A Performance Ranking of Seven Different Types of Loudspeaker Line Arrays

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(AES Paper Given Nov. 2010)
Overview

• Introduction
  • Arrays Analyzed
  • Arrays Not Analyzed
  • Performance Parameters Evaluated
  • Array Simulation Conditions
  • Performance Ranking

• Analysis

• Analysis Results and Ranking

• Summary
Arrays Analyzed

1. An un-shaded straight-line array
2. A Hann-shaded straight-line array
3. An un-shaded “J”-line array with straight top half and circular-arc bottom half
4. An un-shaded spiral- or progressive-line array
5. An un-shaded circular-arc array
6. A Legendre-shaded circular-arc CBT array
7. A Legendre-shaded delay-curved straight-line CBT array
Arrays Not Analyzed!

- Any array that requires complex DSP frequency-dependent processing.

- Other potentially complicated constant beamwidth designs such as:
  - Arrays that maintain a constant acoustic aperture size in wavelengths.
  - Horbach-Keele pair-wise symmetric multi-way crossover-based designs.
  - Etc.
Caution! Disclaimer!

- Take what you are going to hear in the following presentation with a grain of salt!
- CBT = Constant Beamwidth Transducer
- The CBT technology was first described by the U.S. Military in a series of JASA papers describing simple spherical-cap underwater transducers that provide wide-band extremely constant beamwidth and directivity behavior with virtually no side lobes.
- I was the first to apply the CBT concept to loudspeakers.

**Therefore, I’m biased!!!**
Array Depictions

![Diagram showing various array configurations with dB levels](image)
Array Depictions
Array Depictions

The diagram compares the performance of different line array configurations, including straight-line arrays, spiral-line arrays, and circular-arc line arrays, with and without shading. The graphs illustrate the level in dB at various positions 2 meters away from the arrays.

- **Straight-Line Array**
  - No Shading: Consistent level across 0 dB.
  - Hann Shading: Decrease in level from 0 dB to -17 dB at the edges.

- **Spiral-Line Array**
  - No Shading: Level remains at 0 dB across.

- **Circular-Arc Line Array**
  - Legendre Shading: Levels vary from -15 dB to -1 dB at the edges.

The graphs indicate improvements in coverage and sound quality with the use of shading, particularly for the spiral-line and circular-arc arrays.
Array Depictions

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Array Depictions

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Array Depictions

- Straight-Line Array
  - No Shading
  - Hann Shading
- "J"-Line Array
  - No Shading
- Spiral-Line Array
  - No Shading
- Circular-Arc Line Array
  - No Shading
  - Legendre Shading

2 m
Performance Parameters Evaluated

- Beamwidth uniformity
- Directivity uniformity
- Vertical sound-field uniformity
- Polar side lobe suppression
- Uniformity of polar response
- Smoothness and flatness of off-axis frequency response
- Sound pressure rolloff versus distance, and
- Near-far polar pattern uniformity.
Array Simulation Conditions

- All modeled arrays were 2m high and composed of 100 equal-spaced point sources.
- Each of the circular-arc arrays were 60°.
- No complicated signal processing was permitted except for frequency-independent inter-element shading and delay, plus in-line equalization to flatten the frequency response at a specific location.
- All data was calculated at one-third-octave intervals over the range of 20 Hz to 20 kHz.
Array Rotation Point for Polars

- Most arrays were rotated around the front center of the array.

- The circular-arc arrays were rotated around the arc’s center of curvature.
Performance Ranking

- The eight performance parameters were simulated for each array type and then *subjectively* (by me!) scored on a scale from 1 to 10 with 10 highest.
- The subjective score of the eight parameters was then used to rank each array with respect to each other for each parameter.
- The final array ranking was calculated by adding up the individual performance parameter scores for each array in a table which then determined the final ranking.
Analysis: Beamwidth Uniformity

Ideal Beamwidth

![Beamwidth Uniformity Graph]

- Frequency (Hz)
- Beamwidth (°)
- Horizontal and Vertical Comparisons
Analysis: Beamwidth Uniformity

Un-Shaded Straight-Line Array

Shaded Straight-Line Array

Un-Shaded “J”-Line Array

Un-Shaded Spiral-Line Array

Un-Shaded Circular-Arc Line Array

Shaded Circular-Arc CBT Line Array

Shaded Delay-Curved CBT Straight-Line array

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Analysis: Beamwidth Uniformity

- Un-shaded straight-line array
Analysis: Beamwidth Uniformity

- Hann-shaded straight-line array
Analysis: Beamwidth Uniformity

- Un-shaded “J”-line array
Analysis: Beamwidth Uniformity

- Un-shaded spiral- or progressive-line array
Analysis: Beamwidth Uniformity

- Un-shaded circular-arc array
Analysis: Beamwidth Uniformity

- Legendre-shaded CBT circular-arc array
Analysis: Beamwidth Uniformity

- Legendre-shaded delay-curved CBT straight-line array
Beamwidth Ranking

Un-Shaded Straight-Line Array
Shaded Straight-Line Array
Un-Shaded “J”-Line Array

Un-Shaded Spiral-Line Array

Un-Shaded Circular-Arc Line Array

Shaded Circular-Arc CBT Line Array

Shaded Delay-Curved CBT Straight-Line array

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Analysis: Directivity Uniformity

Ideal Directivity

![Graph showing Directivity Index and Q vs Frequency in dB and Q Scale.]

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Analysis: Directivity Uniformity

Un-Shaded Straight-Line Array

Shaded Straight-Line Array

Un-Shaded “J”-Line Array

Un-Shaded Spiral-Line Array

Un-Shaded Circular-Arc Line Array

Shaded Circular-Arc CBT Line Array

Shaded Delay-Curved CBT Straight-Line array

Nov. 4, 2010 AES San Francisco  Keele - Ranking of Loudspeaker Line Arrays
Analysis: Directivity Uniformity

- Un-shaded straight-line array
Analysis: Directivity Uniformity

- Hann-shaded straight-line array
Analysis: Directivity Uniformity

- Un-shaded “J”-line array
Analysis: Directivity Uniformity

- Un-shaded spiral- or progressive-line array
Analysis: Directivity Uniformity

- Un-shaded circular-arc array
Analysis: Directivity Uniformity

- Legendre-shaded CBT circular-arc array
Analysis: Directivity Uniformity

- Legendre-shaded delay-curved CBT straight-line array
Directivity Ranking

Un-Shaded Straight-Line Array

Shaded Straight-Line Array

Un-Shaded “J”-Line Array

Un-Shaded Spiral-Line Array

Un-Shaded Circular-Arc Line Array

Shaded Circular-Arc CBT Line Array

Shaded Delay-Curved CBT Straight-Line array

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Analysis: Sound-Field Uniformity with Frequency

Ideal Vertical Sound-Field

Nov. 4, 2010 AES San Francisco  Keele - Ranking of Loudspeaker Line Arrays
Analysis: Sound-Field Uniformity

Ideal Vertical Sound-Field

- Stays the same with frequency!
- Stays the same with distance!
- No near-field chaos or disorder!
- No Lobes!
Analysis: Sound-Field Uniformity

Un-Shaded Straight-Line Array

Shaded Straight-Line Array

Un-Shaded “J”-Line Array

Un-Shaded Spiral-Line Array

Un-Shaded Circular-Arc Line Array

Shaded Circular-Arc CBT Line Array

Shaded Delay-Curved CBT Straight-Line array

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Analysis: Sound-Field Uniformity

- Un-shaded straight-line array
  - Mid Frequencies (1 kHz)
  - High Frequencies (8 kHz)
Analysis: Sound-Field Uniformity

- Hann-shaded straight-line array

Mid Frequencies (1 kHz)  
High Frequencies (8 kHz)
Analysis: Sound-Field Uniformity

- Un-shaded “J”-line array
  
  Mid Frequencies (1 kHz)
  
  High Frequencies (8 kHz)

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Analysis: Sound-Field Uniformity

- Un-shaded spiral- or progressive-line array

Mid Frequencies (1 kHz)  High Frequencies (8 kHz)
Analysis: Sound-Field Uniformity

- Un-shaded circular-arc array

Mid Frequencies (1 kHz)

High Frequencies (8 kHz)
Analysis: Sound-Field Uniformity

- Un-shaded circular-arc array

Mid Frequencies (1 kHz)

High Frequencies (8 kHz)

Note near-field chaos!
Analysis: Sound-Field Uniformity

- Un-shaded circular-arc array

Mid Frequencies (1 kHz) vs. High Frequencies (8 kHz)
Analysis: Sound-Field Uniformity

- Legendre-shaded CBT circular-arc array

Mid Frequencies (1 kHz)

High Frequencies (8 kHz)

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Analysis: Sound-Field Uniformity

- Legendre-shaded delay-curved CBT straight-line array

Mid Frequencies (1 kHz)  High Frequencies (8 kHz)

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Analysis: Sound-Field Ranking

Un-Shaded Straight-Line Array

Shaded Straight-Line Array

Un-Shaded “J”-Line Array

Un-Shaded Spiral-Line Array

Un-Shaded Circular-Arc Line Array

Shaded Circular-Arc CBT Line Array

Shaded Delay-Curved CBT Straight-Line array

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Analysis: Sound-Field Uniformity

- Note: The appendix of my paper has a complete set of octave sound-fields for each array from 125 Hz to 16 kHz!
Analysis: Polar Side-Lobe Suppression

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Analysis: Polar Side-Lobe Suppression

Bad!

Good!

Nov. 4, 2010 AES San Francisco    Keele - Ranking of Loudspeaker Line Arrays
Analysis: Polar Side-Lobe Suppression

Un-Shaded Straight-Line Array  Shaded Straight-Line Array  Un-Shaded “J”-Line Array

Un-Shaded Spiral-Line Array

Un-Shaded Circular-Arc Line Array  Shaded Circular-Arc CBT Line Array  Shaded Delay-Curved CBT Straight-Line array

Nov. 4, 2010 AES San Francisco  Keele - Ranking of Loudspeaker Line Arrays
Analysis: Polar Side-Lobe Suppression

- Un-shaded straight-line array
  - Mid Frequencies (1 kHz)
  - High Frequencies (8 kHz)
Analysis: Polar Side-Lobe Suppression

- **Hann-shaded straight-line array**
  - Mid Frequencies (1 kHz)
  - High Frequencies (8 kHz)
Analysis: Polar Side-Lobe Suppression

- Un-shaded “J”-line array
  - Mid Frequencies (1 kHz)
  - High Frequencies (8 kHz)
Analysis: Polar Side-Lobe Suppression

- Un-shaded spiral- or progressive-line array
  - Mid Frequencies (1 kHz)
  - High Frequencies (8 kHz)
Analysis: Polar Side-Lobe Suppression

- Un-shaded circular-arc array
- Mid Frequencies (1 kHz)
- High Frequencies (8 kHz)
Analysis: Polar Side-Lobe Suppression

- Legendre-shaded CBT circular-arc array
  - Mid Frequencies (1 kHz)
  - High Frequencies (8 kHz)
Analysis: Polar Side-Lobe Suppression

- Legendre-shaded delay-curved CBT straight-line array
- Mid Frequencies (1 kHz)
- High Frequencies (8 kHz)
Analysis: Side-Lobe Supp. Ranking

Un-Shaded Straight-Line Array

Shaded Straight-Line Array

Un-Shaded “J”-Line Array

Un-Shaded Spiral-Line Array

Un-Shaded Circular-Arc Line Array

Shaded Circular-Arc CBT Line Array

Shaded Delay-Curved CBT Straight-Line Array

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Analysis: Uniformity of Vertical Polar Response with Frequency

250 Hz  500 Hz  1 kHz  2 kHz  4 kHz  8 kHz

250 Hz  500 Hz  1 kHz  2 kHz  4 kHz  8 kHz
Analysis: Uniformity of Vertical Polar Response with Frequency

250 Hz  500 Hz  1 kHz  2 kHz  4 kHz  8 kHz

Bad! ➔

250 Hz  500 Hz  1 kHz  2 kHz  4 kHz  8 kHz

Good! ➔
Analysis: Uniformity of Polar Response with Frequency Ranking

Un-Shaded Straight-Line Array

Shaded Straight-Line Array

Un-Shaded “J”-Line Array

Un-Shaded Spiral-Line Array

Un-Shaded Circular-Arc Line Array

Shaded Circular-Arc CBT Line Array

Shaded Delay-Curved CBT Straight-Line Array

Nov. 4, 2010 AES San Francisco  Keele - Ranking of Loudspeaker Line Arrays
Note: The appendix of my paper has a complete set of octave polars for each array from 125 Hz to 16 kHz!
Analysis: Smoothness and Flatness of Off-Axis Response

Ideally, the off-axis frequency response should be well-behaved, smooth and flat, and be independent of distance. In order to assess this, the off-axis frequency response of the arrays was simulated at two distances of 3 m and 18 m. Frequency responses were simulated at six on- and off-axis angles from 0° to 30°, with a step of 6°, with the on-axis response equalized flat.
Analysis: Smoothness and Flatness of Off-Axis Response

Un-Shaded Straight-Line Array

Shaded Straight-Line Array

Un-Shaded “J”-Line Array

Un-Shaded Spiral-Line Array

Un-Shaded Circular-Arc Line Array

Shaded Circular-Arc CBT Line Array

Shaded Delay-Curved CBT Straight-Line array

Nov. 4, 2010 AES San Francisco  Keele - Ranking of Loudspeaker Line Arrays
Analysis: Smoothness and Flatness of Off-Axis Response

- Un-shaded straight-line array
  - 3 m
  - 18 m
Analysis: Smoothness and Flatness of Off-Axis Response

- Hann-shaded straight-line array
  - 3 m
  - 18 m

Frequency Response vs. Angle at a Distance of 3 m

Frequency Response vs. Angle at a Distance of 18 m
Analysis: Smoothness and Flatness of Off-Axis Response

- Un-shaded “J”-line array
  - 3 m
  - 18 m
Analysis: Smoothness and Flatness of Off-Axis Response

- Un-shaded spiral- or progressive-line array
  - 3 m
  - 18 m

[Graphs showing frequency response vs. angle at distances of 3 m and 18 m]
Analysis: Smoothness and Flatness of Off-Axis Response

- Un-shaded circular-arc array

3 m 18 m
Analysis: Smoothness and Flatness of Off-Axis Response

- Legendre-shaded CBT circular-arc array

3 m

18 m
Analysis: Smoothness and Flatness of Off-Axis Response

- Legendre-shaded delay-curved CBT straight-line array

3 m

18 m
Analysis: Smoothness and Flatness of Off-Axis Response Ranking

Un-Shaded Straight-Line Array

Shaded Straight-Line Array

Un-Shaded “J”-Line Array

Un-Shaded Spiral-Line Array

Un-Shaded Circular-Arc Line Array

Shaded Circular-Arc CBT Line Array

Shaded Delay-Curved CBT Straight-Line array

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Analysis: Sound Pressure Level vs. Distance

The sound pressure level (SPL) versus distance of the arrays was evaluated at octave frequencies of 62.5 Hz to 8 kHz. The SPL vs. distance was evaluated at two different array launch heights: a) the center of the array and b) the top of the array.
SPL Launch Points and Trajectories

Draw Away Lines:

- **Straight-Line Array**: Top → Center
- **Curved-Arc Line Array**: Top → Center
- **Spiral Line Array**: Top → Center
Analysis: SPL vs. Distance

Un-Shaded Straight-Line Array  Shaded Straight-Line Array  Un-Shaded “J”-Line Array

Un-Shaded Spiral-Line Array

Un-Shaded Circular-Arc Line Array  Shaded Circular-Arc CBT Line Array  Shaded Delay-Curved CBT Straight-Line array

Nov. 4, 2010 AES San Francisco  Keele - Ranking of Loudspeaker Line Arrays
Analysis: SPL vs. Distance

- Un-shaded straight-line array

From Center

From Top
Analysis: SPL vs. Distance

- Hann-shaded straight-line array

From Center

From Top
Analysis: SPL vs. Distance

- Un-shaded “J”-line array

From Center

From Top
Analysis: SPL vs. Distance

- Un-shaded spiral- or progressive-line array

From Center

From Top
Analysis: SPL vs. Distance

- Un-shaded circular-arc array

From Center

From Top
Analysis: SPL vs. Distance

- Legendre-shaded CBT circular-arc array

From Center

From Top
Analysis: SPL vs. Distance

- Legendre-shaded delay-curved CBT straight-line array

From Center

From Top
Analysis: SPL vs. Distance Ranking

1. Shaded Circular-Arc CBT Line Array
2. Shaded Delay-Curved CBT Straight-Line Array
3. Un-Shaded Circular-Arc Line Array
4. Un-Shaded Spiral-Line Array
5. Un-Shaded “J”-Line Array
6. Shaded Straight-Line Array
7. Un-Shaded Straight-Line Array

Keele - Ranking of Loudspeaker Line Arrays

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Analysis: Near-Far Polar Pattern Uniformity

- The polar pattern of the array was evaluated for its uniformity with distance.
- The following graphs show polar pattern shapes and beamwidth vs. frequency data at three distances from the array: 2 m, 6 m, and 18 m.
- Two sets of polars are shown for the three distances at 800 Hz and 8 kHz.
- This information yields a reasonable estimate of the changes in the polar patterns with distance.
Analysis: Near-Far Polar Pattern Uniformity

Un-Shaded Straight-Line Array

![Graphs of 800 Hz and 8 kHz for 2 m, 6 m, and 18 m distances]

Shaded Straight-Line Array

![Graphs of 800 Hz and 8 kHz for 2 m, 6 m, and 18 m distances]

Un-Shaded “J”-Line Array

![Graphs of 800 Hz and 8 kHz for 2 m, 6 m, and 18 m distances]

Un-Shaded Spiral-Line Array

![Graphs of 800 Hz and 8 kHz for 2 m, 6 m, and 18 m distances]

Un-Shaded Circular-Arc Line Array

![Graphs of 800 Hz and 8 kHz for 2 m, 6 m, and 18 m distances]

Shaded Circular-Arc CBT Line Array

![Graphs of 800 Hz and 8 kHz for 2 m, 6 m, and 18 m distances]

Shaded Delay-Curved CBT Straight-Line Array

![Graphs of 800 Hz and 8 kHz for 2 m, 6 m, and 18 m distances]
Analysis: Near-Far Polar Pattern Uniformity

- Un-shaded straight-line array

800 Hz:

8 kHz:

Beamwidth:
Analysis: Near-Far Polar Pattern Uniformity

- Hann-shaded straight-line array

- 800 Hz:

- 8 kHz:

- Beamwidth:
Analysis: Near-Far Polar Pattern Uniformity

- Un-shaded “J”-line array

800 Hz:

8 kHz:

Beamwidth:
Analysis: Near-Far Polar Pattern Uniformity

- Un-shaded spiral- or progressive-line array

800 Hz:

8 kHz:

Beamwidth:
Analysis: Near-Far Polar Pattern Uniformity

- Un-shaded circular-arc array

800 Hz:

8 kHz:

Beamwidth:
Analysis: Near-Far Polar Pattern Uniformity

- Legendre-shaded CBT circular-arc array

800 Hz:

8 kHz:

Beamwidth:
Analysis: Near-Far Polar Pattern Uniformity

- Legendre-shaded delay-curved CBT straight-line array

**800 Hz:**

- 2 m
- 6 m
- 18 m

**8 kHz:**

- 2 m
- 6 m
- 18 m

**Beamwidth:**

Nov. 4, 2010 AES San Francisco   Keele - Ranking of Loudspeaker Line Arrays
Analysis: Near-Far Polar Pattern Uniformity Ranking

Un-Shaded Straight-Line Array

Shaded Straight-Line Array

Un-Shaded “J”-Line Array

Un-Shaded Spiral-Line Array

4

Un-Shaded Circular-Arc Line Array

Shaded Circular-Arc CBT Line Array

5

Shaded Delay-Curved CBT Straight-Line array

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# Analysis Results and Final Ranking

## Table: Array Performance Ranking

<table>
<thead>
<tr>
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</thead>
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<tr>
<td>Beamwidth uniformity:</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>9</td>
<td>8</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Directivity uniformity:</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>7</td>
<td>5</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Vertical soundfield uniformity:</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Polar side lobe suppression:</td>
<td>1</td>
<td>9</td>
<td>6</td>
<td>7</td>
<td>7</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Uniformity of polar response:</td>
<td>1</td>
<td>2</td>
<td>5</td>
<td>6</td>
<td>6</td>
<td>10</td>
<td>10</td>
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<tr>
<td>Smoothness and flatness of off-axis frequency response:</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>8</td>
<td>10</td>
<td>9</td>
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<tr>
<td>Sound pressure rolloff versus distance:</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>8</td>
<td>10</td>
<td>9</td>
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<td>Near-field polar pattern uniformity:</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>7</td>
<td>8</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td><strong>TOTALS:</strong></td>
<td><strong>10</strong></td>
<td><strong>23</strong></td>
<td><strong>26</strong></td>
<td><strong>46</strong></td>
<td><strong>54</strong></td>
<td><strong>80</strong></td>
<td><strong>77</strong></td>
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(Scale 8 to 80)
## Analysis Results and Final Ranking

### Table: Array Performance Ranking

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<td>1</td>
<td>4</td>
<td>2</td>
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<td>9</td>
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<td>1</td>
<td>2</td>
<td>4</td>
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<td>8</td>
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<td>Uniformity of polar response:</td>
<td>1</td>
<td>2</td>
<td>5</td>
<td>6</td>
<td>6</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Smoothness and flatness of off-axis frequency response:</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>8</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>Sound pressure rolloff versus distance:</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>8</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>Near-far polar pattern uniformity:</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>7</td>
<td>8</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td><strong>TOTALS:</strong></td>
<td><strong>10</strong></td>
<td><strong>23</strong></td>
<td><strong>26</strong></td>
<td><strong>46</strong></td>
<td><strong>54</strong></td>
<td><strong>80</strong></td>
<td><strong>77</strong></td>
</tr>
</tbody>
</table>

(Scale 8 to 80)
Final Ranking (with scores, range 8 -80)

1. CBT circular-arc array: 80
2. CBT delay-curved straight-line array: 77
3. Un-shaded circular-arc array: 54
4. Spiral-line array: 46
5. “J”-line array: 26
6. Straight-line array (Hann shaded): 23
7. Straight-line array (not shaded): 10
Summary

- This paper presented simulated performance data that allowed several different types of loudspeaker line arrays to be compared and ranked.

- The performance data for all the arrays was subjectively ranked for each performance type on a scale from 1 to 10 and then totaled (scale 8 to 80) for each array, to yield the final array rankings.
Summary, Cont.

• The performance data clearly shows the *superiority of the circular-arc and delay-curved CBT arrays*. All the performance data for these two arrays was extremely uniform and well behaved.

• The Legendre-shaded *circular-arc CBT array is clearly the winner here* because of its uniformity of coverage and the independence of its performance with distance.

• The performance of the *delay-curved straight-line CBT array is also very uniform and well behaved* and nearly matches the performance of the circular-arc CBT array.

• A distant third to the CBT arrays is the spiral-line array with the remaining “J”-line and straight-line arrays holding up the bottom of the rankings.
The End.

Phew, I’m glad that guy stopped talking!!!