad Binaural**

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Direct pinnae filtering.</td>
<td>• Inaccurate localisation and comb-filtering due to crossfading between ear signals.</td>
</tr>
<tr>
<td>• No need for extra binaural synthesis.</td>
<td>• Not possible to use personal HRTFs.</td>
</tr>
<tr>
<td></td>
<td>• Only for horizontal head rotation.</td>
</tr>
<tr>
<td></td>
<td>• Expensive.</td>
</tr>
</tbody>
</table>
Psychoacoustic considerations for VR

- In VR, it is important to match the actual and perceived source positions.
Psychoacoustic considerations for VR

- The perceived source position should stay the same as the head rotates.

![Mic Array](Image)

**Recording**

-45°  

**Reproduction**

+135°  

**Binauralisation**
Psychoacoustic considerations for VR

- The perceived source position should stay the same as the head rotates.
Psychoacoustic considerations for VR

- Limitation of FOA
  - Quadraphonic Cardioid decoding.
Psychoacoustic considerations for VR

- Limitation of FOA
  - Only 6dB ICLD (interchannel level difference) for the front pair for a source at 45°.
  
  → Not sufficient for a full phantom image shift to 45°.
Psychoacoustic considerations for VR

• Limitation of FOA
  – Another 6dB ICLD for the left pair.
  – The image is perceived almost at the front left speaker (mainly one ear → no effective interaural difference)
Psychoacoustic considerations for VR

- Limitation of FOA
  - The resulting image position in the quadraphonic reproduction is still not fully shifted to 45°.

ICLD = 6dB

-135°  +135°  +45°
Psychoacoustic considerations for VR

- Problems of B-format (FOA) binauralisation for VR
  - Inaccurate localisation due to insufficient ICLD.
  - The image follows you when you rotate the head.
Proposed Technique
Design philosophy

• Equal Segment Microphone Array (ESMA)
  – A design concept proposed by Williams (1991), but for 360 multichannel reproduction.

• Requirements
  1. Equal subtended angle for all stereo segments (±45°).
  2. The stereophonic recording angle (SRA) of each segment should match the subtended angle of the segment. (±45°)
Design philosophy

- **IRT-Cross by Theile**
  - Originally designed for ambience capture.
  - $d = 20$ to $25cm$.

- **ORTF-Surround (or 3D)**
  - SRA not consistent for every segment.
  - Not suitable for ESMA.
Design philosophy

- BBC Proms using ORTF 3D
• The SRA of ±45° for quadraphonic ESMA
  → A source at ±45° in recording should be localised at ±45° in reproduction.

\[
\text{SRA} = \pm 45°
\]
• The SRA of ±45° for quadraphonic ESMA
  → A source at ±45° in recording should be localised at ±45° in reproduction.
Design philosophy

- Suitable for VR applications with head-tracking.
Psychoacoustic basis

- The appropriate spacing between microphones to produce the ±45° SRA?
  - Depends on what psychoacoustic time-level trade-off model is used for calculating the SRA.

<table>
<thead>
<tr>
<th>Model</th>
<th>Microphone spacing</th>
<th>Source to mic array distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Williams</td>
<td>23.8cm</td>
<td>unknown</td>
</tr>
<tr>
<td>Sengpiel</td>
<td>25cm</td>
<td>unknown</td>
</tr>
<tr>
<td>Wittek + Theile</td>
<td>24cm</td>
<td>2m</td>
</tr>
<tr>
<td>Lee + Theile</td>
<td>30cm</td>
<td>2m</td>
</tr>
<tr>
<td>Lee</td>
<td>50cm</td>
<td>2m</td>
</tr>
</tbody>
</table>

Based on ICTD and ICLD data obtained using ±30 setup°

Optimised for ±45 setup°
Designing a near-coincident VR mic array

- Linear time-level trade-off functions (Lee 2016)
  - Shift region dependent.
  - Loudspeaker base angle dependent.

Interchannel Time Difference (ICTD) in ms

Interchannel Level Difference (ICLD) in dB

- ICTD and ICLD image shift factors change in proportion to the change of ITD and ILD.
- Shift factors for ±45° base angle.
  8.8%/0.1ms; 6%/dB (< 30°)
  4.4%/0.1ms; 3%/dB (30°- 45°).
Experiments
Aim

• To evaluate the localisation accuracies of the quadraphonic FOA and ESMA.
  – If the SRA of ±45° can be achieved.
  – Loudspeaker and headphone reproduction tests in simulated head rotation scenarios.

• Microphone spacing tested:
  – 0cm (FOA)
  – 24cm (Wittek + Theile)
  – 30cm (Lee + Theile)
  – 50cm (Lee)
Stimuli creation

- Recording setup

  - ITU-R BS.1116 standard room.
  
  - 8 Genelec 8040As arranged in an octagonal layout.
  
  - Room impulse responses (RIRs) captured for 0° and 45°.
  
  - Soundfield SPS 422b for FOA.
  
  - Neumann KM184 for ESMA.
Stimuli creation

• Stimuli for Experiment 1 (Loudspeaker playback)
  
  – An anechoic speech signal was convolved with the direct sounds of the RIRs (reflections removed).
  
  – Head rotations simulated for 0°, ±45°, ±90°, ±135° and ±180° (Soundfield rotation).
Stimuli creation

• Stimuli for Experiment 1 (Loudspeaker playback)
  
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  - An anechoic speech signal was convolved with the direct sounds of the RIRs (reflections removed).
  
  - Head rotations simulated for 0°, ±45°, ±90°, ±135° and ±180° (Soundfield rotation). 

Simulating 135° head rotation
Stimuli creation

- Stimuli for Experiment 1 (Loudspeaker playback)
  - An anechoic speech signal was convolved with the direct sounds of the RIRs (reflections removed).
  - Head rotations simulated for 0°, ±45°, ±90°, ±135° and ±180° (Soundfield rotation).
Stimuli creation

• Stimuli for Experiment 1 (Loudspeaker playback)
  
  – An anechoic speech signal was convolved with the direct sounds of the RIRs (reflections removed).
  
  – Head rotations simulated for 0°, ±45°, ±90°, ±135° and ±180° (Soundfield rotation).
Stimuli creation

- Stimuli for Experiment 1 (Loudspeaker playback)

  - An anechoic speech signal was convolved with the direct sounds of the RIRs (reflections removed).

  - Head rotations simulated for 0°, ±45°, ±90°, ±135° and ±180° (Soundfield rotation).
Stimuli creation

• Stimuli for Experiment 2 (Binaural playback)
  – Same conditions as Experiment 1, but with the full RIRs (reflections included).
  – The multichannel stimuli were binauralised with dry KU100 dummy head HRIRs from the ‘SADIE’ database (Kearney 2015).
Listening tests

- Experiment 1 (Loudspeaker playback)
  - Loudspeakers hidden by acoustically transparent curtains.
  - Small markers were placed on the curtain from 0° with 22.5° intervals.
  - 70dBA playback level.
Listening tests

• Experiment 1 (Loudspeaker playback)
  – 9 experienced subjects repeated each test twice.
  – The task was to mark down the perceived image position on a horizontal circle on a GUI with markers indicated with 22.5° intervals.
• Experiment 2 (Binaural playback)

  – The same room, subjects, task and method as Experiment 1.

  – Equalised Sennheiser HD650 headphones were used.

  – Loudness matched to the playback levels of multichannel stimuli.
Results – Loudspeaker experiment

• **0° source position**
  - **0° and 180° target**: accurate for all arrays.
  - **45° target**: statistically accurate for 50, 30 and 24cm, but not for 0cm (Wilcoxon tests).
  - **90° target**: front-back confusion (cone-of-confusion) in general.
  - **135° target**: significantly bimodal for 0 and 30cm.
Results – Loudspeaker experiment

- **45° source position**
  - **0° target**: accurate for all arrays.
  - **45° target**: accurate only for 50cm.
  - **90° target**: accurate except for 0cm (sig. bimodal).
  - **135° target**: accurate except for 0cm (MED = 152°).
  - **180° target**: accurate only for 50cm.
Results – Binaural experiment

- **0° source position**
  - **0° target**: significant bimodality for all arrays.
  - **45° target**: significant bimodality for 50cm.
  - **90° target**: significant bimodality except for 50cm.
  - **135° target**: significantly bimodal for all arrays.
  - **180° target**: accurate except for 30cm.
Results – Binaural experiment

- **45° source position**
  - **0° target**: bimodal (50cm & 30cm); inaccurate (24cm & 0cm).
  - **45° target**: accurate for 50 and 24cm. MED = 27° for 0cm.
  - **90° target**: significant bimodality for 0cm.
  - **135° target**: accurate only for 50cm.
  - **180° target**: accurate only for 50cm and 24cm.
Results – Real source

- **Loudspeaker**
  - Loudspeaker: accurate for all source angles.

- **Binaural**
  - Binaural responses are generally more spread than loudspeaker ones.
    - 0°: significantly bimodal.
    - 45°: inaccurate, MED = 52°.
    - 90°, 135°: accurate.
    - 180°: inaccurate, bimodal.
Discussion

• Microphone spacing effect

  – 0cm had the worst localisation performance overall.
    • Significant bimodal distributions for many target angle conditions.
    • Perceived to be significantly narrower for the 45° source in both loudspeaker (MED = 30°) and binarual (MED = 27°).

  – 50cm was the only spacing that achieved the SRA of ±45°.
    • Seems to validate the new psychoacoustic model.

  – 50cm had slightly better consistency and accuracy than the other configurations overall.
    • But a smaller size might be more beneficial in practical situations.
    • Practical importance of localisation accuracy in VR?
Discussion

• Source angle effect

  – The 0° source produced larger response spreads and more bimodal distributions than the 45°.
    • Front-back confusion (Cone of confusion), especially for the 90° target angle.
    • Lateral phantom image localisation is highly unstable (Theile and Plenge 1977, Martin et al 1999).
Discussion

• Loudspeaker vs. Binaural

  – Front-back confusion was more frequently observed in the binaural presentation, but not in the loudspeaker one.
  – The binaural presentation had more spread responses.
  – Real source results also show similar tendencies for the 0° and 45°.

  – Might be due to the use of non-individualised HRTF, rather than the microphone arrays.
  – But more about the lack of head movement?
    • FB confusion can occur even with individualised HRTF when head rotation is not allowed (Wightman and Kistler 1999).
  – The FB confusion problem might be largely resolved in practical VR applications with head tracking.
Discussion

- Higher Order ESMA
  - For an octagonal setup, each segment should have the SRA of 45° (±22.5°).
  - Can potentially solve the problem of unstable side image localisation.
  - Mic spacing $d$
    - *Williams*: 82cm
    - *Lee*: 55cm
Discussion

• Adding vertical dimension to ESMA
  – Cardioid + Figure-of-eight in a vertically coincident fashion.
    • Vertical Mid-Side decoding.
    • Vertical microphone spacing has little effect on LEV (Lee and Gribben JAES 2014).
    • Vertical level panning can provide source imaging with a limited resolution (Barbour 2003, Mironovs and Lee 2016).
    • Vertical time panning is highly unstable (Wallis and Lee JAES 2015).
Conclusions

• ESMAs had a better localisation accuracy than FOA.

• 50cm spacing had the best localisation accuracy, but 30cm or 24cm might still be acceptable.

• Front-Back confusion in binaural reproduction without head rotation.

• Ongoing works
  – Investigations on different attributes.
  – Externalisation, tonal quality, spaciousness, naturalness, etc.
  – Practical evaluations with head tracking.
Thank you for listening.

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