

1. INTRODUCTION

Sound Field Reproduction Technique Based on Wavefield Synthesis

- Applications to tele-conference system and tele-ensemble system
- It needs a great number of channel signals.
 - ⇒ **It is very important to evaluate the number of required channel signals.**

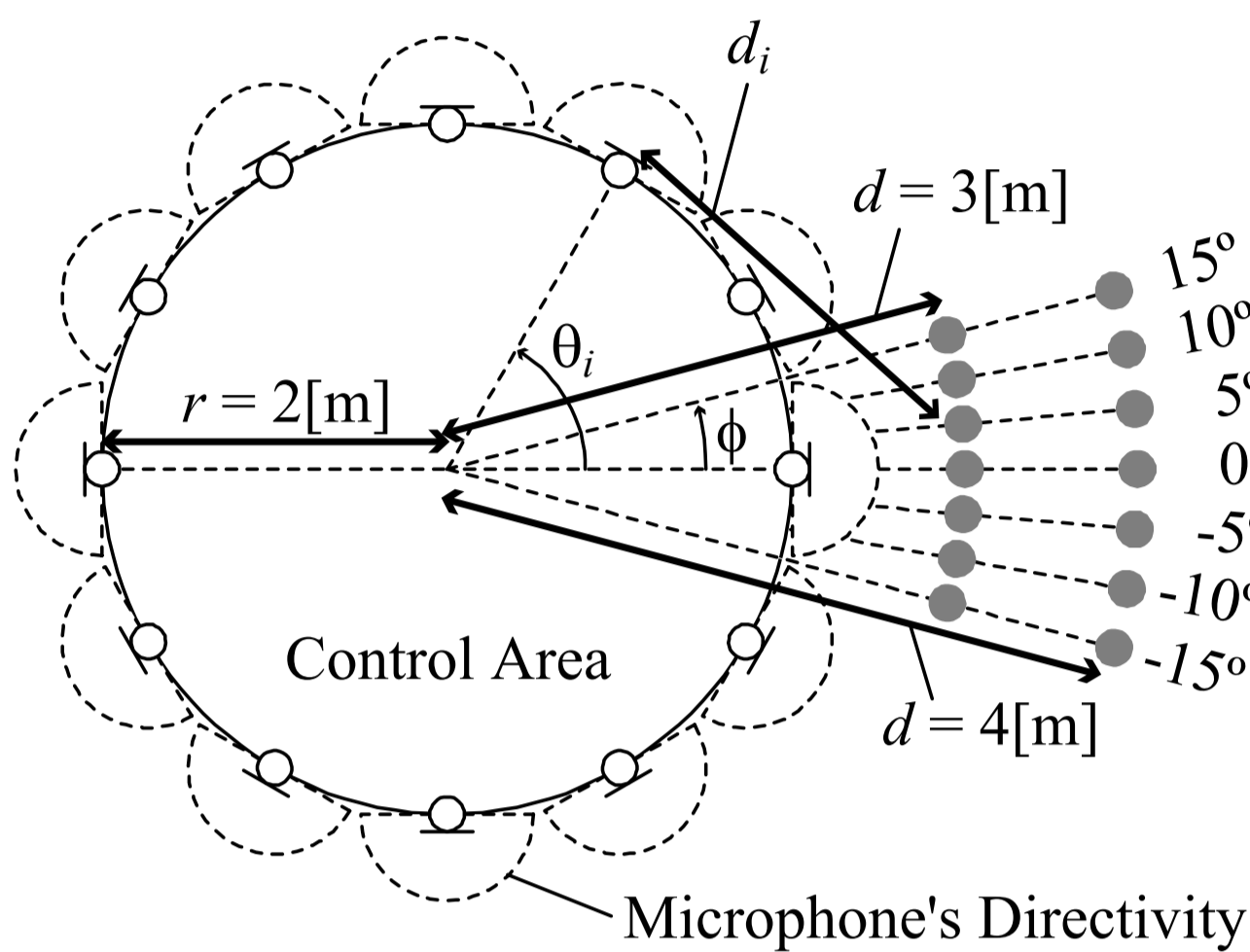
Evaluation of the Number of Required Channel Signals

- Effect on the accuracy of physical wavefronts
 - The threshold level of RMS error is not clear although there have been several studies.
- Effect on sound field perception (direction, distance and spatial impression etc.)
 - There are few studies, so 2 subjective assessments were designed.
 - 2...Subjective assessment for directional perception
 - 3...Subjective assessment for spatial impression

2. SUBJECTIVE ASSESSMENT FOR DIRECTIONAL PERCEPTION

2.1. Synthesis of Multi-channel Audio Signals

- Control area...Circle of radius 2 meters



- d_i : Distance between the sound source and the i th microphone
- $g_i(n)$: Room transfer function from the sound source to the i th microphone

$$d_i = \sqrt{d^2 + r^2 - 2dr \cos(\phi - \theta_i)}$$

$$g_i(n) = \frac{d-r}{d_i} \delta(n - \text{round}\left(\frac{d_i F_s}{c}\right))$$

$F_s (=48[\text{kHz}])$: Sampling frequency
 $c (=340[\text{m/s}])$: Sound velocity

- $s(n)$: Dry source (White noise & Speech, Duration...1 second)
- $x_i(n)$: Channel signal of the i th microphone

$$x_i(n) = D(\theta_i, \phi) \{g_i(n) * s(n)\} = D(\theta_i, \phi) \frac{d-r}{d_i} s(n - \text{round}\left(\frac{d_i F_s}{c}\right))$$

- $D(\theta_i, \phi)$: Directional sensitivity of the i th microphone

$$D(\theta_i, \phi) = \begin{cases} 1 & (\cos(\theta_i - \phi) \geq r/d) \\ 0 & (\cos(\theta_i - \phi) < r/d) \end{cases}$$

2.3. Experimental Design

- Subjects... 8 graduate students (4 males & 4 females)

Subjective Assessment	
Session 1	Session 2
Order...Randomized (White Noise or Speech)	
Session	
Practice (14 trials)	Main (336 trials)
(84)	(84) (84) (84)
Trial (Procedure)	
Stimulus (1sec)	Answer (4sec)

Trial Condition

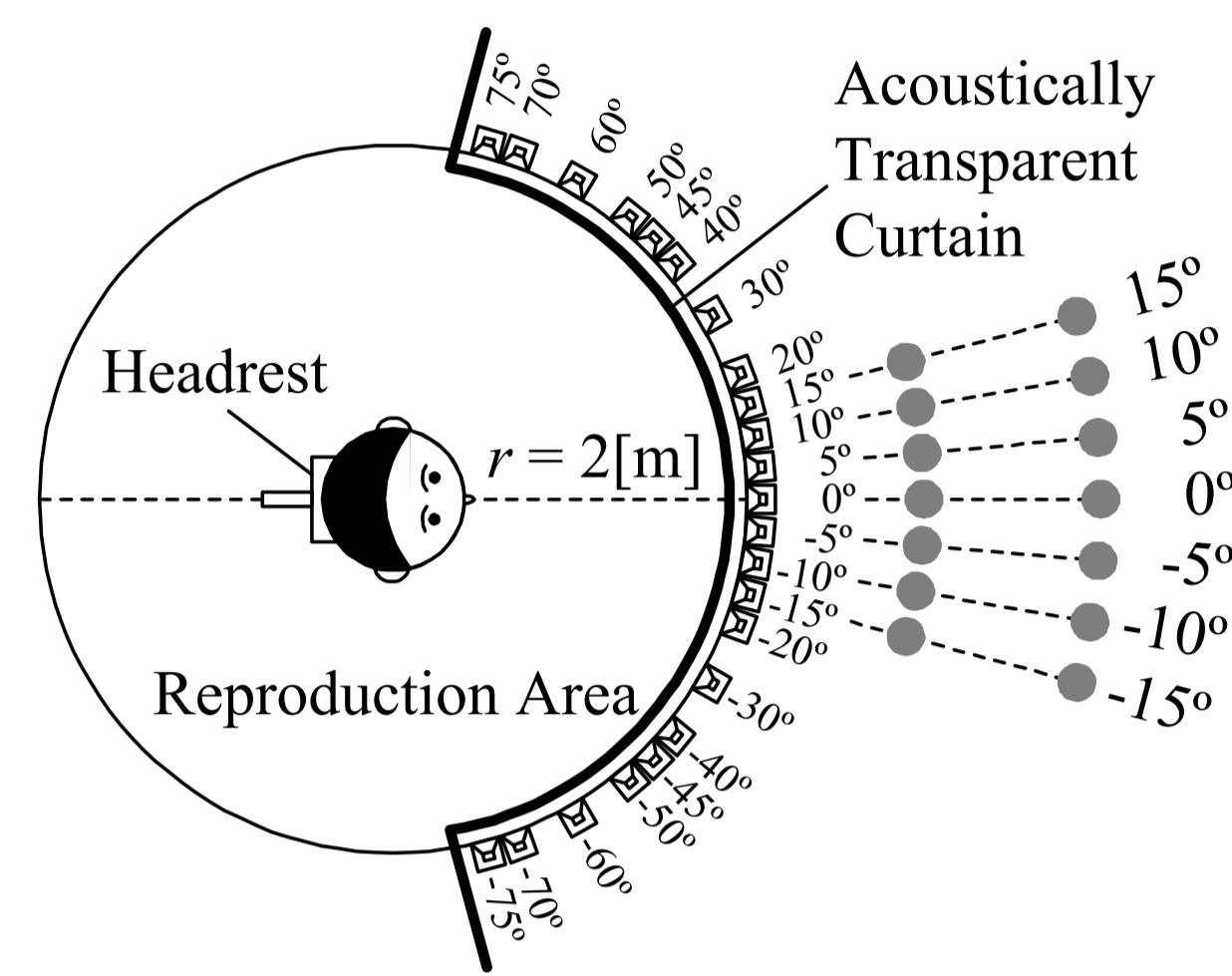
	Level	Parameter / Pattern
Practice (14)	= 1 distance	3m
	× 7 directions	$0^\circ, \pm 5^\circ, \pm 10^\circ, \pm 15^\circ$
Main (336)	× 2 conditions	(a) & (b)
	= 2 distances	3 & 4m
	× 7 directions	$0^\circ, \pm 5^\circ, \pm 10^\circ, \pm 15^\circ$
	× 6 conditions	(a)–(f)
	× 4 repetitions	

Procedure

- The direction of sound is reported.
- Answering scale...placed in front of the subject marked from -25° to 25° at 2.5° intervals

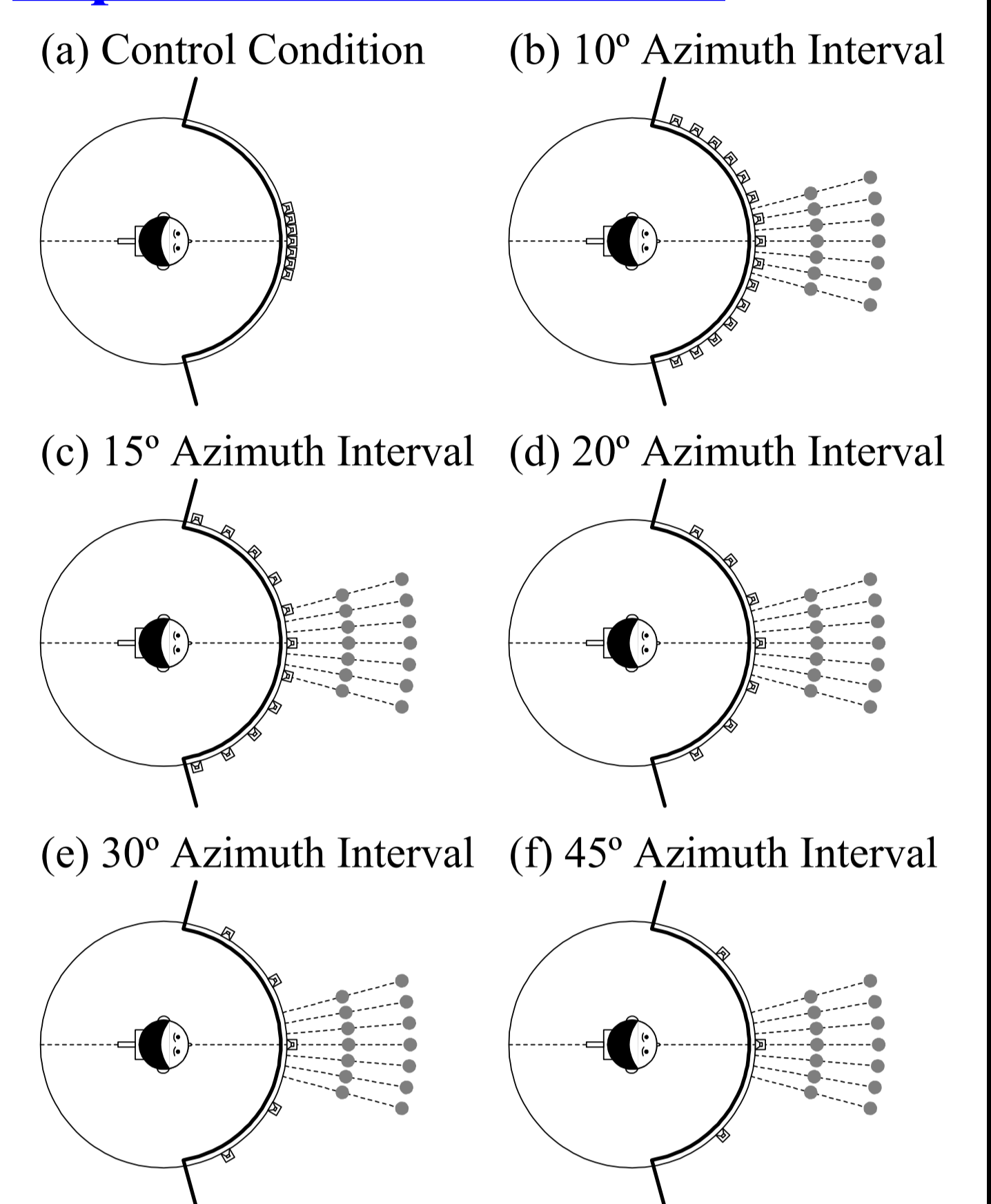
2.2. Experimental Environment

- Reproduction area...Circle of radius 2 meters



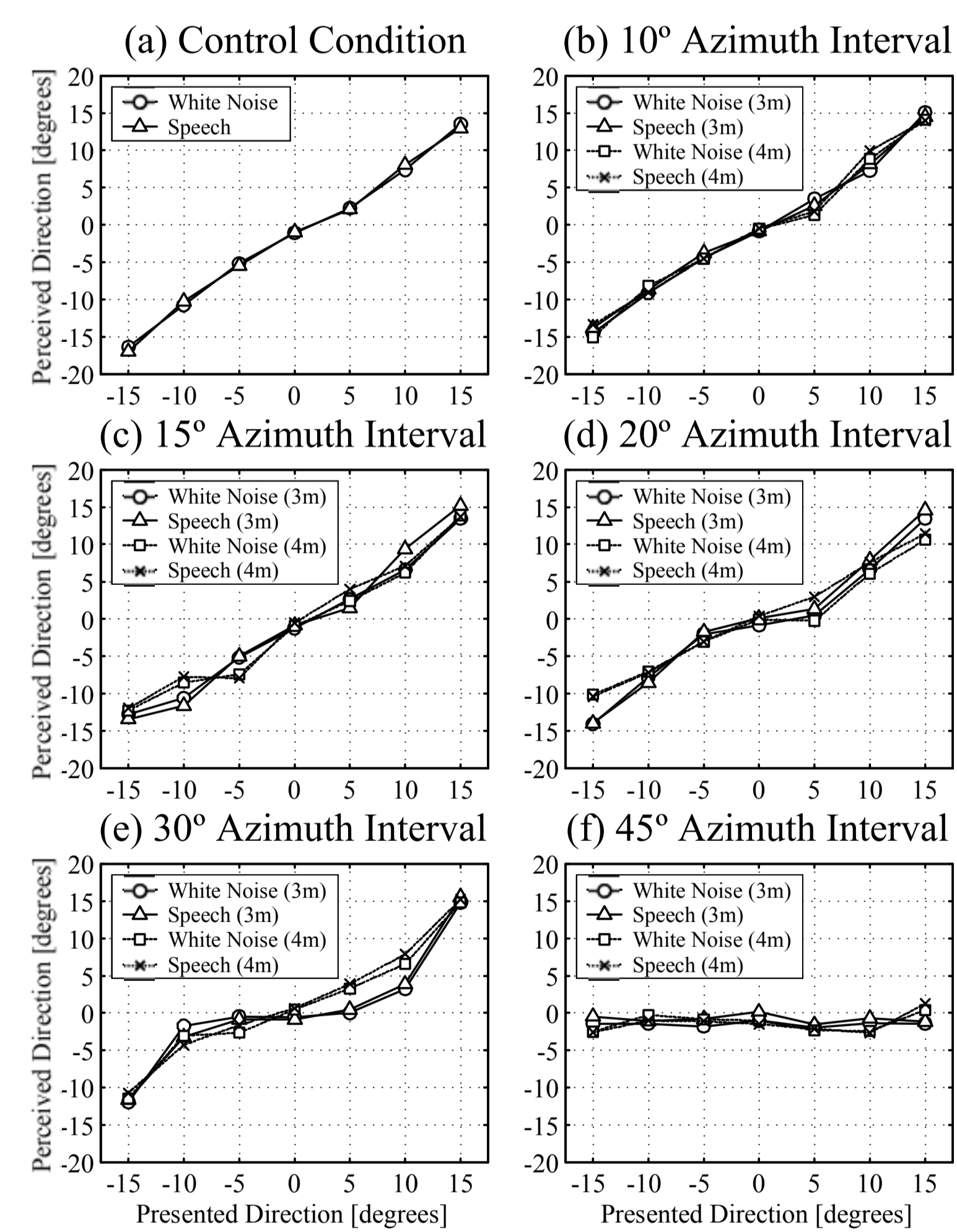
- Room reverberation time...About 80ms
- Room background noise...25.0dB(A)
- Sound pressure level...About 60dB(A)
- Headrest...Subject's head is fixed.
- Acoustical transparent curtain...Subject can't see loudspeakers

Experimental Conditions

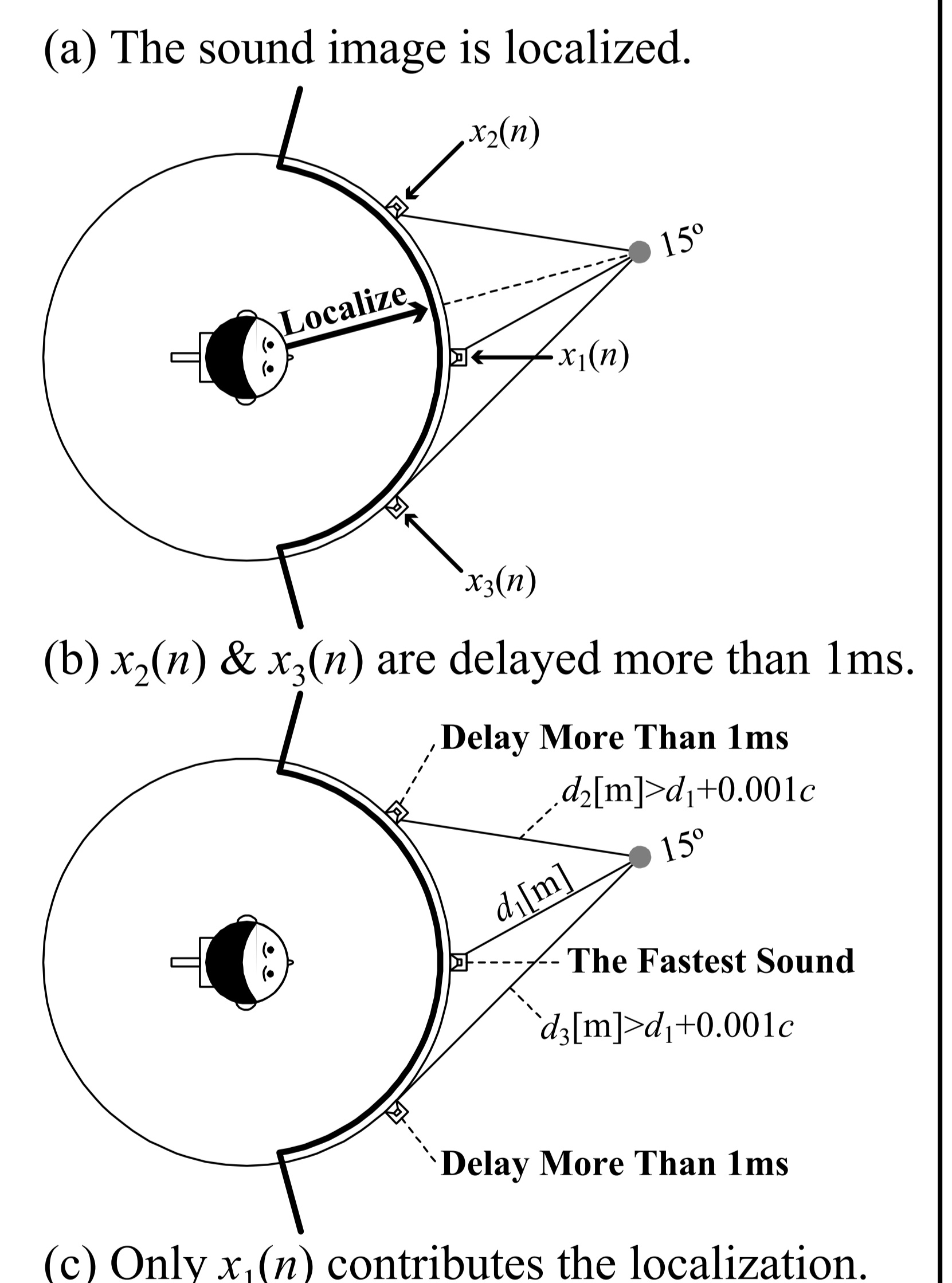


2.4. Results and Discussions

- 10° & 15° azimuth interval...Near to those of the control condition
- $20^\circ, 30^\circ, 45^\circ$ azimuth interval...Biased towards 0° due to the precedence effect
 - ⇒ **Sound images can't be localized at desired directions when the number of channel signals is very few.**



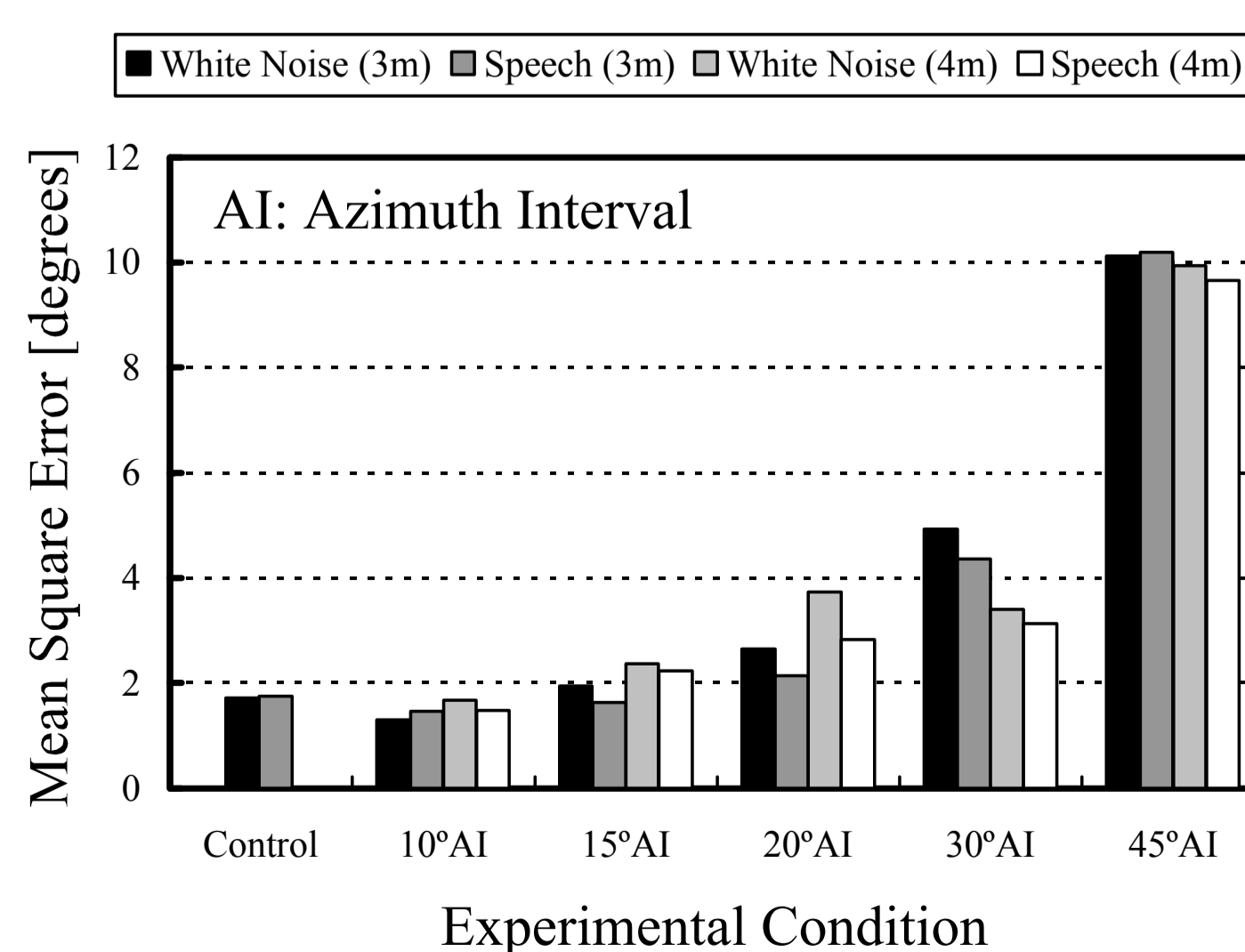
Reason of the bias



Results of Mean Square Errors

$$\text{MSE}[\text{degrees}] = \sqrt{\frac{\sum_{\phi} \{\phi'(\phi) - \phi\}^2}{7}}$$

$\phi'(\phi)$: Perceived direction when presented direction is ϕ

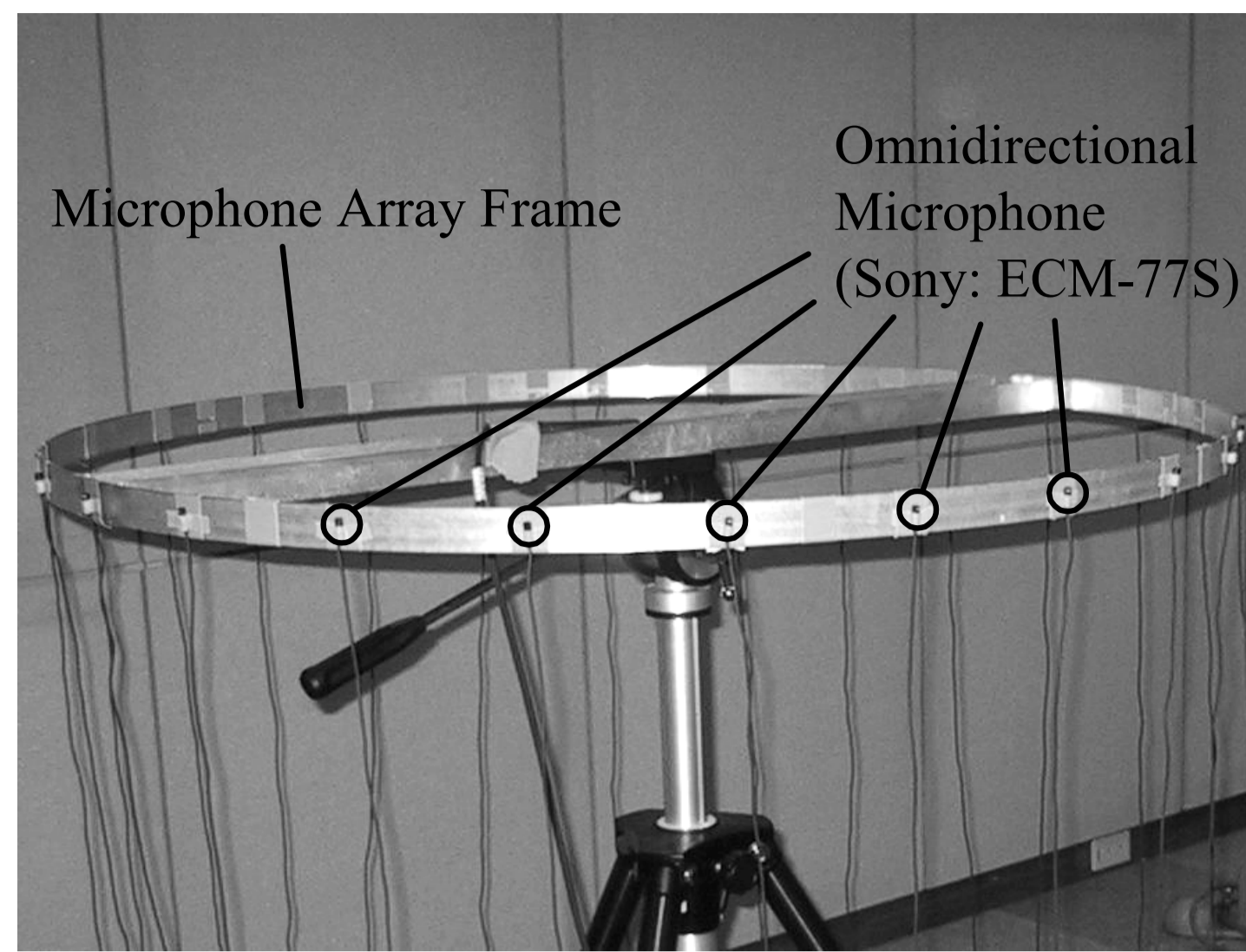
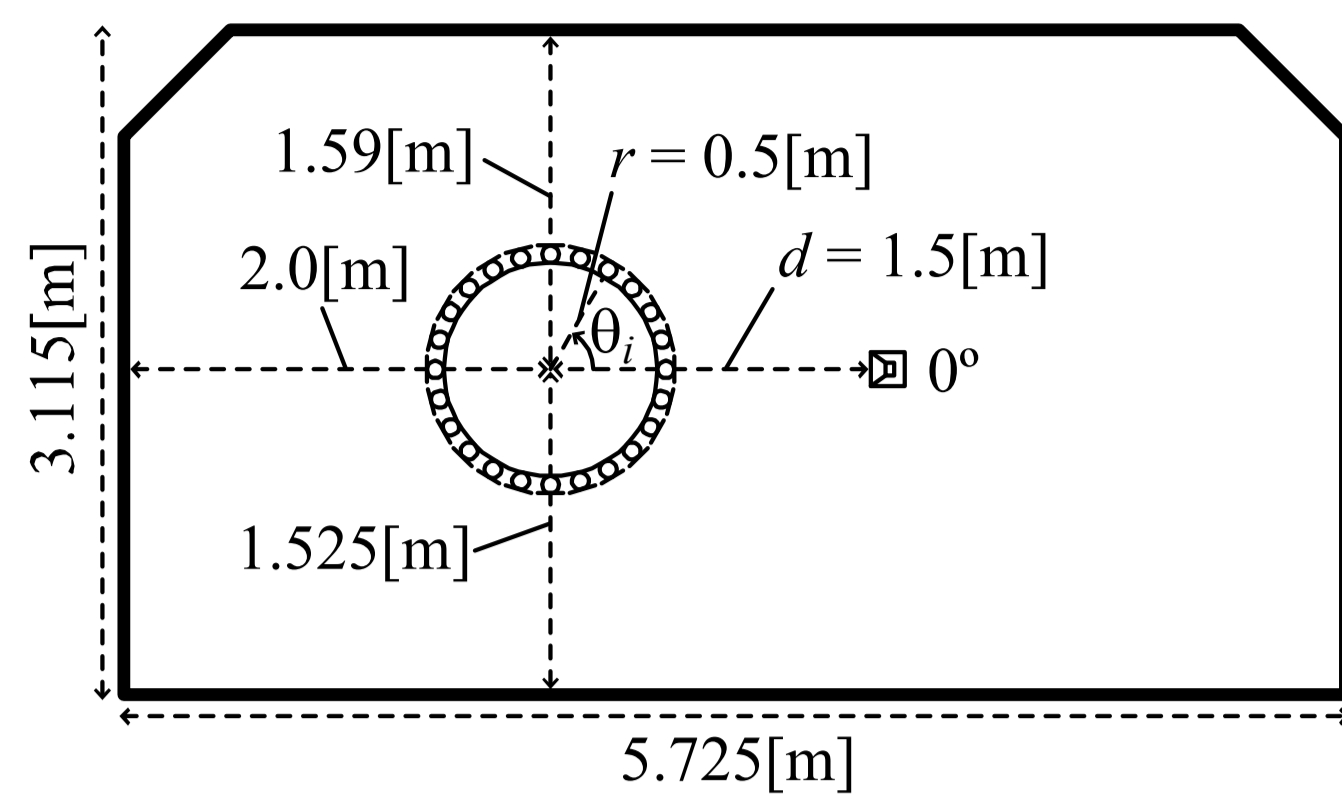


- 10° & 15° azimuth interval...Same as that of the control condition at about 2°
 - ⇒ **The number of required channel signals... 15° azimuth interval (=24)**

3. SUBJECTIVE ASSESSMENT FOR SPATIAL IMPRESSION

3.1. Synthesis of Multi-channel Audio Signals

Measurement of Room Transfer Functions



Measurement Conditions

Reverberation time	300ms
Room temperature	19.2°C
Background noise level	19.4dB(A)
Reference signal	Time Stretched Pulse
Sampling frequency of TSP signal	48kHz
Duration of TSP signal	65536 points
Sound pressure level of TSP signal	91.6dB(A)
FIR filter order	14400

Convolution of the dry source

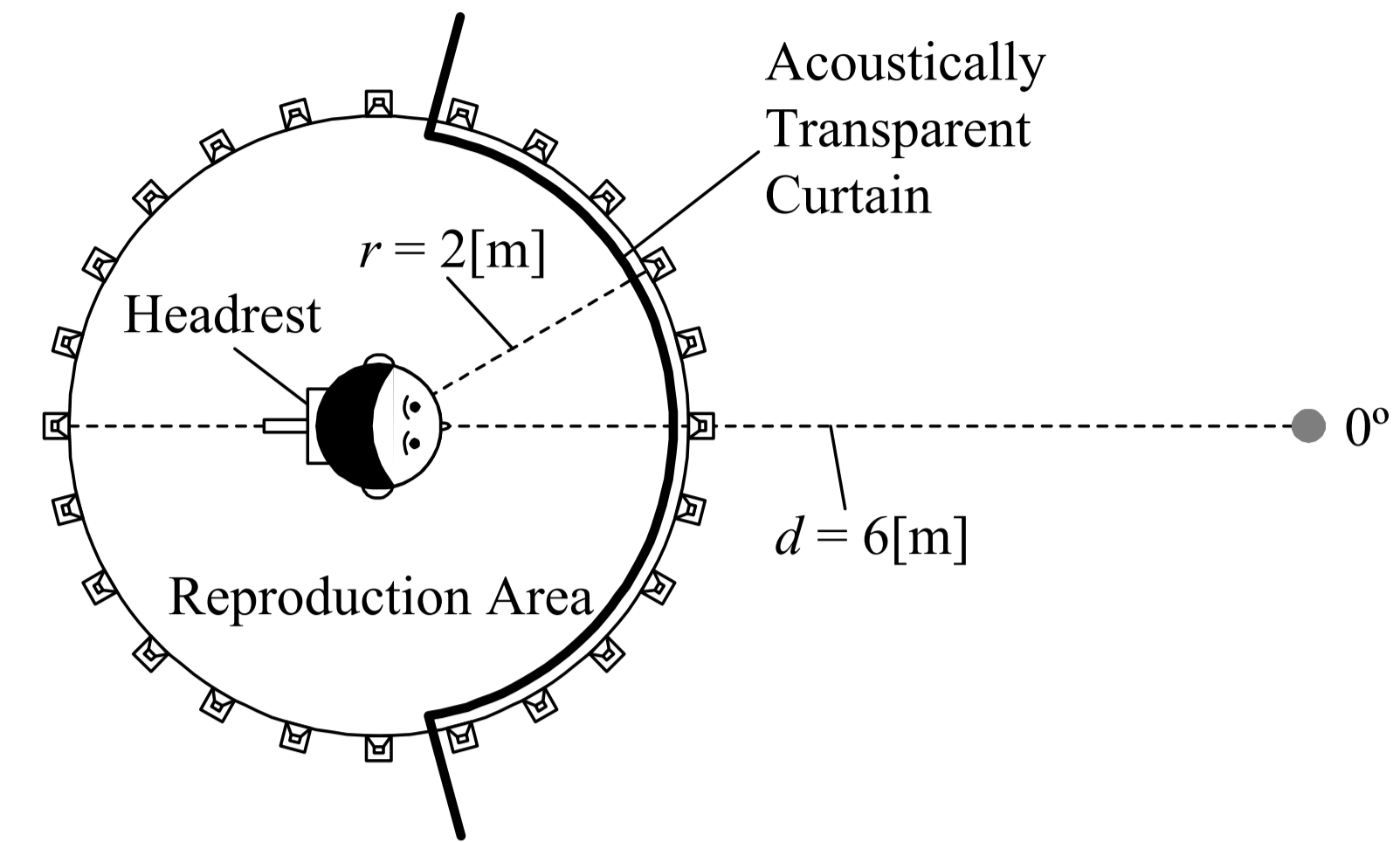
- Reverberation time...300[ms]×4=1.2[s]
- r ...0.5[m]×4=2[m]
- d ...1.5[m]×4=6[m]

Dry Source Conditions

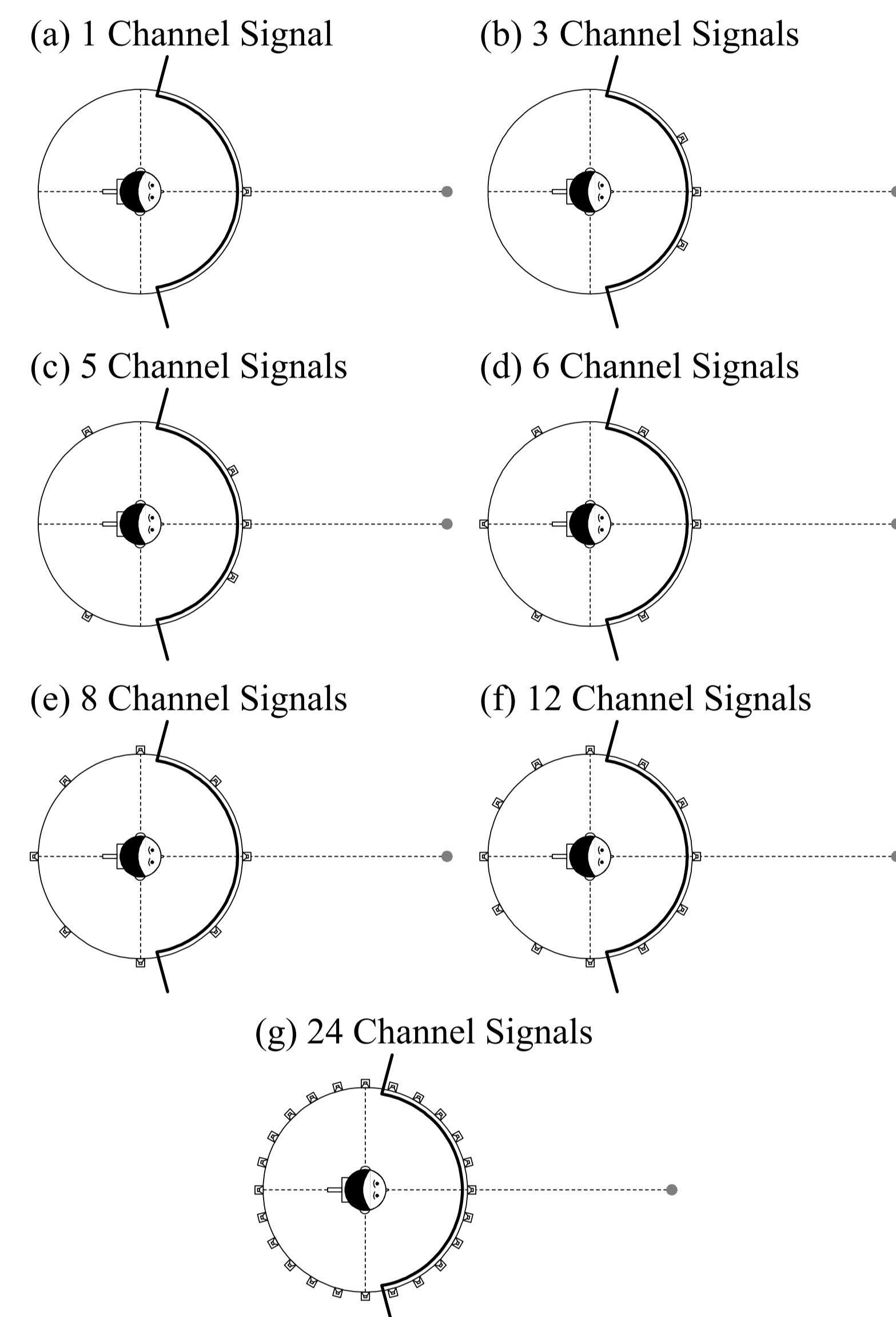
Type	Speech & Flute
Sampling frequency	12kHz
Duration	4 seconds

3.2. Experimental Environment

- Room reverberation time...About 80ms
- Room background noise...25.0dB(A)
- Sound pressure level...About 70dB(A)
- Headrest...Subject's head is fixed.
- Acoustical transparent curtain...Subject can't see loudspeakers



Experimental Conditions



3.3. Experimental Design

- Subjects...8 males
- Method...Scheffé's paired comparison

Procedure

- Grading stimulus B compared with Stimulus A

Subjective Assessment

Auditory Source Width	Listener Envelopment				
Session 1	Session 2				
Order...Randomized (Speech or Flute)					
Practice (6 trials)	Main (42 trials)				
Signal (0.1sec)	Break (0.9sec)	Stimulus A (4sec)	Break (2sec)	Stimulus B (4sec)	Answer (4sec)

Grading Scale

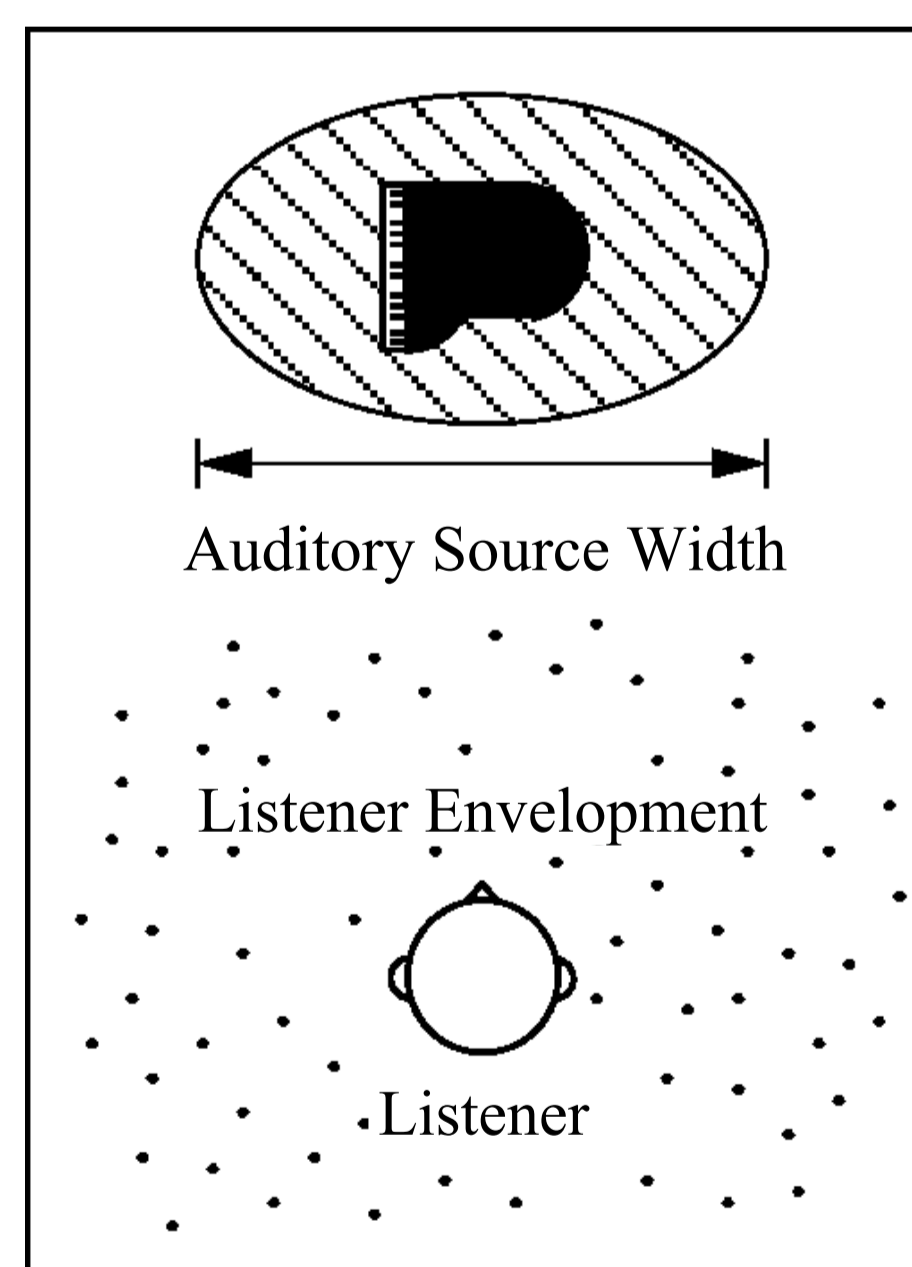
Grade	ASW	LEV
3	Very wide	Very enveloped
2	Fairly wide	Fairly enveloped
1	Little wide	Little enveloped
0	The same	The same
-1	Little narrow	Not little enveloped
-2	Fairly narrow	Not fairly enveloped
-3	Very narrow	Not very enveloped

Combination of Stimuli

- Practice (6 trials)...Permutation of 3 conditions: (a), (b) & (g) (=3×2)
- Main (42 trials)...Permutation of 7 conditions: (a)-(g) (=7×6)

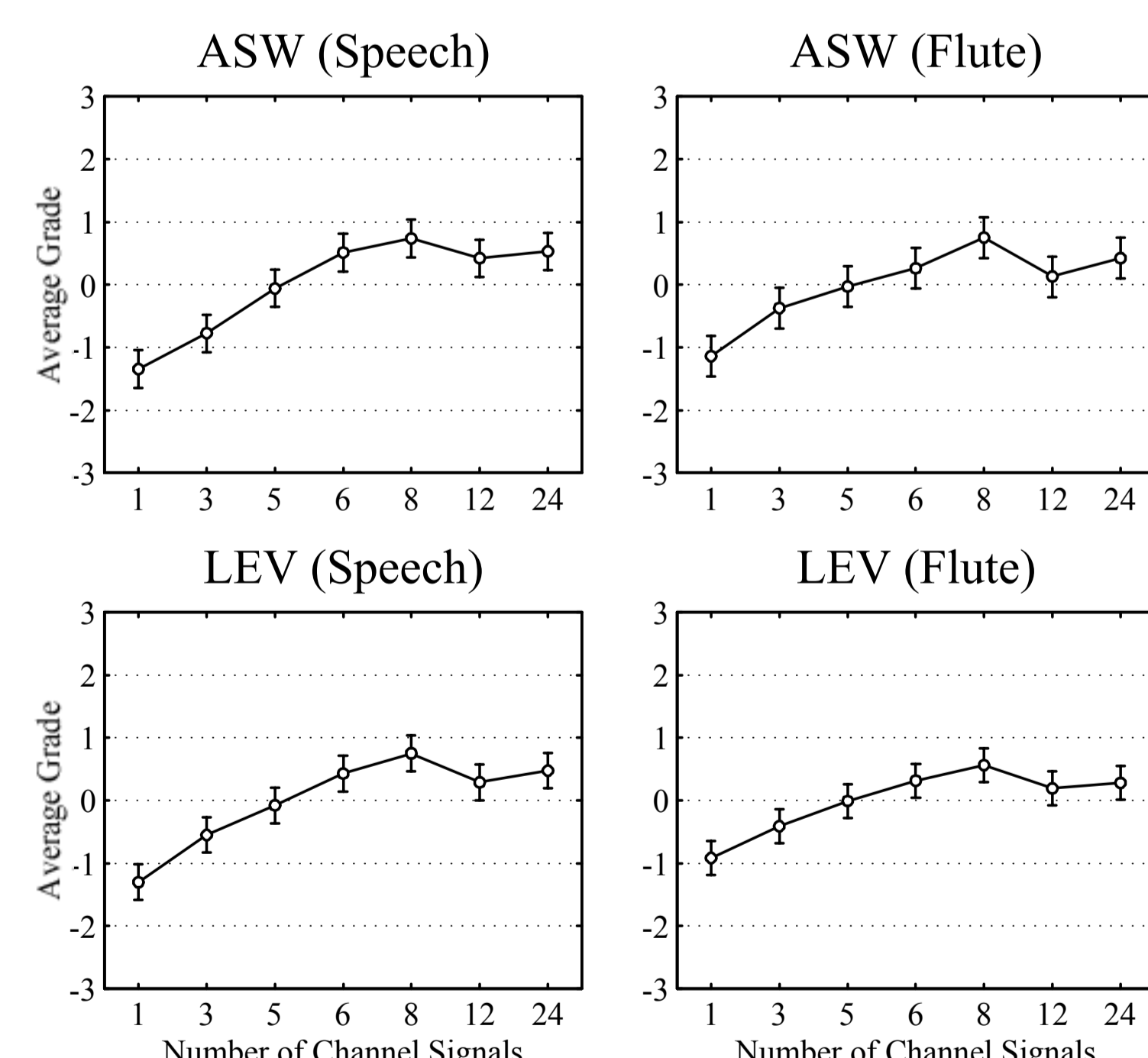
Definition of ASW and LEV (by Morimoto)

- The minimum factors which construct the spatial impression
- Auditory Source Width (ASW)
 - The width of a sound image fused temporally and spatially with the direct sound image
- Listener Envelopment (LEV)
 - The degree of fullness of sound images around the listener, excluding the precedent sound image composing ASW



3.4. Results and Discussions

- Average Grade
 - 1, 3 & 5 channel signals...Significantly lower (5% level) than 24 channel signals
 - 6, 8 & 12 channel signals...Same as 24 channel signals
- ⇒ There is no perceptual difference for the spatial impression when the number of channel signals is ≥ 6 .
- ⇒ **The number of required channel signals...6**



4. CONCLUSION

■ The number of required channel signals

in a sound field reproduction system based on wavefield synthesis

- Evaluation of the effect on directional perception and spatial impression by 2 subjective assessments
 - ◆ Subjective assessment for directional perception...The number of required channel signals is 24.
 - ◆ Subjective assessment for spatial impression...The number of required channel signals is 6.

⇒ 24-channel signals system is enough to realize practical directional perception and spatial impression if control area is limited to a circle of radius 2 meters.