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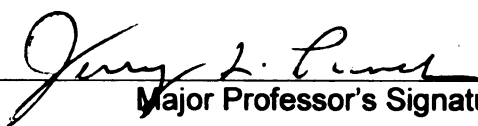
PAIRED-COMPARISON PREFERENCES
FOR POLAR DIRECTIVITY PATTERNS IN
DIFFERENT LISTENING ENVIRONMENTS

presented by

Amy M. Amlani

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of the requirements for the

Ph.D. degree in Audiology and Speech Sciences



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**PAIRED-COMPARISON PREFERENCES FOR POLAR DIRECTIVITY
PATTERNS IN DIFFERENT LISTENING ENVIRONMENTS**

By

Amy M. Amlani

A DISSERTATION

**Submitted to
Michigan State University
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ABSTRACT

PAIRED-COMPARISON PREFERENCES FOR POLAR DIRECTIVITY PATTERNS IN DIFFERENT LISTENING ENVIRONMENTS

By

Amy M. Amlani

Experiment 1 of this investigation was aimed at determining the extent to which listeners prefer different hearing aid microphone response patterns in different listening environments, and whether three groups of listeners differ in such preferences. In Experiment 2, the aim was to determine whether a modified paired-comparison procedure (ABN) improved the sensitivity to listeners' polar-pattern preferences over that of a traditional paired-comparison procedure (AB). A group of normal-hearing listeners and two groups of hearing-impaired listeners participated in both experiments. In Experiment 1, listeners made judgments of speech clarity for an omnidirectional and two directional (cardioid and hypercardioid) hearing aid microphone response patterns using an AB paired-comparison method. The hearing-impaired groups differed only in that one group had had ≥ 1 year of experience with amplification, and the other ≤ 3 months of experience. Each group of listeners made preference judgments of clarity based on speech passages recorded in noise at a fixed signal-to-noise ratio, in a laboratory environment (sound-treated room) and in two rooms (living room and classroom) that simulated real-world communication environments. In the second

experiment, the same three groups made judgments of speech clarity using an ABN method in which listeners were allowed an option of No Preference.

Experiment 1 revealed that all three groups of listeners preferred directional microphones over omnidirectional microphones in all room conditions. In addition, listeners preferred different directional polar patterns across room conditions. This finding suggests that multiple directional polar patterns should be considered during the selection and fitting of hearing aids.

In Experiment 2, a comparison between the AB and ABN methods revealed comparable findings for the two psychophysical procedures, as demonstrated by statistical analyses of the effects of microphone and room across groups, and as measured by the number of preferences. Results for the No-Preference component of ABN revealed relatively few ties between comparisons, suggesting that listeners found the differences between paired conditions to be highly perceptible. Under such conditions, the ABN method demonstrated no substantial functional advantage over the traditional AB paired-comparison procedure.

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In loving memory of my grandparents, Kassam and Dolatkhanu Amlani

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KEY TO ABBREVIATIONS

AB	Two-Alternative, Forced-Choice Task
ABN	Three-Alternative, Forced-Choice Task
AI-DI	Articulation Index-Weighted Directivity Index
ANOVA	Analysis of Variance
BTE	Behind-the-Ear Hearing Aid
CD	Critical Distance
CI ₉₅	95-Percent Confidence Interval
DAT	Digital Audiotape
DF	Directivity Factor
DI	Directivity Index
DMHA	Directional-Microphone Hearing Aid
FBR	Front-to-Back Ratio
HINT	Hearing in Noise Test
HL	Hearing Level
ITE	In-the-Ear Hearing Aid
KEMAR	Knowles Electronics Manikin for Acoustic Research
Leq	Equivalent Sound Level
Lin	Linear (Unweighted) Sound Level
ODHA	Omnidirectional-Microphone Hearing Aid
RMS	Root Mean Square
RSIR	Revised Speech Intelligibility Rating Test
RT	Reverberation Time

SIR	Speech Intelligibility Rating test
SNR	Signal-to-Noise Ratio
SPL	Sound Pressure Level
UI	Unidirectional Index
WDRC	Wide Dynamic Range Compression

CHAPTER 1

INTRODUCTION

The primary objective of any hearing aid selection and fitting procedure is to optimize speech intelligibility in everyday listening conditions. The ability to predict a patient's success or failure with amplification in real-world environments, however, remains elusive (e.g., Cord, Surr, Walden, & Olsen, 2002; Cox & Alexander, 1991; Humes & Hackett, 1990; Keidser, 1996; Leijon, Lindkvist, Ringdahl, & Israelsson, 1990; Punch, Robb, & Shovels, 1994; Sullivan, Levitt, Hwang, & Hennessey, 1988; Walden, Surr, Cord, Edwards, & Olsen, 2000). This shortcoming can be attributed, in part, to the fact that audiologists generally attempt to predict real-world performance based on clinical measures of pure-tone sensitivity and word-recognition scores, and on manufacturer-reported electroacoustic measurements, none of which is obtained in environments typical of everyday listening situations. Manufacturer-reported electroacoustic measures are used primarily for purposes of quality control, and the pertinence of clinical word-recognition testing has recently come under scrutiny (Hall, 2001; Wiley, Stoppenbach, Feldhake, Moss, & Thordardottir, 1995). In addition, empirical evidence has largely failed to demonstrate a strong, predictable relationship between electroacoustic features of hearing aids and behavioral performance (e.g., Fabry & Van Tasell, 1990; Stelmachowicz, Kopun, Mace, Lewis, & Nittrouer, 1995; Van Tasell, Larsen, & Fabry, 1988). As a result, a current need in hearing aid research is "the routine specification of technical

performance in a way that approximates performance as measured on the user” (Beck, 1991, p. 4).

A common complaint of hearing-impaired listeners is the inability to understand speech in the presence of competing noise. Behavioral studies have demonstrated that directional-microphone hearing aids (DMHAs) are a means of improving speech intelligibility in the presence of background noise by attenuating those sounds from the sides and rear of the listener (Preves, 1997; Ricketts & Mueller, 1999a; Valente, 1999, 2000). Laboratory studies have often shown a substantial advantage of directional microphones over omnidirectional microphones. The extent to which this advantage is realized in the real world, however, is less clear. The amount of real-world advantage remains unknown, in part, because listeners have a tendency not to toggle between omnidirectional and directional modes when afforded the opportunity (Cord et al., 2002; Sommers, 1979). Furthermore, empirical evidence indicates that listeners often perceive significant improvement in speech intelligibility for directional microphones over omnidirectional microphones under laboratory conditions, but that they seldom perceive differences between microphones in their daily lives (Cord et al., 2002; Walden et al., 2000).

To date, there is relatively little information in the literature comparing performance for different directional polar patterns in real-world environments. This is especially true with respect to studies of perceived intelligibility of hearing aid-processed stimuli. The potential clinical utility of evaluating the perceived intelligibility of aided speech is evident from previous research suggesting that

perceived intelligibility varies as a function of listening environment (Cox & Alexander, 1991; Punch et al., 1994; Keidser, 1996; Ricketts & Dhar, 1999). One purpose of this study, therefore, was to determine, based on judgments of speech clarity and a traditional paired-comparison (AB) approach, if differences exist in polar-pattern (omnidirectional, cardioid, hypercardioid) preferences among listeners in different real-world environments. Another purpose was to determine whether a modified paired-comparison procedure (ABN) could improve the sensitivity of paired-comparison judgments over that produced by the AB procedure, in the context of investigating the efficiency of DMHAs. This aspect of the study was motivated largely by a recent investigation by Punch, Rakerd, and Amlani (2001), which suggested that the ABN approach might improve the sensitivity of paired-comparison judgments of hearing aid-processed speech. That study evaluated ABN in the context of perceived differences in aided frequency-response patterns, while the current investigation extended the exploration of ABN to perceived differences in aided polar-response patterns.

Background

This chapter describes the objective and subjective behavioral measurements used in the assessment of speech intelligibility in noise for different hearing aid microphones under both laboratory and real-world conditions. For the interested reader, additional information on the different types of hearing aid microphones, procedures used to quantify directivity in the

laboratory, and procedures used to quantify directivity in the clinic can be found in Appendices A, B, and C, respectively.

Assessment of DMHAs Using Objective Methods

As stated in the introduction to this chapter, methods to predict how well a listener will perform under real-world conditions based on measures of electroacoustic characteristics remain elusive. As a result, researchers have turned to various behavioral methods to quantify speech-recognition performance and listener preferences under both laboratory and everyday listening conditions. This section summarizes those studies that have used various objective methods for assessing behavioral performance with single- and dual-microphone devices. Table 1.1 summarizes the experimental conditions used in these studies. To distinguish behavioral assessments of performance with directional hearing aids from electroacoustic measurements of *directivity*, this paper uses the term *directionality* when referring to behavioral measurements, as suggested by Ricketts and Dittberner (2002).

A number of studies on DMHAs have been conducted under laboratory and real-world conditions in which percent-correct scores were obtained for monosyllabic words in noise. Many of these studies were undertaken to determine if single-microphone directional devices did indeed provide listeners with improved signal-to-noise ratios (SNRs).

Lentz (1972) was one of the first to evaluate differences in performance between omnidirectional and single-microphone directional behind-the-ear (BTE)

devices. Twenty hearing aid users served as subjects. CID W-22 monosyllabic words (Hirsh, Davis, Silverman, Reynolds, Eldert, & Benson, 1952) were presented from directly in front (0° azimuth), and white noise was presented simultaneously from 180° azimuth. Word-recognition performance was assessed for each microphone condition in quiet, 0 and -6 dB SNR. In quiet, the directional device was found to provide a mean improvement of only 0.9% over its omnidirectional counterpart, indicating no difference. At 0 dB SNR and -6 dB SNR, the DMHA provided mean advantages of 17.5% and 24.9%, respectively, relative to the omnidirectional hearing aid (ODHA).

Frank and Gooden (1973) reported the results of three experiments using normal-hearing listeners. In each experiment, word-recognition performance was assessed for 20 listeners who were presented PAL PB-50 (Egan, 1948) words processed through an ODHA and DMHA at 45° azimuth at an intensity of 55 dB sound pressure level (SPL). As seen in Table 1.1, the experiments differed only in that multitalker babble (i.e., student chatter) was presented at 0° azimuth in Experiment 1, 180° azimuth in Experiment 2, and at azimuths of both 0° and 180° in Experiment 3. For each experiment, data were taken for monosyllabic words presented in quiet, and at fixed SNRs of +6, 0, -6, -12, and -18 dB. Results of the first experiment demonstrated no differences between microphone conditions in quiet or for any of the fixed SNRs. When noise was presented from directly behind the listener (180° azimuth), results revealed an advantage for the DMHA condition over the ODHA condition in every listening condition except in quiet and at +6 dB SNR. In the third experiment, in which noise was presented from

both 0° and 180° azimuth, differences in average performance were noted between microphone conditions at 0-, -6-, and -12-dB SNR, but not at +6- and -18-dB SNR. Based on this latter finding, the authors suggested that conventional directional microphones would not provide listeners with an advantage when the listening situation is either very easy (quiet or +6-dB SNR) or very difficult (-18-dB SNR).

In 1973, Nielsen compared word-recognition performance in noise for omnidirectional and single-microphone directional devices. Twenty-two hearing-impaired listeners served as subjects. Monosyllabic words were presented at 0° azimuth at an intensity level of 55 dB SPL. A competing cafeteria noise was presented concurrently from speakers arranged at azimuths of 90° , 180° , and 270° , and at fixed SNRs of +5, +10, +15, and +20 dB. At SNRs of +5 and +10 dB, respectively, average directional advantages of 17.2% and 18.2% were found. At +15 and +20 dB SNR, there were no differences between devices.

Nielsen (1973) scrutinized single-microphone DMHAs under everyday listening conditions, and found that hearing-impaired listeners preferred ODHAs and DMHAs equally in those situations, based on judgments of speech clarity. (Additional details of this study are provided elsewhere in this paper.) This finding suggested that conditions in daily life are not as close to ideal as those found in the laboratory. Specifically, Nielsen noted that speech-intelligibility performance with directional hearing aids (i.e., directionality) deteriorated in reverberant conditions consisting of a diffuse noise background. Reverberation time (RT), defined as the duration required for the sound pressure level of a sound to

decrease 60 dB from its offset (ANSI-S1.1, 1999), has been shown to affect speech recognition in normal-hearing and hearing-impaired listeners. Namely, an inverse relationship exists between RT and speech intelligibility (e.g., Finitzo-Hieber & Tillman, 1978; Nabelek & Pickett, 1974; Nabelek & Robinson, 1982; Neuman & Hochberg, 1983). This reduction in speech-recognition performance is created by the reflection of sound energy, particularly low-frequency energy, which causes overlap masking (i.e., masking across sounds) and self-masking (i.e., smearing of internal energy within a sound) (Nabelek, Letowski, & Tucker, 1989). In general, the amount of directionality is reduced as RT increases (e.g., Studebaker et al., 1980; Hawkins & Yacullo, 1984; Ricketts & Dhar, 1999; Amlani, 2001).

Sung, Sung, and Angelelli (1975) assessed performance variability across different brands of hearing aids equipped with directional microphones (manufacturer and model not stated). Thirty-two hearing-impaired listeners were fit monaurally with three different DMHAs and an ODHA. CID W-22 monosyllabic words (Hirsh et al., 1952) and a cocktail party noise were presented concurrently at matching levels (i.e., 0-dB SNR) from 45° and 225° azimuths, respectively. Results revealed that the average performance with the first DMHA was 5.9% poorer than that with the ODHA. Comparisons between the second DMHA and the ODHA yielded no average difference. The third DMHA was found to yield a considerable average increase in performance of 8.9% over the omnidirectional device. Differences were also found for this DMHA over the other two directional devices. The overall findings of this study suggested that directional benefit

varied across different brands of hearing aids equipped with directional microphones.

In 1983, Madison and Hawkins evaluated the word-recognition performance of 12 normal-hearing listeners who responded to monosyllabic words presented from 0° azimuth, while a competing noise was positioned at 180° azimuth. Specifically, subjects were presented NU-6 words (Tillman & Carhart, 1966) recorded in an anechoic chamber and in a reverberant room having an RT of 0.6 s, and processed through an ODHA and a DMHA fitted on an acoustic manikin (KEMAR) (Knowles Electronics Manikin for Acoustic Research; Burkhard & Sachs, 1975). Results showed that the directional condition provided an advantage in word-recognition performance of 10.7 dB in the anechoic room and 3.4 dB in the reverberant room.

Hawkins and Yacullo (1984) took the findings from the Madison and Hawkins (1983) study one step further. Twelve normal-hearing and 11 hearing-impaired subjects listened through headphones to monosyllabic words in noise, as processed through an ODHA and a DMHA in three reverberant rooms (Table 1.1). Recordings of hearing aid-processed speech in noise were made by placing monaural and binaural hearing aids on KEMAR, with speech presented from a loudspeaker at 0° azimuth and multitalker babble presented from a loudspeaker at 180° . The loudspeakers were located just beyond the respective critical distances (CDs) in each of the reverberant rooms (i.e., RTs of 0.3, 0.6, and 1.2 s). Speech was presented through headphones at a constant level of 65 dB SPL for normal-hearing listeners and at the most comfortable listening level (MCL) for

hearing-impaired listeners. In an adaptive test paradigm, each subject was asked to repeat NU-6 words (Tillman & Carhart, 1966) as the presentation level of the noise was varied in 2-dB steps until an SNR yielding 50% correct recognition was determined. For all conditions, tasks were performed monaurally and binaurally. Results indicated several effects: (1) a binaural advantage of 2-3 dB, which was independent of microphone type and reverberation time, (2) a directional-microphone advantage of 3-4 dB, which was dependent on reverberation time, but independent of whether the hearing aid arrangement was monaural or binaural, (3) a reverberation effect, which was greater than either the binaural or directional-microphone effects, and (4) additive binaural and directional-microphone advantages. The authors described their results as suggesting that the SNR can be maximized by using binaural hearing aids having directional microphones, at least in environments with short and moderate reverberation times.

Leeuw and Dreschler (1991) compared the effectiveness of DMHAs and ODHAs in rooms with low and high amounts of reverberation (Table 1.1). Speech reception thresholds (SRTs), using Danish sentences (Plomp & Mimpen, 1979) against background noise, were established in 12 normal-hearing listeners in the two rooms. Listeners were aided in the right ear with a commercially available hearing aid, equipped with an omnidirectional microphone, and a custom-manufactured version of the same hearing aid model equipped with a directional microphone. Throughout the experiment, the left ear was sealed with an earplug. The speech signal was presented from directly in front (0° azimuth), while noise

was presented at the same time from various azimuths ranging from 0° to 180° in 45° steps. Results across microphones and room conditions were statistically different. Specifically, the behavioral advantage of the directional microphone was substantial and progressively greater in the room with the lower reverberation time when the noise was presented to each listener at azimuths between 45° and 180° . In the more reverberant room, a directional-microphone advantage was also observed, but the behavioral advantage was less substantial and did not grow as the azimuth of the noise increased.

In the early 1980s, single-microphone directional hearing aids constituted 20% of the hearing aids sold in the United States (Mueller, 1981, as reported by Ricketts & Mueller, 1999a). In subsequent years, the use of directional devices steadily decreased, in part, because of the increasing popularity of custom in-the-ear (ITE) products and the reduced number of directional ITEs offered by manufacturers. In the mid 1990s, directional-microphone hearing aids having two omnidirectional microphones (i.e., dual-microphone directional hearing aids) were introduced, and based on comparisons to the single-microphone devices, were generally found to provide greater SNR improvement (Ricketts & Mueller, 1999a).

Chasin (1994) was one of the first researchers to report on the advantages of dual microphones housed in ITE-style hearing aids (Table 1.1). To assess the validity of directional microphones in ITE-style devices, Chasin examined the SNR improvement with a commercially available device in 10 hearing aid users. SNR improvement was measured for omnidirectional and

directional modes using NU-6 words (Tillman & Carhart, 1966) presented from 0° azimuth and speech-weighted noise from 180° azimuth. Throughout the study, the speech signal was presented at a fixed level of 65 dB SPL, while the noise was varied. Results from the 10 subjects indicated a directional advantage ranging from 4 to 12 dB, with a mean improvement of 8.2 dB.

Voss (1997) evaluated the directional advantage of a dual-microphone BTE hearing aid fitted binaurally on 13 hearing-impaired listeners. Danish monosyllabic words (DANTALE; Elberling, Ludvigsen, and Lyreegard, 1989) were presented from a loudspeaker positioned at 0° azimuth against a babble noise presented from azimuths of 45°, 135°, 225°, and 315°. The speech in noise was presented at fixed SNRs of 0, -10, and -15 dB. The subjects' task was to repeat the monosyllabic words under each of the three SNR conditions, after the hearing aid was programmed to match *basic* omnidirectional, *party* omnidirectional and *party* dual-microphone conditions. *Basic* is the manufacturer's term referring to the type of frequency response that, according to the author, was based on the half-gain prescriptive formula. The *party* frequency response is a proprietary algorithm aimed at improving speech intelligibility in noise. According to Bachler and Vonlanthen (1994), the *party* frequency response is one of many *comfort* programs designed to maximize the audibility index and/or listening comfort in a target noise condition. This is accomplished by using a *super compression* (i.e., compression limiting) *plus adaptive recovery* (i.e., release) *time* (SC + aRT) processing strategy, while reducing the low- to mid-frequency amplification, and enhancing the high-frequency gain of the

hearing aid relative to the *basic* program. Results revealed no significant differences between conditions at the 0-dB SNR. In the -10-dB SNR condition, however, the *party* directional mode was found to produce a 16% advantage over the *basic* omnidirectional mode and an 11% advantage over the *party* omnidirectional mode. These differences were found to be statistically significant. At the less favorable -15-dB SNR, the directional mode resulted in 30% and 22% improvements in word-recognition scores over the *basic* and *party* omnidirectional modes, respectively. These differences were also found to be statistically significant.

Larsen (1998), as reported by May (1998), evaluated differences in performance between a programmable dual-microphone BTE hearing aid and an omnidirectional BTE with digital signal processing (DSP) for 19 hearing aid users. The frequency-gain response of the BTE with analog processing was based on the manufacturer's best-fit method, while the NAL-R fitting formula (Byrne & Dillon, 1986) was used for those hearing aids having DSP. The subjects wore the aids for two months prior to any data collection. During data collection, subjects were required to repeat DANTALE monosyllabic words (Elberling et al., 1989) presented from directly in front (0° azimuth). Simultaneously, an ICRA (International Collegium of Rehabilitative Audiology)¹ competing noise was presented from azimuths of 45° , 135° , 225° , and 315° , and adaptively adjusted

¹ ICRA noise refers to a collection of noise signals that can be used as background noise in clinical tests of hearing aids, including digital and nonlinear instruments. The signals consist of well-defined spectral and temporal characteristics similar to those typically found in real-life speech signals and speech babble. They are based on male- and female-produced English speech, in which the spectra and modulation of normal, raised, and loud speech are preserved, and are available from ICRA on a commercial compact disc.

until 50% of the monosyllabic words could be identified. Overall, a 3.6-dB improvement was noted for the dual-microphone BTE when compared to the average performance with the omnidirectional BTE incorporating DSP. While this outcome suggests an improvement due to the directional microphone, the extent to which directionality per se accounted for the improvement is difficult to establish because of the many independent variables (i.e., analog vs. digital processing, manufacturer's best-fit vs. NAL-R method, and omnidirectional vs. directional microphones) operative in the study.

More-recent studies have assessed behavioral performance with dual-microphone devices using adaptive speech-in-noise tests that measure performance based on the level of the speech compared to the level of the noise. Specifically, these tests require the listener to repeat sentences in noise at various SNRs. Depending on the test, either the speech level or noise level is adaptively increased or decreased until a criterion of 50% speech intelligibility is met, and the findings are reported in dB SNR. Examples of these tests include the Speech in Noise (SIN) test (Killion & Fikret-Pasa, 1993) and Hearing in Noise Test (HINT; Nilsson, Soli, & Sullivan, 1994). Recent studies have evaluated the dual-microphone configuration based on the presumption that such devices provide listeners with better directionality than single-microphone devices under everyday listening situations (Valente, Fabry, and Potts, 1995).

Valente et al. (1995) used the HINT to evaluate the performance of a three-memory programmable dual-microphone BTE aid. Participants, from two sites, were 50 hearing aid users. During the experimental task, subjects listened

to sentences of the HINT, presented at 0° azimuth, as competing noise—which was temporally and spectrally matched to the sentences—was presented simultaneously from directly behind. The experimental conditions, which were programmed into the hearing aid, included *basic* omnidirectional, *party* omnidirectional, *basic* directional and *party* directional (Table 1.1).

The *basic* omnidirectional condition was programmed so that the real-ear insertion gain (REIG) matched the NAL-R (Byrne & Dillon, 1986) target prescription. As described earlier, the specific algorithm for the *party* program is one of several proprietary programs designed to maximize the audibility index. Overall, results revealed a mean directional improvement of 7.4 dB (Site I) and 7.8 dB (Site II) when the omnidirectional and directional *basic* programs were compared. There was an improvement in speech intelligibility for the *party* directional condition over the *party* omnidirectional condition. When the *basic* omnidirectional condition was compared to the directional *party* condition, results indicated an average directional improvement of 7.7 dB (Site I) and 8.5 dB SNR (Site II). HINT scores did not differ between the *party* directional and *basic* directional modes.

Agnew and Block (1997) evaluated the performance of a dual-microphone BTE hearing aid in 20 subjects with bilaterally symmetrical hearing loss. Each subject was fit binaurally, and the frequency-gain responses of the devices were adjusted so that the measured REIG approximated that subject's NAL-R (Byrne & Dillon, 1986) target. Subjects were seated in a sound-treated room equidistant from a loudspeaker located at 0° azimuth and another located at 180° azimuth.

Sentences from the HINT were presented from the front speaker, and the HINT (i.e., speech-weighted) noise was presented from the rear speaker at 65 dBA. Results showed that the mean SNR required to produce 50%-correct speech intelligibility was found to be 2.35 dB in the omnidirectional condition and -5.18 dB in the directional condition. The directional advantage, therefore, was 7.53 dB.

Preves, Sammeth, and Wynne (1999) undertook a two-part experiment that evaluated the speech-intelligibility performance of 10 hearing-impaired subjects with a dual-microphone ITE device. The hearing aid was equipped with a toggle switch on the faceplate that allowed the user to switch between the omnidirectional and directional modes. In the first experiment, the low-frequency response in the directional mode was unequalized. In the second experiment, the frequency-gain response in the low frequencies for the directional mode was increased to match, or equalize, the low-frequency response of the omnidirectional condition. For both experiments, subjects listened to HINT sentences presented from 0° azimuth, while an uncorrelated HINT noise, fixed at 65 dB SPL, was presented simultaneously from azimuths of 115° and 245°. Results revealed mean improvements in the directional over the omnidirectional conditions of 2.8- and 2.4-dB SNR for the respective unequalized and equalized frequency-response conditions. The small difference between frequency-response conditions was not statistically significant.

In 1999, Gravel, Fausel, Liskow, and Chobot evaluated the advantage provided by a dual-microphone BTE hearing aid on two groups of children with

mild-to-severe sensorineural hearing impairment. The first group consisted of 10 hearing-impaired children aged 4 to 6 years, while the second group consisted of 10 hearing-impaired children aged 7 to 11 years. As shown in Table 1.1, subjects listened to words and sentences of the Pediatric Speech Intelligibility (PSI) test (Jerger and Jerger, 1984) presented from a loudspeaker at 0° azimuth.

Multitalker babble was presented simultaneously from loudspeakers located at azimuths of 72° , 144° , 216° and 288° . For both the omnidirectional and directional conditions, the PSI test was presented at a level of 50 dB HL, and the noise was adaptively varied in 2-dB steps. Each child's task was to repeat the words and sentences until 50% intelligibility was established. Results revealed that the directional condition provided all children with an average SNR improvement of 4.7 dB across both types of stimuli. For the younger group, mean directional advantages of 4.6 and 5.1 dB were noted for words and sentences, respectively. For the older group, an SNR improvement of 5.3-dB was noted for words, and a 4.2-dB SNR improvement was noted for the sentence material.

The ability of the clinician to predict hearing aid performance in everyday listening conditions has been elusive, in part, because of the lack of consensus among researchers on valid measurement tools (Byrne, 1998; Walden, 1997) and, in part, because of the rapid technological advances in hearing aid fitting. Despite these problems, Walden et al. (2000) attempted to compare the benefits of different hearing aid technologies that are commercially available. Forty hearing-impaired individuals were recruited as participants. Twenty-one of the participants "...wore binaural linear automatic gain control with input compression

limiting (AGC-I) hearing aids....” (p. 541), and the remaining 19 had been fit previously with binaural digitally programmable analog, two-channel, wide-dynamic-range compression (WDRC) hearing aids. Each subject’s own instruments were configured with omnidirectional microphones. Prior to data collection, each was also fit binaurally with fully digital BTE devices. These BTE devices were programmed based on the manufacturer’s recommendations, with omnidirectional and directional modes stored in different memories. Specifically, program 1 was configured for omnidirectional mode, program 2 for a directional mode, and the third program for directional + noise-reduction mode. Performance indices included the Connected Speech Test (CST; Cox, Alexander, & Gilmore, 1987; Cox, Alexander, Gilmore, & Pusakulich, 1988), the Profile of Hearing Aid Benefit (PHAB; Cox & Gilmore, 1990; Cox and Rivera, 1992), and subjective ratings of speech understanding, listening comfort, and sound quality/naturalness. Performance on the CST was measured with the speech stimuli presented from a loudspeaker positioned at 0° azimuth and with multitalker babble presented concurrently from loudspeakers positioned at azimuths of 90°, 180°, and 270° under three different listening situations. These situations included: (1) listening to soft speech in low-level noise (+10-dB SNR), (2) listening to speech in reverberation, and (3) listening to speech in background noise (0- and +2-dB SNR). The second situation was accomplished by digitally processing the CST to simulate an RT of 0.78 s. Substantial performance advantages, with respect to CST and APHAB scores and the subjective ratings,

were found for the directional-microphone mode over the omnidirectional mode. There was not a significant difference between directional modes.

Ricketts and Dhar (1999) evaluated the behavioral performance of an analog directional device (Phonak Audio-Zoom) and two digital directional devices (Siemens Prisma, Widex Senso C9). All three hearing aids were BTEs, and the Phonak and Siemens devices were configured with dual microphones. Twelve hearing-impaired individuals participated in the study. All were administered the HINT under anechoic and reverberant ($RT = 0.642$ s) conditions. For both speech tasks, the target signal was presented from 0° azimuth and the competing noise (uncorrelated cafeteria noise) was presented simultaneously from speakers positioned at 90° , 135° , 180° , 225° , and 270° azimuth. Under both the anechoic and reverberant conditions, speech-in-noise performance was significantly better in the directional mode when compared to the omnidirectional mode for each of the devices. The observation of Ricketts and Dhar that advantages of directional microphones occur in reverberant, as well as anechoic, rooms is a departure from the general notion that increased RT reduces speech intelligibility. For the anechoic condition, overall performance, based on SNRs reached at 50% intelligibility, was 6.5 dB, 7.5 dB, and 5.0 dB for the C9, Audio-Zoom, and Prisma devices, respectively. The differences among devices were not statistically significant. Under the reverberant condition, mean SNRs were 4.5 dB for the C9 hearing aid, 6.5 dB for the Audio-Zoom device, and 5.0 dB for the Prisma device. Again, differences across devices were not significant. Findings revealed nearly equal speech-intelligibility performance in

noise across directional devices manufactured by different companies, under both laboratory and real-world conditions.

Wouters, Litire, and van Wieringen (1999) evaluated whether dual-microphone configurations provide greater speech-intelligibility performance in noise than their single-microphone counterparts. Ten hearing-impaired listeners participated in the experiment. Each subject was seated in a room having an RT of 0.45 s. Two loudspeakers, placed at azimuths of 0^0 and 90^0 , were used to present speech and competing noise, respectively. The speech material consisted of 10 lists of 13 sentences and 15 lists of 10 bisyllabic words from the BLU lists (Plomp & Mimpen, 1979; Wouters, Damman, & Bosman, 1994), and the noises consisted of the BLU speech-weighted noise, traffic noise, and multitalker babble. During the experiment, each subject was asked to repeat Dutch sentences and bisyllabic words presented in the presence of different competing noises. In addition to their own bilateral omnidirectional single-microphone devices, subjects were fit binaurally with an experimental hearing aid equipped with dual microphones. Listeners switched to either omnidirectional or directional (cardioid) mode through the use of a hand-held remote. Differences between each listener's own omnidirectional device and the omnidirectional mode of the experimental device were not statistically different. There was, however, a difference between listeners' hearing aids configured with an omnidirectional pattern and the experimental device equipped with a directional microphone, with the directional device demonstrating improved speech intelligibility. A significant difference was also noted between the omnidirectional

and directional condition for the experimental hearing aid. Lastly, statistical differences were not observed across the different noise conditions.

In sum, it is quite evident that DMHAs can improve speech-intelligibility performance in noise. The amount of directional advantage reported across studies is variable, however, based on differences in methodology (i.e., test stimuli, test environments, loudspeaker azimuths, types of hearing aids, programming algorithms). To establish the degree of directional advantage provided by DMHAs, Amlani (2001) compiled data from 72 ODHA and 74 DMHA experiments that utilized a 50% criterion-to-performance procedure, independent of the stimuli used. Using a meta-analytic approach, his results confirmed the inverse relationship between speech intelligibility in noise and RT for both normal-hearing and hearing-impaired listeners. Despite this general finding, his study revealed an overall mean weighted directional advantage (mean ODHA – mean DMHA) of about 4-dB SNR for normal-hearing and hearing-impaired listeners in both less reverberant ($RT < 0.6$ s) and more reverberant ($RT > 0.6$ s) environments.

Ricketts, Lindley, and Henry (2001) examined the effect of low-threshold compression and hearing aid style on directionality. The authors were primarily interested in determining whether a difference in directivity was present as a function of hearing aid style. They proposed that an interaction effect could be found between low-threshold compression and directivity based on the fact that DMHAs change the input level of sounds relative to their angle of arrival. Consequently, the listener may note perceptual differences. Forty-seven hearing-

impaired subjects were recruited to participate at two sites. The HINT and CST were used to obtain speech-intelligibility judgments under one BTE condition and four ITE conditions. The authors specified neither the model of the hearing aids nor the polar pattern of the directional devices. The single BTE device and one of the ITE devices (ITE 1) were both analog programmable devices, and comparable electroacoustically in nearly all respects, including output limiting. Two ITE devices (ITE2, ITE3) differed in signal processing (i.e., analog vs. digital), fixed compression threshold level, number of bands, release time, and compression ratios, while the final ITE aid (ITE4) was an analog, linear instrument with hard peak clipping. Directivity Index (DI) measures were obtained on each aid used in the study, and average values in the omnidirectional condition were similar across the four ITE hearing aids. A lower DI value was noted for the BTE device when measured under the same microphone condition. The improvement in DI, when switching from omnidirectional to directional modes, was greatest for the BTE and two ITEs (ITE3, ITE4). The frequency-gain response of each device was programmed using the NAL-NL1 (Byrne, Dillon, Ching, Katsch, & Keidser, 2001; Dillon, 1999) procedure. Testing was performed in a moderately reverberant room, where RTs were determined to be 0.37 s and 0.46 s for Sites 1 and 2, respectively. Prior to data collection, the CST was pre-recorded at a fixed SNR of +4 dB at Site 1 and at an SNR of +1 dB at Site 2. The single-source competing noise of the CST was replaced with five uncorrelated noise samples of cafeteria noise. The same five uncorrelated noise samples were used with the HINT. These noise sources were filtered and modified,

however, to provide a long-term average spectrum similar to the sentence stimuli. During testing, the speech target was presented from 0° azimuth and the competing noise sources, presented simultaneously, were arrayed at azimuths of 30° , 105° , 180° , 255° , and 330° to simulate listening in a restaurant.

Results from the Ricketts et al. (2001) study showed that listeners performed considerably better with the directional devices than with the omnidirectional devices. The effect of compression was found not to be a factor in listener performance or directional advantage. This finding was based, however, on the premise that the competing noise and target signal are presented at the same time. With regard to hearing aid style, two ITE devices (ITE2, ITE3) provided listeners with greater speech-recognition ability than the BTE hearing aid. This finding, according to the authors, was expected based on the higher DI value measured in the omnidirectional mode.

More recently, Ricketts and Henry (2002b) compared speech-intelligibility performance for a commercially available hearing aid configured for static and adaptive directional modes across a variety of competing noise configurations. Twenty individuals with hearing loss served as subjects. Each was seated in a moderately reverberant room ($RT = 0.37$ s) while wearing bilateral BTE devices programmed to the NAL-NL1 fitting procedure (Byrne et al., 2001; Dillon, 1999). The hearing aids were programmed so that directional/adaptive, directional/fixed, and omnidirectional microphone configurations could be evaluated. The authors defined the directional/fixed condition by grouping together the two static cardioid and hypercardioid polar patterns, and reported the combined results. To measure

speech-intelligibility performance, the HINT and CST materials were presented to each subject. Specifically, two blocks of 10 sentences of the HINT were presented using four different loudspeaker configurations in which the noise source (uncorrelated cafeteria noise) was fixed. These conditions included: (a) diffuse – competing noise presented from five speakers spaced equally, (b) two-source side – noise presented only from two speakers positioned at 160° and 200° azimuth, and (c) two-source back–competing noise presented from two speakers placed at 70° and 100° azimuth. The fourth loudspeaker configuration, termed *panning*, was one in which the amplitude of the competing noise was panned from one speaker to an adjacent speaker in a clockwise rotation over the duration of a single sentence. For the fourth configuration, only one block of 10 HINT sentences was presented for each pair of sentences. Data were also collected using the CST for each of the four noise conditions at an SNR of +2 dB. Similar to the Ricketts et al. (2001) study, the single competing noise sample from the CST was replaced with the uncorrelated cafeteria noise. Results showed that both fixed- (combined cardioid and hypercardioid) and adaptive-directional conditions improved speech-intelligibility performance over the omnidirectional condition. Differences between adaptive- and fixed-directional technologies were statistically significant for the two-source side configuration as measured by both stimuli, and for the panning configuration as measured by the HINT.

Summary: Assessment of DMHAs Using Objective Methods

Under laboratory and everyday listening conditions, DMHAs designed with single-microphone directionality have been shown to provide listeners with an improvement in speech-recognition ability over ODHAs. Although the amount of improvement provided by single-microphone directional devices is generally reduced by reverberation and placement of the source loudspeaker location at azimuths other than at 180^0 , speech-recognition performance with these devices appears to be either equal to or better than performance with omnidirectional devices.

Like their single-microphone directional predecessors, hearing aids with dual-microphone directional technology have generally resulted in a performance advantage with respect to SNR over aids with an omnidirectional microphone. Limited evidence suggests that a slight performance advantage may exist for dual-microphone devices over single-microphone devices, but the current data are inconclusive. No studies were found that showed a specific directional polar pattern to be superior in SNR performance over another directional pattern.

Assessment of DMHAs Using Subjective Methods

In contrast to objective behavioral performance measures, data on subjective performance with DMHAs suggest that real-world preferences of listeners do not correlate well with laboratory measures (e.g., Cord et al., 2002; Kuk, 1996; Walden et al., 2000). To assess subject preferences, various

methods have been used. These include surveys, category scaling, and paired comparisons. Table 1.2 summarizes the experimental conditions used in these investigations.

Questionnaire and Survey Methods

Mueller, Grimes, and Erdman (1983) investigated differences in subjective preferences for omnidirectional and single-directional microphones in two experiments. In the first, 24 hearing-impaired listeners were fit monaurally with a device that could be toggled between omnidirectional and directional modes. After a trial period in which subjects wore the hearing aids in their everyday environments, a questionnaire was administered to determine if differences between microphone types were evident for quiet and noisy conditions. Results showed no clear microphone preference in the quiet condition. In the 69% of listeners who had a clear preference in noise, the preference was for the directional condition. In the second experiment, 30 subjects exhibiting high-frequency sensorineural hearing loss and no previous experience with amplification were fit with the same hearing aid used in the first experiment. They were asked to alternate between omnidirectional and directional microphones in four everyday listening conditions that varied in degree from optimum to extremely adverse, with respect to noise and reverberation. Approximately 65% of the subjects showed no clear microphone preference and, for those expressing a preference, the differences were not statistically significant. Preferences for the directional microphone tended to increase, however, as the

listening condition became more adverse. In attempting to explain the outcomes of their study, the authors conjectured that many subjects left their devices set in the directional mode and did not manually toggle between microphone modes. This may have resulted from their failure to experience perceptual differences in quiet, thus leading them to preset the aids in the directional mode in anticipation that listening conditions might become more adverse. In fact, Sommers (1979), who surveyed users of hearing aids that could be toggled between omnidirectional and directional modes, found that only 26% of respondents actively switched between modes, 41% chose to leave the hearing aid in the directional position, and the remaining 33% opted to leave the hearing aid in the omnidirectional position.

Kuk (1996) surveyed 100 hearing-impaired listeners who had recently acquired an analog-programmable device designed so that users can switch between its omnidirectional and dual-microphone directional modes. Listeners were asked to rate their preference for a microphone condition in several quiet (e.g., TV, radio, familiar talker, next room, quiet restaurant) and noisy environments (e.g., restaurant, large store, large group, car). Findings from the survey revealed that in quiet situations, 65% preferred the omnidirectional mode, 25% preferred the directional mode, and 10% reported no preference. In the noisy condition, there was a strong preference for the directional mode.

A potential reason that listeners prefer the omnidirectional mode of a contemporary hearing aid in quiet environments could be that there is an improvement in speech intelligibility when soft speech is presented to listeners at

a level around 50 dB SPL. Lee, Lau, and Sullivan (1998) found that an increase in speech-intelligibility performance was achieved using a WDRC device with a very low compression threshold (CT) of 20 dB HL. That is, the lower CT provided an increase in gain for those sounds below CT (Kuk, 1998).

Kuk, Kollofski, Brown, Melum, and Rosenthal (1999) further tested this hypothesis on a school-aged population. Twenty hearing-impaired children, aged 7.6 to 13.9 years, were recruited as subjects (Table 1.2). Prior to data collection, each subject was fit binaurally with digital BTE hearing aids and given a 30-day trial period. Specifically, the Widex Senso C9 was fit on children needing moderate gain and the Widex Senso C19 was fit on those requiring high amounts of gain. In its directional mode, the C9 model employs a supercardioid pattern, while the C19 model is designed with a cardioid pattern. The effectiveness of the digital hearing aids in the children's academic environments was evaluated using the Listening Inventory for Education (LIFE) questionnaire (Anderson & Smaldino, 1998). The LIFE is an efficacy tool used to evaluate changes in a child's perception of listening difficulty (Student Appraisal of Listening Difficulty), as well as teachers' perceptions of children's school and classroom behaviors (Teacher Appraisal of Listening Difficulty, Teacher Opinion and Observation List) as a function of a specific intervention, such as an amplification system. In addition, the parents of the participants were also asked to keep diaries of their children's experiences with the hearing aids. Overall findings showed a Preference, based on the LIFE, teacher's perceptions, and parental diaries, for the digital hearing aids over each child's own omnidirectional analog hearing aid.

Category-Scaling Methods

Researchers have also used categorical-scaling methods to measure listener preferences for various hearing aid characteristics. Categorical scaling allows the listener to rate the perceptual effects of selected electroacoustic characteristics by choosing numbers or adjectives from a fixed range of scale values having a lower and upper limit.

As part of Chasin's (1994) study, described earlier, subjects were queried **about** their microphone preferences. The 10 hearing-impaired listeners wore a **commercially** available device for a month in their everyday environments. After **the** trial period, they were administered a non-standardized 7-point scale and **asked** to rate their preference for either the omnidirectional or directional modes **in** each of three conditions: (a) quiet, (b) easy listening with noise (i.e., up to two **persons**), and (c) difficult conditions with noise (i.e., more than two persons). On **the** 7-point scale, complete preference for the directional mode was denoted by a **7**, no preference by a 4, and complete preference for the omnidirectional mode **by** a 1. Two subjects used their devices sparingly, and results for the remaining **eight** revealed no statistical difference between microphone modes in the quiet **condition**. A statistical difference was noted, however, between microphone **conditions** in the easy and difficult listening conditions, with preferences for the **directional** mode.

In the Walden et al. (2000) study, also described earlier, 40 hearing-**impaired** listeners were asked to provide subjective data on their real-world **experiences** with binaural BTE hearing aids programmed with omnidirectional,

directional, and directional + noise-reduction microphone configurations. The hearing aids were programmed to the manufacturer's recommendations, with omnidirectional and directional (hypercardioid) modes stored in memories 1 and 2, respectively. Listener performance was assessed using the Profile of Hearing Aid Benefit (PHAB; Cox & Gilmore, 1990; Cox & Riveria, 1992) and an 11-point scale (0 = very poor, 10 = very good) for each program. For the latter scale, subjects were asked to rate speech understanding for three dimensions (quiet, reverberation, background noise), sound comfort for two dimensions (nonspeech sounds, speech in background noise), and sound quality and naturalness for two dimensions (sounds of nature/music, speech in background noise). The overall finding for these subjective tasks was that subjects did not generally perceive the directional advantages measured in the laboratory in their daily lives, especially when listening in noise.

More recently, Cord et al. (2002) queried experienced users of binaural, switchable omnidirectional/directional devices regarding patterns and benefits of directional technology in real-world situations (Table 1.2). Subjects were queried using the Microphone Performance Questionnaire (MPQ; Cord et al., 2002) and telephone interviews. The MPQ is a 31-item, 7-point scale, survey that elicits subjective responses to listening conditions with respect to the presence or absence of noise, amount of reverberation, location of the signal, location of the noise, and the distance of the listener relative to the signal. It was found that Patients who regularly switch between microphone modes toggle the directional mode about 25% of the time. Furthermore, it was found that in real-world

situations, in which a directional microphone was hypothesized to be favored, subjects instead reported an overall preference for the omnidirectional microphone. Despite the greater use of, and superior preference for, the omnidirectional mode, subjects reported the same level of satisfaction across microphone types.

In an editorial, Jerger (2000) suggested that “A profitable approach might **be** a search for the characteristics of real-life acoustic environments that the **hearing** aid user can exploit to maximize the undoubted advantage that is **available** from directional microphone technology” (p. 521). Surr, Walden, Cord, **and** Olsen (2002) undertook this task. Eleven hearing aid users were fit **binaurally** with fully digital, two-memory, programmable BTE hearing aids. The **two** switchable memories were programmed for omnidirectional and directional **modes**. The directional mode was set for adaptive processing. For a period of six **weeks**, subjects were asked to identify and describe in a daily journal at least one **listening** situation in which one memory outperformed its counterpart. The journal **consisted** of two rating scales and 16 multiple-choice items describing the **characteristics** of the listening situation. Participants were prohibited from rating a **listening** situation more than once. Subjective reports of participants revealed **difficulty** in identifying situations in which a difference between microphone **modes** was observable. Raw data were reduced to a smaller data set **encompassing** the characteristics of primary talker, background noise, and **environment**. Of the 215 samples, 155 descriptions favored the directional mode

across the three characteristics. Microphone preference was related to the location of the primary talker, the presence or absence and type of background noise, and the type of space in which communication occurred.

Paired Comparisons

As discussed previously, DMHAs have been evaluated behaviorally using various objective and subjective measures. The paired-comparison method is a subjective task that has been relatively ignored in assessing directionality characteristics. Fechner first introduced the paired-comparison approach as a technique for the study of sensory perception (Thurstone, 1927). In this approach, a person is asked to make binary decisions on a number of stimuli presented in pairs relative to the experimental criterion. Zerlin (1962) was the first to apply this approach to hearing aid research. Since then, the method of paired comparisons has been used empirically to recommend a *best* hearing aid or to recommend a combination of settings in a programmable hearing aid (e.g., Kam & Wong, 1999; Keidser, Dillon, & Byrne, 1995; Keidser & Grant, 2001a, b; Kuk & Pape, 1992; Levitt & White, 1978; Naidoo & Hawkins, 1997; Neuman, Levitt, Mills, & Schwander, 1987; Punch, 1978; Punch, Montgomery, Schwartz, Walden, Prosek, & Howard, 1980; Studebaker, Bisset, Van Ort, & Hoffnung, 1982). Over the past 30 years, the paired-comparison approach has gradually gained momentum as a clinical tool in the selection and fitting of hearing aids. This momentum is due, in part, to the increased sensitivity of the paired-comparison method over speech-recognition tests in differentiating improvements achieved

by different electroacoustic characteristics (Punch, 1978; Punch & Howard, 1978; Studebaker et al., 1982; Studebaker & Sherbecoe, 1988; Tecca & Goldstein, 1984; Witter & Goldstein, 1971). In addition, the method of paired comparison also demonstrates a high reliability for a preferred hearing aid (e.g., Punch, 1978; Punch et al., 2001; Zerlin, 1962) and good validity as a predictor of hearing aid performance under real-world listening conditions (e.g., Punch & Howard, 1978; Studebaker et al., 1982).

With respect to DMHAs, few studies have employed the method of paired comparisons. As part of the Nielsen (1973) study, 22 subjects were asked to state their microphone preference for a male voice presented at 0° azimuth relative to three simultaneous noise sources (young female voice at 90° azimuth, cafeteria noise at 180°, and older female voice at 270°). Results revealed that 15 (68%) reported preferences for the directional device, while 5 (23%) stated preferences for the ODHA. Two individuals, or 9%, reported no preference. As a means to determine real-world preference, the subjects were afforded the opportunity to wear each hearing aid for three weeks in their everyday environments. Based on these experiences, 9 listeners (41%) reported a preference for the directional design. Similar to the laboratory condition, 5 (23%) preferred the omnidirectional design, and 8 (36%) reported no preference for either design. (The article fails to report whether the same 5 subjects preferred the ODHA under the laboratory and everyday listening conditions.)

More recently, Preves et al. (1999) assessed listener preference between Omnidirectional and directional conditions during a field trial of a dual-microphone

directional device. Ten hearing-impaired listeners were fit binaurally. Each listened to connected speech presented from 0° azimuth at 65 dB SPL in two conditions: (1) quiet, and (2) in the presence of 57-dB SPL multitalker babble presented concurrently at azimuths of 115° and 245° . Each subject was administered five trials and asked to state a preference between the omnidirectional and directional-microphone modes based on judgments of speech clarity, quality, background noise, and overall impression in quiet and in noisy listening conditions. During the comparisons, the microphone mode was randomly selected. Findings revealed that for all conditions in noise, seven or more subjects out of 10 preferred DMHAs. In quiet, however, it was found that the microphone conditions were preferred equally.

A problem with the paired-comparison approach, as pointed out by Punch et al. (2001), is that subjects who judge paired stimuli to be equally desirable or equally undesirable are nonetheless forced to choose between the stimuli. According to the authors, "At best, such data could represent random guesses that reduce efficiency and are not useful in determining the preferred value, or winner. At worst, the forced-choice nature of the paired-comparison method could substantially limit the data's overall reliability and may weaken a listener's confidence in the ability of the method to establish an optimal set of values for his or her hearing aid" (p.191). To overcome this limitation of the traditional paired-comparison method (AB), these researchers introduced a modified paired-comparison technique, ABN, where N stands for No Preference. In their study, 15 normal-hearing listeners compared nine frequency-response slopes in a

round-robin tournament as they listened to passages of the Revised Speech Intelligibility Rating (RSIR; Speaks, Trine, Crain, & Niccum, 1994) test against a competing background noise at a +3-dB SNR. All subjects made comparisons using the traditional and modified procedures on two separate days, at least two weeks apart. Based on a criterion of speech clarity, a statistically significant difference was noted between the methods, with the ABN task providing greater reliability for the most preferred responses.

In a recent study, Preminger and Cunningham (2002) evaluated the sensitivity of the traditional AB task by comparing judgments among four hearing-impaired listeners having minimally one year of experience with amplification and four hearing-impaired listeners having no experience with amplification. Subjects were fit with unspecified multimemory, WDRC, BTE devices, and frequency-gain characteristics were determined based on subjective ratings of *good* and *bad* clarity from each listener. For all subjects, the good frequency response provided more high-frequency gain and the poorer frequency-response greater low-frequency gain. Subjects then wore the aids set to each frequency response during two separate one-week intervals in their everyday environments. After each trial period, subjects listened to continuous discourse and made judgments about clarity of speech as the frequency response was changed. The percentage of time that the good frequency response was chosen was quantified and evaluated statistically. Results showed good sensitivity, validity, and reliability for listeners with amplification experience, but not for listeners inexperienced with amplification. Preminger and Cunningham (2002) concluded that "...new hearing

aid users should be given an introductory period with amplification before they are asked to make comparisons between hearing aid technologies” (p.8).

One potential explanation for the findings reported by Preminger and Cunningham (2002) might be based on a limitation of the traditional paired-comparison described by Punch et al. (2001). The use of the nonforced-choice paired-comparison paradigm (ABN) by listeners who are inexperienced with hearing aids may result in improved sensitivity of subjective judgments of speech clarity. At a minimum, the ABN procedure might provide a basis for differentiating the speech-intelligibility performance of experienced versus inexperienced listeners. This speculation led us to explore, as a secondary purpose of this investigation, whether the ABN paradigm can improve the sensitivity of paired-comparison judgments over that produced by the AB procedure, in the context of investigating the efficiency of DMHAs.

Summary: Assessment of DMHAs Using Subjective Methods

Questionnaires, surveys, categorical scaling, and—to a limited extent—paired comparisons have been undertaken in the assessment of behavioral performance with hearing aids featuring different directional properties. In general, these methods suggest that listeners prefer DMHAs in difficult listening situations, but that they may not perceive DMHAs as distinctly advantageous on a functional level in their everyday lives. It is apparent that laboratory measures of behavioral performance with DMHAs do not correlate well with subjective reports of performance in the real world. Studies that have utilized survey

questionnaires and categorical scaling have found that hearing aid users do not regularly toggle between omnidirectional and directional modes when afforded the opportunity. Further investigations of DMHAs are warranted using the paired-comparison method because the method has been relatively unexplored in the assessment of directionality characteristics. It deserves closer scrutiny, therefore, as a means to reveal behavioral differences in directional and omnidirectional hearing aids.

Purposes of the Study

The purposes of this study were: (1) to examine listener preferences for omnidirectional and two types of directional microphones (cardioid and hypercardioid) in an audiometric sound room and in two real-life rooms for an ITE hearing aid, using a paired-comparison paradigm, and (2) to determine whether the ABN paradigm offers any substantive advantages over those produced by the more traditional AB procedure in the evaluation of paired-comparison judgments of directionality in these circumstances. The motivation to study the ABN paradigm in conjunction with an investigation of DMHAs stemmed from the recent finding of Punch et al. (2001) that the reliability of preferred frequency-response slopes in a simulated programmable hearing aid was greater under an ABN paradigm than under a traditional AB paradigm. In addition, Preminger and Cunningham (2002) showed that while paired comparisons are more sensitive than category ratings in differentiating speech-intelligibility performance, they are relatively insensitive in hearing-impaired listeners who are inexperienced with

amplification. Although the data addressing both of the above purposes were gathered in the same experimental session in a repeated-measures design, the data from the AB and ABN measurements were treated as two separate experiments, from which answers to the following research questions were sought:

Experiment 1:

1. Which polar pattern—omnidirectional, cardioid, or hypercardioid—do listeners prefer in real-world environments, based on judgments of speech clarity?
2. Do preferences for polar patterns, based on speech clarity, differ among a group of normal-hearing listeners, a group of hearing-impaired listeners who are inexperienced with amplification, and a group of hearing-impaired listeners who are experienced with amplification?

Experiment 2:

1. Does a modified paired-comparison technique (ABN) improve the reliability and sensitivity of paired-comparison judgments when contrasted with the AB procedure used in Experiment 1?

2. Is the overall or specific structural pattern of the preference data obtained with the ABN procedure different from that observed with the AB procedure?
3. Does the No-Preference (N) component of the ABN procedure yield additional information not otherwise found with the AB procedure?

CHAPTER 2

METHOD

This chapter describes, for Experiments 1 and 2, procedures used in the measurement of room characteristics, calibration of the equipment, recording of the speech stimuli in noise, tasks performed by subjects, collection of data, and the statistical analyses of data.

Pre-Experimental Procedures

Target Audiometric Range and Thresholds

To provide a specific prescriptive target for programming the experimental hearing aid prior to stimulus recordings, audiometric threshold data were obtained from 10 clinical case files of the Michigan State University Oyer Speech-Language-Hearing Clinic. The 10 files were selected from the pool of files of adult patients having bilaterally symmetrical sensorineural hearing loss who were waiting to be fit with amplification. Mean air-conduction thresholds were calculated at octave frequencies from 250 - 8000 Hz, and because such thresholds are established clinically in 5-dB increments, these mean values were rounded to the nearest 5-dB step. Based on these mean thresholds, prescriptive target values were derived using the NAL-NL1 fitting procedure (Byrne et al., 2001). These prescriptive values were used to program the experimental hearing aid prior to stimulus recordings.

The audiometric range shown in Figure 2.1, which was derived from the 10 sample cases just described, was used in the recruitment of participants for the study. As seen in the figure, this audiometric range encompasses a ± 15 dB area around the target audiometric thresholds. This audiometric range was derived from the average of the standard deviations associated with the target audiometric thresholds. Specifically, the average of these standard deviations, across frequency, resulted in a mean value of 16.1 dB HL, which was rounded to 15 dB HL.

Subjects

Twelve normal-hearing adult listeners (Group 1), 12 hearing-impaired adult listeners experienced with amplification (Group 2E), and 12 hearing-impaired adult listeners inexperienced with amplification (Group 2I) participated in this study. All listeners were recruited from the Michigan State University and greater-Lansing communities. Ages of subjects in Group 1 ranged from 21 to 35 years, with a mean of 24.6 years (SD = 4.4). Ten were female. Ages of subjects in Group 2E ranged from 22 to 88 years, with a mean of 61.8 years (SD = 20.9). Nine were male. Subjects in Group 2I ranged from 34 to 82 years, with a mean of 65.1 years (SD = 14.2). Eight were male. The hearing-impaired groups differed in that Group 2E had experience with amplification for ≥ 1 year, while Group 2I had ≤ 3 months experience with amplification, including the trial period. The test ear for all subjects was that preferred by individual subjects.

Normal-Hearing Listeners

The criteria for subject participation in Group 1 included:

- (a) normal hearing sensitivity ≤ 15 dB HL bilaterally for the audiometric frequencies 250 - 8000 Hz;
- (b) no significant (> 10 dB) air-bone gap at any two consecutive frequencies in either ear;
- (c) normal (Type A) tympanograms bilaterally;
- (d) normal ipsilateral acoustic reflexes at 500 and 1000 Hz in both ears;
- (e) absence of active upper respiratory infection;
- (f) a negative history of vertigo and tinnitus;
- (g) a negative history of middle ear surgery; and
- (h) a negative history of retrocochlear pathology.

Hearing-Impaired Listeners

For both Groups 2E and 2I, the criteria for subject participation included:

- (a) acquired bilateral sensorineural hearing loss with pure-tone thresholds (250 – 8000 Hz) approximating the target audiogram, with no thresholds (in either ear) outside of the dashed region shown in Figure 2.1;
- (b) no significant (> 10 dB) air-bone gap at any two consecutive frequencies in either ear;
- (c) normal (Type A) tympanograms bilaterally;

- (d) normal ipsilateral acoustic reflexes at either 500 or 1000 Hz in each ear;
- (e) absence of active upper respiratory infection;
- (f) a negative history of vertigo and tinnitus;
- (g) a negative history of middle ear surgery; and
- (h) a negative history of retrocochlear pathology.

Tables 2.1 – 2.3 show the age, gender, test ear, audiometric data, and immittance data for each individual and group. Each potential subject was asked to provide verbally a brief case history covering information relevant to his or her participation in the experiment. Thirty-six subjects were recruited and found to meet their respective group's criteria. Audiological test results and subject history information were recorded on a form devised for that purpose (Appendix D), and each participant signed an informed-consent release form (Appendix E) approved by the Michigan State University Committee on Research Involving Human Subjects (UCRIHS).

Hearing Aid

A Unitron Nexus, full-shell, in-the-ear (ITE) hearing aid was used in this study. The aid was used in recording all experimental stimuli. This hearing aid is a three-memory, programmable device, with a Class D amplifier and WDRC processing at low- and moderate-input levels. For high-input level sounds, the aid employs output-limiting compression. The Nexus device also allows for its three

memories to represent either an omnidirectional-, cardioid-, or hypercardioid-microphone configuration, which can be activated by means of a push button located on the faceplate.

The hearing aid did not incorporate venting. Use of an unvented hearing aid reduced the potential for acoustic feedback that could have otherwise been problematic in recording the numerous stimulus conditions when the aid was placed in KEMAR's ear. Because venting decreases directionality for frequencies below 2000 Hz (Mueller & Wesselkamp, 1999; Ricketts, 2000), use of an unvented hearing aid effectively enhanced the prospect for maximum directionality. The manufacturer reported the directivity characteristics of the Nexus hearing aid based on an unvented device, as measured in an anechoic room at 2000 Hz. The DI values for the cardioid and hypercardioid polar patterns, respectively, were 4.5 dB and 5.9 dB, based on the weighting of the frequency-importance function at 2000 Hz used in the AI-DI formula (Equation 3 in Appendix B).

Polar Plots

Polar patterns were derived for each of the microphone conditions used in this study. These measurements were undertaken to verify the directional characteristics provided by the manufacturer. Procedurally, the hearing aid was reprogrammed to Test mode using the Unifit software.² Polar-pattern measurements were made in an anechoic chamber under each of the three

² Test mode is a default program provided by the manufacturer, which sets the electroacoustic characteristics to linear mode.

microphone modes. Prior to the task, a 28-in by 40-in template for a polar pattern, depicted in Figure B.1, was centered on the floor of the anechoic chamber. The hearing aid was then attached to a 2-cc coupler fastened to a padded speaker stand. The coupled hearing aid was positioned at a height of 1.5 m from the floor and atop the polar-pattern template. A Realistic Minimus-3.5 loudspeaker was placed at 0° azimuth, and at a distance of 1 meter from the position of the hearing aid (Figure 2.2). A 2000 Hz pure tone was then presented at a level of 60 dB SPL, and the hearing aid output level was measured via the 2-cc coupler and sound level meter (Larson-Davis 800B). The values obtained at this azimuth for each microphone condition served as reference levels in the calculations of the polar plots. Levels were then obtained for comparison angles by rotating the hearing aid 350° in 10° increments, beginning at an azimuth of 5° and ending at an azimuth of 355°.

Polar plots for the omnidirectional, cardioid, and hypercardioid patterns are shown in Figures 2.3, 2.4, and 2.5, respectively. These plots were found to represent well the expected patterns, and the measured DI values for the various microphones were found to be within ± 1.3 dB of the manufacturer-reported DI values (Ricketts and Dittberner, 2002).

Programming of Hearing Aid

The hearing aid was programmed via NOAH-compatible Unifit fitting software (version 4.3) on a Madsen Aurical system, using the target thresholds derived during subject recruitment (Figure 2.1). The omnidirectional microphone configuration was programmed in memory 1, and the cardioid and hypercardioid

microphone configurations were programmed in memories 2 and 3, respectively. The electroacoustic characteristics in each memory were matched for compression threshold, compression ratio, and crossover frequency using the Unifit software, and the frequency-gain response was based on the NAL-NL1 prescriptive formula (Byrne et al., 2001; Dillon 1999).³ To ensure that judgments of clarity were based primarily on directionality, the noise reduction and expansion features of the aid were disabled, and the low-frequency response of the directional patterns was programmed to match (i.e., equal) the low-frequency response of the omnidirectional microphone. Figure 2.6 illustrates the hearing aid's frequency-gain response in the omnidirectional mode for a 50-dB input signal. (Frequency-gain responses were not measured for either directional microphone because the hearing aid test box provides a uniform sound pressure level. As noted in Appendix C, this uniform sound pressure level limits measuring changes in output as the orientation of the signal changes with respect to the aid.)

In addition, electroacoustic measurements were made using the ANSI S3.22-1996 standard. This task was undertaken to verify that the device was within manufacturer's specifications. Frequency response, gain, output sound pressure level, equivalent input noise, harmonic distortion, and the input-output

³ The NAL-NL1 formula was used in programming the hearing aid because researchers at Unitron Hearing found the NAL-NL1 frequency-gain response to provide listeners with less high-frequency gain compared to the alternative DSL[i/o] (Cornelisse, Seewald, & Jamieson, 1995) nonlinear fitting formula (Tellier, 2003). Specifically, the reduction in high-frequency gain provided by NAL-NL1 resulted in better sound quality to listeners.

function were measured electroacoustically after the hearing aid was reprogrammed to Test mode using the Unifit software. These measurements were made prior to experimental recordings in the omnidirectional condition. These same electroacoustic measurements were also verified after all experimental recordings had been completed. Both sets of measurements revealed these electroacoustic characteristics to be within manufacturer's specifications. Comparisons of the manufacturer-reported, pre-experiment, and post-experiment electroacoustic characteristics of the aid are shown in Table 2.4.

Stimuli

The 12 most homogeneous passages of the Revised Speech Intelligibility Rating (RSIR) test (Table 1 in Speaks et al., 1994) were used as stimuli in this study. This open-response test, originally described by Cox and McDaniel (1989) as the Speech Intelligibility Rating (SIR) test, was designed as a measure for comparisons of aided speech intelligibility. Each passage of both the original SIR and the RSIR covers a separate topic based on subject matter from a children's encyclopedia, and is read by a male talker with general American dialect. The RSIR test consists of the original 72 SIR test passages of connected discourse and multitalker babble (cafeteria noise). The RSIR differs from the SIR in that the long-term root mean square (rms) levels of each RSIR passage in noise have been adjusted to be within ± 0.5 dB using a one-third octave band-averaging technique.⁴ Using 18 normal-hearing listeners, Speaks and colleagues (1994)

⁴ Data on spectral differences among the RSIR passages are not reported by Speaks et al. (1994).

found that 50% speech intelligibility was achieved for 64 of the 72 RSIR passages when SNRs were within ± 0.5 dB. This stimulus set, obtained from Speaks et al. (1994), has been used in a previous study conducted at Michigan State University (Punch et al., 2001). The RSIR passages and the accompanying multitalker babble were low-pass filtered at 5000 Hz, digitized with 12-bit resolution at a sampling rate of 12800 Hz, and stored on a compact disc. The 12 experimental passages used in this study ranged in duration from 38.8 – 48.7 s. To allow listeners a consistent and sufficient time period to make judgments of speech clarity, only the first 30 seconds of each passage was used. The 30-s experimental passages were transferred onto the hard-disc drive of a notebook computer (HP Pavilion ZT1130). Table 2.5 details the passage number and topic content of each of the 12 experimental passages. The long-term average speech spectrum (LTASS) for the (averaged) 12 experimental RSIR passages and the long-term average spectrum of the competing noise are shown in Figure 2.7.

Loudspeaker Frequency-Response Measurements

Four Realistic (Realistic Minimus-3.5) loudspeakers, nominally labeled A, B, C, and D, were used throughout this study. The frequency-response characteristics of each speaker were measured in an anechoic chamber. Each loudspeaker was mounted atop a loudspeaker stand by means of a bracketing assembly. Measurements were made by placing each loudspeaker at a height of 1.5 m from the floor and at a distance of 1 m from the microphone of a sound level meter (Larson-Davis 800B). Using a pink-noise input signal delivered from a

BSR equalizer (14/14 XVR) with a flat frequency response at 70 dB Lin, one-third-octave band measurements were made for each speaker independently using the Larson-Davis 800B sound level meter. For each measurement, the microphone of the sound level meter was placed at the center-head position of an absent KEMAR manikin, at approximately 1.5 m above the floor. As illustrated in Figure 2.8, results showed a relatively flat frequency response (± 5 dB) for all speakers between 200 and 6300 Hz. There was very good agreement overall among the four loudspeaker responses.

Rooms

To model a range of different listening conditions, three rooms within the Department of Audiology and Speech Sciences were used for the recording of hearing aid-processed stimuli. These rooms were (a) a double-walled audiometric sound room (Industrial Acoustics Company), (b) a simulated living room, and (c) a classroom. The simulated living room is located in the Oyer Speech-Language-Hearing Clinic and is used for counseling and other forms of audiologic rehabilitation. The room is furnished with a sofa, a table, a credenza, a desk, and three chairs. The physical dimensions, ambient noise levels, and RT measurements for each of the three rooms are given in Tables 2.6 – 2.9.

Dimensions

Room dimensions were measured from wall to wall and floor to ceiling. These measurements were then used to calculate the volume of each room. All of these values are reported in Table 2.6.

Ambient-Noise Levels

Measurements of ambient-noise levels (see Table 2.7) were performed in each room during off-peak hours. These levels were determined as follows. The microphone of the Larson-Davis 800B sound level meter was placed in the center of the room at the center-head position of an absent KEMAR manikin (i.e., 1.5 m above the floor). All values shown were made using the linear-weighting scale for one-third-octave bands. Measurements were also made using the level equivalent (Leq) feature of the Larson-Davis 800B sound level meter for a period of 60 s, as needed for subsequent RT measures. Leq measures were found to be 30.1, 52.5, and 46.4 dB for the sound-treated room, living room, and classroom, respectively. In all cases, the ambient-noise levels were at least 15 dB below the presentation levels for the experimental speech passages and competing noise established for the experiments (see below).

Reverberation Measurements

All RT measurements were made after room dimensions and ambient noise levels were determined. Prior to RT measurements, estimated CD values were derived for each room condition using the formula (Peutz, 1971):

$$CD = 0.2\sqrt{V/RT} \quad (2.1)$$

where CD represents the critical distance in meters (m), V the volume of the room (m^3), and RT the reverberation time in seconds (s). For the sound-treated room, living-room, and classroom conditions, RT was estimated to be 0.05 s, 0.25 s, and 0.35 s, respectively (Table 2.8). The estimated RT s for the sound-treated room and classroom were taken from the results of RT measurements made previously in these same rooms (i.e., Punch et al., 1994), while the estimated RT for the simulated living room was derived simply from the room's volume and absorption coefficients. The resulting CD estimates were used to determine speaker placement during the measurement process by establishing the points in these rooms at which intensities of direct and reflected sound in sound field were comparable. As a precautionary measure, actual RT measurements in the living room and classroom conditions were made based on the CD rounded up to the nearest 0.5 m value.

RT measurements were made with loudspeaker A (Realistic Minimus-3.5) placed at a distance of 1 m from the microphone of the Larson-Davis 800B sound level meter in the sound-treated room. In this room, the distance of loudspeaker placement was restricted to 1 m because of the room's size (see Table 2.6). For the living-room and classroom conditions, the distance between the microphone of the Larson-Davis 800B sound level meter and the same loudspeaker was measured to be 3.02 and 4.62 m, respectively. During RT measurements, the loudspeaker was placed at a distance of 3.5 m from the microphone of the sound

level meter in the living room, and at a distance of 5 m in the classroom. Also, in the living-room condition, curtains and wall hangings that might aid in reducing the overall RT were absent. To account acoustically for these common household items, nine 1-m-long foam wedges were positioned across a radiator and two identical wedges were positioned across an exposed windowpane. These modifications reduced the RT in this room from an initial value of 0.299 s to 0.245 s, which is consistent with a living room having a similar volume (Kuttruff, 1991). For all measurements, the microphone of the sound level meter was placed at the center-head position of an absent KEMAR manikin (i.e., 1.5 m above the floor).

As shown in Table 2.9, five reverberation measurements were made at each of four frequencies (500, 1000, 2000, and 4000 Hz) in each room, using narrow-band noise from an audiometer (GSI-16) and amplified through a Crown D75A amplifier. These measurements were then averaged to derive an overall estimate of the RT for a given room. Average RT values for the sound-treated room, living room, and classroom were determined to be 0.054 s, 0.245 s, and 0.420 s, respectively. The values derived for the sound-treated room and classroom were found to be within .05 s of previously published data in these same rooms (Punch et al., 1994). As noted previously, no comparison RT data are available for the simulated living room used in this study.

Recording of Hearing Aid-Processed Stimuli in Rooms

Because the objective of this study was to assess listener preferences for various polar patterns under everyday listening conditions, the 12 RSIR passages were recorded against a competing noise (multitalker babble) through the hearing aid positioned on KEMAR in each room. This subsection describes the procedures used for recording stimuli and for subsequent tasks performed prior to data collection.

Determining a Fixed Signal-to-Noise Ratio

To ensure that listeners perceived intelligibility to be nearer 50% than to either 0% or 100% (i.e., indicating floor and ceiling effects, respectively) across each microphone and room condition, a pilot study was undertaken. A Realistic 33-1073A omnidirectional microphone was suspended in an anechoic chamber over a padded metal beam at a height equal to the midpoint of the loudspeaker's transducer (i.e., 1.5 m) and at a distance of 2 m from the microphone. The physical arrangement of the equipment used during the pilot study is shown in Figure 2.9. A Sony VAIO PCV-RX540 personal computer was used to store and play back the 30-s sample of each stereo RSIR passage and accompanying multitalker babble. Each speech passage (from channel 2) and competing noise (from channel 1) was routed from the computer's sound card to a loudspeaker array by means of a Crown D75A amplifier. Each loudspeaker was positioned 2 m from the suspended microphone and at a height of 1.5 m. Speech passages

were presented to the loudspeaker positioned at 0° azimuth, and noise was presented to the remaining three speakers positioned at 135° , 180° , and 225° .

The gain of the amplifier (in channel 2) was fixed to 68 dB Leq for the speech passage, while the gain level for the competing noise (in channel 1) was set to an arbitrary level. Three normal-hearing listeners heard the speech-in-noise monaurally via Sennheiser HD 535 headphones and, using a method of adjustment, modified the gain of channel 1 on the Crown D75A to a point that yielded an estimated SNR at which 50% speech intelligibility was achieved. As shown in Table 2.10, the SNR estimate for each listener was found to be within ± 0.7 dB of the mean value of -5 dB.

A 1000 Hz sine wave that matched the frequent peaks of speech for the RSIR passages was then created. The purpose of the 1000 Hz sine wave was to ensure that the electrical input (to the loudspeakers) across the amplifier terminals remained consistent during the recording of the experimental stimuli. An electrical measurement was made across the amplifier terminals for channels 1 (noise) and 2 (speech) using the same 1000 Hz sine wave, and found to be 0.814 V and 1.578 V, respectively.

Recording of Stimuli in Rooms

Using the fixed -5-dB SNR value, the stereo WAV files were presented for recording purposes in a sound-treated room, a simulated living room, and a classroom. In each condition, speech was presented from loudspeaker A positioned directly in front (0° azimuth) of KEMAR and the competing noise was

presented simultaneously from loudspeakers B, C, and D, positioned at azimuths of 135° , 180° , and 225° , respectively. KEMAR was fitted with the Nexus device in the right ear and placed on a blanketed table. The middle of KEMAR's head was positioned 1.5 m from the floor, and the height of the speaker stand was adjusted so that the midpoint of each loudspeaker's transducer also measured 1.5 m.

Using the previously described method for playback, recordings of stimuli were made in each of the three rooms (Figures 2.10 – 2.12). In the sound-treated room, the loudspeakers were positioned 1 m from the midpoint of KEMAR's head (Figure 2.10). In the simulated living room and classroom, the speaker array was positioned at a distance of 2 and 3 m, respectively, from the midpoint of KEMAR's head and slightly off-center relative to the room (Figures 2.11 and 2.12). An off-center placement within each room was incorporated to emulate real-world conditions in which the typical listener is not in the center of a given room.

The 12 RSIR passages and competing noise were presented concurrently through the Nexus device, and delivered electrically to an Etymotic Research ER-11 preamplifier. This preamplifier was enabled to exclude external ear effects for each microphone condition (Killion, 1979). Signals were then passed to a Shure FP11 microphone amplifier and delivered to the left channel of a single digital audiotape (DAT) recorder (Sony 75ES). The recording level was adjusted to match the mid-point range of the DAT recorder and was monitored by means of a Sennheiser HD 535 headphone. Ten seconds of silence was recorded

between the individual microphone-condition recordings, and a 30-s interval of silence was inserted between the recordings made in different rooms.

Direct Digital Transfer

The digital audio recordings on DAT were transferred directly to computer files (.wav) by means of a software/hardware interface (USPre, version 1.5). This yielded 9 different computer files (3 microphone conditions x 3 room conditions), each approximately 7 minutes in length. Each file from the DAT contained the 12 RSIR passages in noise as recorded through the hearing aid, at a sampling rate of 48000 Hz. To reduce the amount of space needed for each experimental passage and to speed disc access time, the 12 RSIR passages for each microphone-by-room condition were down-sampled from 48000 Hz (on the DAT) to 11025 Hz at 16-bit resolution. The passages were also ramped on and off with a rise-fall time of 0.02 s before being stored as individual computer sound files. Finally, digital levels were adjusted so that all passages had equal overall rms power.

Long-term Average Speech-in-Noise Spectrum

Figures 2.13 – 2.15 show the long-term average spectrum of a representative speech passage in noise (passage #12), as recorded in each of the three rooms at each of the three microphone settings. Because the signal-to-noise ratio was negative (-5-dB SNR), the energy in these spectra comes predominantly from the background noise. That energy was modulated differently

for each condition, as expected. With respect to microphones, it can be seen that both directional settings (cardioid and hypercardioid) provided somewhat greater low-frequency power, and reduced (in some cases distinctly reduced) mid-frequency power, as compared to the omnidirectional setting. The different room environments affected the extent to which the directional and omnidirectional plots differed, and the portion of the spectrum over which they differed, again as expected. Room effects were most evident at frequencies between 250 and 2000 Hz.

Spectrographic Analysis

Figures 2.16 – 2.18 show spectrographic analyses of RSIR passage #12. The analyses were performed on a two-second segment, over which the formant structure of the target passage was prominent and readily imaged. Each figure shows spectrograms of this time segment as recorded in a different room; each panel within a figure shows the spectrogram for a different microphone setting.

In all three rooms, the formant structure of the target passage stands out from the background noise least distinctly when recorded with an omnidirectional microphone (top panel in each figure). Formants are more clearly visible for the cardioid- and hypercardioid-microphone conditions, due their enhanced ability to suppress the competing background noise.

Room differences are also visible in the spectrograms. Most notably, temporal smearing is greater in the living room and classroom than in the sound room, due to the formers' longer reverberation times.

Experimental Procedures

Paired-Comparison Task

A 3 x 3 (9-cell) matrix, seen in Figure 2.19, was used throughout the study to represent the recorded conditions for playback and data analysis. Rows represent the 3 microphone settings, while columns represent the 3 test rooms.

Both paired-comparison procedures utilized a round-robin tournament strategy. For the nine conditions of the experiment (in Figure 2.19), there was a total of 36 stimulus pairs, based on the formula (Bock & Jones, 1968):

$$p = n(n-1)/2 \quad (2.2)$$

where p represents the number of stimulus pairs and n represents the number of stimulus conditions.

Customized software allowed for the randomization of the microphone-by-room stimuli during each run, as well as the randomization of the sequence of pairs presented. For each stimulus pair selected by the software, the same passage was presented. Paired stimuli were delivered to the left and right channels of a Tucker-Davis Technologies (TDT) two-channel digital-to-analog converter (DAC), which could be alternated between the channels based on subject input via a response box (Figure 2.20). A TDT PA4 programmable attenuator, working in conjunction with the two-channel DAC, attenuated one stimulus and increased the other as conditions A and B were switched. This allowed subjects to listen to each stimulus condition independently, while

avoiding click artifacts. The stimuli were low-pass filtered at 5000 Hz and sent to a mixer. These signals were then amplified (Crown D75A) and delivered to the insert earphone (Etymotic Research ER-3A) worn by the subject.

For Group 1 (normal-hearing listeners), the hearing aid-processed stimuli were always presented at 70 dB SPL. For Groups 2E and 2I, stimuli were presented at each subject's most comfortable loudness (MCL) level. For the MCL procedure, a Madsen Itera audiometer with calibrated Etymotic Research ER-3A insert earphone replaced the amplifier (Crown D75A), as noted in Figure 2.21. MCL levels were derived using a modified version of a method proposed by Joseph, Punch, and Rakerd (2003)⁵, which uses loudness categories used in the Contour Test of the Independent Hearing Aid Fitting Forum (IHAF) protocol (Cox, 1995). Presentations began at 50 dB HL and increased in 2.5 dB steps until a rating of 5 (Comfortable, But Slightly Loud) was verbally reported by a listener. At that point, descending levels were presented in 5 dB steps until the listener verbally reported a loudness value of 2 (Soft). An MCL was determined only after the listener rated loudness to be 4 (Comfortable) on 2 out of 3 ascending trials. The stimuli for the MCL task consisted of randomized RSIR passages only for the cardioid microphone in the living-room condition (Cell 5 in Figure 2.19). These conditions were selected as representative of a directional condition in an everyday room, which reflected the majority of listening conditions

⁵ The procedure used in this study differed from that proposed by Joseph et al. (2003), who studied normal-hearing listeners, in that step-size intervals were decreased from 5 and 10 dB to 2.5 and 5 dB in the ascending and descending directions, respectively. The reduced step sizes were necessitated based on findings from Rakerd, Punch, Hooks, Amlani, and Vander Velde (1999), who observed that loudness magnitude for constant speech loudness averaged 2.4 dB across hearing-impaired listeners exhibiting mild-to-moderate sensorineural hearing loss.

in the experiment. During the task, a given listener made judgments of loudness based on the same passage. This was done to reduce any perceptual variations caused by microphone and reverberation effects, and to provide all listeners with the same reference condition during the MCL procedure. A detailed description of the MCL task can be found in Appendix F.

Data Collection

Testing for both experiments was completed in a single session lasting approximately 90 minutes. During testing, the subject was seated in an anechoic chamber with an insert earphone (Etymotic Research ER-3A) placed in the preferred ear. Listeners were asked to judge the clarity of speech in noise in both a traditional paired-comparison method (AB) and a modified paired-comparison method in which they were allowed a third choice of No Preference (ABN).

Practice Task. Each subject completed a practice task prior to formal testing. During the practice task, 18 of the possible 36 comparisons were administered. The specific pairings were selected randomly by the custom-written software, and the sequence of procedures (AB, ABN) was counterbalanced across subjects and groups. Subjects were given 30 s, or the length of each passage, to indicate their preference via a response box. The response box allowed each subject to start a run by toggling a switch from the off position to the on position. This action triggered the simultaneous onset of three different-colored lights directly above buttons A, B and C. This lighting pattern

cued the subject to listen carefully. After a 2-s pause, a single light randomly selected by the computer remained illuminated above button A or B, indicating which stimulus (A or B) was being heard. The subject was asked to listen to this condition, and to note the percentage of speech intelligibility for the passage. Once the amount of speech intelligibility had been determined for the initial stimulus, the subject's task was to depress the alternate button (A or B) representing the comparison stimulus. The subject's selection was confirmed when the respective light above the alternate button illuminated. Subjects were instructed to alternate between stimulus pairs as often as needed during the 30-s time period. To indicate a preference in the AB task, the subject was instructed to toggle the on-off switch to the off position, and press the button (A or B) corresponding to the preferred stimulus. The computer stored each preference in a 9 x 9 matrix (Table 2.11).

Use of the response box was the same for the ABN task, with the exception that if listeners judged the paired stimuli to be equally good or equally poor (ties), they had the option of depressing button C. After each run, the computer stored preferences for ABN Preference in a 9 x 9 matrix, similar to that seen in Table 2.12. Table 2.13 shows the computer-stored No-Preference (N) data for stimulus pairs that resulted in ties. Subject instructions for both tasks are provided in Appendices G and H.

Based on the findings of Punch and colleagues (2001), it was predetermined that 7 minutes should be sufficient for subjects to perform a given

AB or ABN practice task. To be included in this study, subjects were required to perform each task within the allotted time frame. Each subject recruited for the study was able to meet this predetermined criterion.

Experimental Task. Upon completing the practice task, subjects were reinstructed to judge the relative clarity of the speech-in-noise passages. The instructions to each subject, and the procedures to control the sequence of tasks (AB, ABN), were the same as those given earlier during the practice task. The experimental task differed from the practice task only in that each subject heard all 36 comparisons during each listening condition. Data from both the practice and experimental tasks were collected over a single session lasting approximately 90 minutes.

Experiment 1. For the traditional AB task (Table 2.11), two data matrices resulted for each subject, one each for runs 1 and 2. Each matrix represented each of the nine conditions (3 rooms x 3 microphones) in the columns and rows of a table. In the AB task (Table 2.11), a preference for A or B was stored as a 1 to indicate the row number (preferred cell) as that preferred over the column number (compared cell). Table 2.11 illustrates, for instance, a comparison between cells 3 (row) and 4 (column). Note that a 1 was placed in that cell, indicating that cell 3 was preferred over cell 4. (Cells having the same microphone and room characteristics, e.g., row 3 and column 3, were not compared to each other.) To indicate that these cells were not compared with

themselves, blanks are shown on the diagonal. The number of times a cell was preferred over another, termed *wins*, was also tallied. Wins were then rank ordered from most to least, and cells that resulted in the same number of wins were assigned the same rank.

Experiment 2. For the modified ABN method, there were two matrices per subject per run. One was an AB Preference matrix (Table 2.12), while the other was an ABN No-Preference matrix (Table 2.13). When listeners chose A or B, ABN Preference (Table 2.12) results were stored similarly to those in the AB task. For example, a 1 was stored under row 6 column 8, indicating that the cardioid-microphone pattern in the sound-treated room was preferred over the hypercardioid-microphone pattern in the living room. (Refer, as needed, to Figure 2.19.) Note that a 0 was assigned when either a row was beaten by a column value (e.g., row 8, column 6) or when no preference was observed for either condition (e.g., row 6, column 9). Note that in Table 2.12, a winner emerged in a total of 31 out of a possible 36 comparisons. The remaining 5 judgments are reported in Table 2.13 as No Preference.

In cases in which listeners chose N, or No Preference (Table 2.13), a 1 was stored in the cell intersecting the conditions that were tied (e.g., row 6, column 9). A 0 was stored for those intersecting cells for which there was a preference for either A or B. In Table 2.13, the values of 1 and 0 are stored only in the upper diagonal of the matrix to avoid unnecessary duplication of the No-Preference data.

Statistical Analyses

To answer question 1 with respect to Experiment 1 (differences in polar-pattern preferences across differing room conditions), data were analyzed by a rank-order correlation (Spearman ρ) procedure. For question 2 (differences in polar patterns across listener groups), data were submitted to a three-way repeated-measures ANOVA. The analyses were computed using the Statistical Package for Social Sciences software (SPSS, version 11.01). For the ANOVA procedure, multivariate tests were used because of their greater sensitivity and control over the partitioning of the sum of squares when compared to traditional univariate tests (Stevens, 1996). The Pillai's Trace method was utilized throughout this study because of its sensitivity to small sample sizes (Rechner, 1995). A second rationale for using the multivariate approach was to circumvent problems associated with the sphericity assumption (Stevens, 1996). The sphericity assumption is associated with repeated-measures designs, like the present one, that have three or more conditions. This assumption is violated when the variance of scores across conditions is not homogeneous. Because multivariate tests estimate the covariances between the dependent variables, there is no further need to consider sphericity assumptions (Max & Onghea, 1999).

In Experiment 2, which assessed the sensitivity of the ABN procedure relative to the traditional AB method, the analyses used were the same as those

used in questions 1 and 2 of Experiment 1. Thus a Spearman *rho* procedure and repeated-measures ANOVA were used to analyze the ABN Preference data. For the No-Preference data, a repeated-measures ANOVA was performed.

CHAPTER 3

RESULTS AND DISCUSSION

The purposes of this study were: (1) to examine listener preferences for omnidirectional and two types of directional microphones (cardioid and hypercardioid) in laboratory and real-world rooms for an ITE hearing aid, using a paired-comparison paradigm, and (2) to determine whether the ABN paradigm offers any substantive advantages over those produced by the more traditional AB procedure in the evaluation of paired-comparison judgments of directionality. In Experiment 1, data were analyzed for the traditional paired-comparison paradigm with regard to the following questions:

1. Which polar pattern—omnidirectional, cardioid, or hypercardioid—do listeners prefer in real-world environments, based on judgments of speech clarity?
2. Do preferences for polar patterns, based on speech clarity, differ among a group of normal-hearing listeners, a group of hearing-impaired listeners who are inexperienced with amplification, and a group of hearing-impaired listeners who are experienced with amplification?

For Experiment 2, in which a modified paired-comparison technique was used, the questions posed were:

1. Does a modified paired-comparison technique (ABN) improve the reliability and sensitivity of paired-comparison judgments when contrasted with the AB procedure used in Experiment 1?
2. Is the overall or specific structural pattern of the preference data obtained with the ABN procedure different from that observed with the AB procedure?
3. Does the No-Preference (N) component of the ABN procedure yield additional information not otherwise found with the AB procedure?

Results

Comparison of Hearing Sensitivity between Hearing-Impaired Groups

To assure that any differences between the two hearing-impaired groups were related to hearing aid experience, and not hearing sensitivity, an independent-samples *t* test was performed to compare mean audiometric data across Groups 2E and 2I. Specifically, groups served as the independent variable and pure-tone audiometric thresholds obtained at the six audiometric frequencies between 250 and 8000 Hz of the test ear were used as the dependent variables. The only statistically significant difference ($t(22)$, $p < .05$)

noted between groups was at 500 Hz, where the mean difference in threshold sensitivity was 6.4 dB (see Tables 2.2 and 2.3). This indicates that hearing sensitivity for the frequencies most important to speech intelligibility was nearly identical across groups, and that any differences in clarity judgments could reasonably be attributed to differences in experience with amplification.

Experiment 1 Results - AB Task

Most Preferred Polar Pattern

Question 1 of the first experiment asked whether specific polar patterns were most preferred in specific rooms. Cell preference rankings were analyzed to answer this question. Overall rankings by group are displayed for the AB procedure in Table 3.1.

For the most part, rank-ordered data for the AB task were similar across all three groups. Specifically, the hypercardioid pattern in the sound-treated room (cell 9) and the cardioid pattern in the sound-treated room (cell 6) were rank ordered first or second by all three groups. Table 3.1 also indicates that each group preferred directional microphones to omnidirectional microphones under all conditions tested in this study.

Rank-ordered data from Table 3.1 were also arranged across room and group. This arrangement of the rank-ordered data provided insight on cell preferences across rooms, and by group. Specifically, cells 1, 4, 7 constituted the classroom condition, cells 2, 5, 8, the living-room condition, and cells 3, 6, and 9, the sound-treated room condition. The most preferred cells for each room-by-

group condition are tabulated in Table 3.2. For Group 1, the hypercardioid pattern was preferred 187 times and 74 times in the sound-treated room (cell 9) and classroom (cell 7) conditions, respectively, and the cardioid pattern was judged to provide the greatest amount of clarity 114 times in the living-room (cell 5) condition. Group 2I indicated a preference for the hypercardioid pattern in the classroom (cell 7), and the cardioid pattern in both the sound-treated room (cell 6) and living-room (cell 5) conditions. Group 2E judged clarity to be highest with the cardioid pattern in the sound-treated room (cell 6), and with the hypercardioid pattern in the living room (cell 8) and classroom (cell 7). Note that in the classroom, all three groups judged the hypercardioid pattern (cell 7) to provide the greatest amount of clarity.

A test of proportional differences was used to determine if preferred cells in Table 3.2 differed statistically. Proportions were derived by dividing the total number of wins for the most preferred cell (seen in Table 3.2) by the total number of possible wins, or 864 (12 subjects x 36 comparisons x 2 runs) for each group. Using procedures detailed by Berenson, Levine, and Krehbiel (2003), each proportion was converted to a *z*-score and compared to the others. Findings revealed proportions not to be statistically different ($p > .05$) between groups within a given room, indicating that each group behaved similarly for the same room condition.

Test-Retest Reliability

A test-retest reliability analysis was performed in which rank orderings of conditions were compared across runs. The rank-order correlation of results for runs 1 and 2 was calculated for each group. The results, as seen in Table 3.3, ranged from a .97 to 1.00 across the three groups for runs 1 and 2 of the AB task. This result indicates strong test-retest reliability, which was found to be statistically significant at the .01 level.

Rho values were then broken down by room condition for each group, based on preferences across both runs (see Table 3.4). The purpose of this analysis was to determine the test-retest reliability across rooms and groups. For Group 1, *rho* values of 1.00 were found for the AB task across the three room conditions. As expected, these values were significant ($p < .01$).⁶ For Group 2E, preferences by room condition revealed statistically significant values of 1.00 for the classroom and living room conditions in the AB task. Group 2I also demonstrated statistically significant *rho* values of 1.00 for the classroom and living room conditions in the AB paradigm. These findings indicate that listener preferences were highly repeatable under the specified conditions.

Polar-Pattern Preference across Rooms and Groups – AB Task

The second research question addressed in Experiment 1 asked whether subjective ratings of clarity across microphone and room conditions differed for

⁶ The Spearman *rho* correlation coefficients were derived using SPSS (version 11.01) software. Results are reported using an alpha of .01 (two-tailed) and not .05, based on the limitations of this software.

the three groups of listeners. This question was examined by summing cell preferences across microphones, rooms, and groups, and using a three-way repeated-measures ANOVA to assess differences. Table 3.5 represents the outcome derived for cell preferences in the AB task.

Main Effects. Statistically significant main effects were found for the within-subjects conditions of microphone ($F [2, 32] = 271.92, p < .001$) and room ($F [2, 32] = 613.37, p < .001$). Figure 3.1 reports the mean number of wins (times preferred) for each microphone condition. Bonferroni-corrected CI_{95} pairwise comparisons for the microphone condition revealed differences ($p < .05$) between the omnidirectional and cardioid patterns, and between the omnidirectional and hypercardioid patterns. The cardioid and hypercardioid directional patterns, which differed by less than one mean win, were found not to be different ($p > .05$). This outcome indicates that the omnidirectional microphone was less preferred than either of the directional microphones, and that the two directional patterns were about equally preferred overall.

For the variable of room condition, as seen in Figure 3.2, pairwise comparisons indicated that each room condition differed statistically from each of the others, with the sound-treated room most preferred, the classroom least preferred, and the living room intermediate. This finding suggests an inverse relationship between RT and preference based on clarity.

Interaction Effects. There were significant interactions between microphone and room ($F [4, 30] = 6.79, p < .01$) and between room and group ($F [4, 66] = 2.80, p < .05$). These interactions are depicted in Figures 3.3 and 3.4, respectively.

Figure 3.3 shows that the interaction between room and microphone was driven by a slight but consistent listener preference for the hypercardioid pattern in the classroom environment. As shown in Figure 3.4, the room-by-group interaction effect emerged from Group 1's stronger preference for the sound-room environment, when compared to the two hearing-impaired groups.

A statistically significant three-way interaction effect between microphone, room, and group was also found ($F [8, 62] = 2.23, p < .05$). This interaction effect is displayed in Figure 3.5. Post-hoc analyses were again conducted using CI_{95} pairwise comparisons. These comparisons revealed, as noted above, that Group 1 preferred the sound-room environment. That preference is visibly more pronounced than for either of the other two groups. Group 1 had an affinity for the hypercardioid pattern in the sound-treated room. No other statistically significant findings were noted.

In both Figures 3.4 and 3.5, the two hearing-impaired groups performed similarly overall. Hence, the data seem to indicate that experience with hearing aids is not a critical factor in determining speech-clarity judgments with respect to directional-microphone preferences.

Experiment 2 Results - ABN Preference

Most Preferred Polar Pattern

Similar to the analysis undertaken for the AB task, ABN Preference data were also analyzed to assess whether specific polar patterns were most preferred in specific rooms. ABN Preference findings for overall rankings by group are reported in Table 3.6. Rank ordering across all three groups revealed that the hypercardioid pattern in the sound-treated room (cell 9) was most preferred, followed by the cardioid pattern in the sound-treated room (cell 6). Table 3.6 indicates that, for the most part, each group preferred directional patterns to the omnidirectional pattern under the conditions tested in this study.

Data in Table 3.6 were next sectioned by room condition and by group. Results, tabulated in Table 3.7, revealed that all three groups favored the hypercardioid pattern in the sound-treated room (cell 9). Group 2I also favored the hypercardioid pattern (cell 8) in the living-room condition. For Groups 1 and 2E, however, the cardioid pattern was preferred in the living-room condition (cell 5). In the most reverberant condition (i.e., classroom), directional patterns were also preferred over the omnidirectional pattern. Specifically, Groups 1 and 2I judged the hypercardioid pattern (cell 7) to provide the greatest amount of clarity, while Group 2E preferred the cardioid microphone (cell 4).

To determine if cell preferences in Table 3.7 differed statistically, the total number of wins for the most preferred cell was divided by 864 (12 subjects x 36 comparisons x 2 runs), or the total possible number of wins, resulting in a proportion. Each proportion was converted to a z-score and compared for

statistical significance. No significant differences ($p > .05$) were found between groups within a given room. This finding indicated that each group behaved similarly within the same room condition.

Test-Retest Reliability

Rank ordering, as described previously in Experiment 1, was constructed for each run across all subjects in a given group. This was achieved by tabulating the number of wins (i.e., 1s) across the nine microphone-by-room cells for each group of 12 listeners. These wins were then converted to ranks prior to statistical analysis.

For ABN Preference, the Spearman ρ correlations between preference rankings, as seen in Table 3.8, ranged narrowly from 0.97 to 0.98 across the 3 groups in runs 1 and 2. All comparisons were found to be statistically significant at the .01 level, suggesting that listener judgments were not due to chance.

ρ values were then broken down by room condition for each group based on preferences across both runs. The purpose of this analysis was to determine the test-retest reliability across groups and rooms. Results are presented in Table 3.9. For Groups 1 and 2I, a statistically significant ($p < .01$) ρ value of 1.00 was found for each of the three room conditions. For Group 2E, a statistically significant ρ of 1.00 was found for the sound-treated room and living-room conditions. These findings suggest that listener judgments were highly repeatable.

Polar-Pattern Preference Across Rooms and Groups – ABN Preference

In Experiment 2, question 2 was directed at determining whether the ABN procedure produced essentially the same pattern of subjective ratings of speech clarity across room and microphone conditions as that produced by the AB procedure. As a result, ABN data were addressed in essentially the same manner as described earlier for the AB task. Specifically, cell preferences across groups, room, and microphone were summed, and a three-way repeated-measures ANOVA performed. Results of the three-way repeated measures ANOVA for ABN Preference data are shown in Table 3.10.

Main Effects. Significant main effects were found for microphone ($F [2, 32] = 426.15, p < .001$) and room ($F [2, 32] = 616.25, p < .001$) (Figures 3.6 and 3.7, respectively). There were significant pairwise differences between the omnidirectional and cardioid microphone patterns, and between the omnidirectional and hypercardioid patterns (right panel of Figure 3.6). A comparison of room condition, shown in the right panel of Figure 3.6, revealed differences ($p < .05$) between each room condition. This finding suggests that as RT increased, the number of preferences based on clarity decreased.

One of the important questions addressed in Experiment 2 is whether the overall structure of the preference judgments for ABN Preference is similar to that found under the AB procedure. Figures 3.6 and 3.7 provide a direct comparison of the main effects of microphone and room (right-hand panel of each figure) with the corresponding AB-only plots (left-hand panel). The plots for

both microphone and room are very similar for the two experiments, with the exception that use of the No-Preference option of the ABN procedure resulted in fewer overall preferences than occurred with the AB procedure.

Interaction Effects. There were significant two-way interactions between microphone and room ($F [4, 30] = 20.78, p < .001$), room and group ($F [4, 66] = 4.04, p < .01$), and microphone and group ($F [4, 66] = 3.69, p < .01$). These interactions are illustrated in the right panel of Figures 3.8 and 3.9, and in Figure 3.10, respectively. The results seen in Figures 3.8 and 3.9 are very similar to those obtained (in Experiment 1) with the AB paradigm. The microphone-by-group interaction effect was not statistically significant for the AB procedure and, therefore, results of this interaction effect are shown for ABN Preference only (Figure 3.10). CI_{95} pairwise comparisons revealed that this interaction effect occurred because Group 2I had a greater preference for the cardioid microphone when compared to Group 2E.

Experiment 2 Results – ABN No Preference

Polar-Pattern Preference across Rooms and Groups – ABN No Preference

Descriptive and inferential analyses were also undertaken to evaluate the use of the No Preference, or N, option available to listeners during the ABN task. Recall that subjects were instructed to use the N option when they judged paired stimuli to be equally good or equally poor (i.e., tied). A descriptive analysis revealed that Group 1 (normal-hearing listeners) utilized the N option a total of

146 times out of a possible 864 (12 subjects x 36 comparisons x 2 runs) times—16.9% of all trials. Groups 2E and 2I used the N option in 17.8% and 23.0% of all trials, respectively. Across all groups, the omnidirectional pattern generated the greatest number of N responses (283), followed by the cardioid pattern (194 responses). In contrast, the hypercardioid pattern elicited an N response just 22 times. This indicates that when the hypercardioid pattern was involved as one of paired stimuli, preferences—generally for the hypercardioid pattern—tended to be strong. Findings, tallied across all subjects, revealed 193, 181, and 125 N responses for the classroom, living-room, and sound-treated room conditions, respectively.

No-Preference data were analyzed using a three-way repeated-measures ANOVA. These data did not constitute cell preferences, but rather the number of times the reference and compared cells were found to provide equal intelligibility, as illustrated previously in Table 2.13. The results of the ANOVA are shown in Table 3.11.

Main Effects. There were significant main effects for microphone ($F [2, 32] = 79.83, p < .001$) and room ($F [2, 32] = 7.39, p < .01$) (Figures 3.11 and 3.12, respectively). No significant difference ($F [2] = 1.57, p > .05$) was found for the between-subjects main effect of group.

Interaction Effects. There were no statistically significant interaction effects.

Discussion

One purpose of this study was to determine, based on judgments of speech clarity, whether directional hearing aid microphone patterns were preferred over an omnidirectional pattern in different real-world environments. The motivation for the study was based on findings in the literature suggesting that directional microphones often show a substantial advantage over omnidirectional microphones, primarily under controlled laboratory conditions, but that such an advantage has been evident in only a limited number of studies incorporating everyday conditions. In fact, the amount of directional advantage realized in the real world remains unknown, in part, because previous studies have shown that listeners have a tendency to use exclusively the default mode, often omnidirectional, after being fit with a switchable omnidirectional/directional hearing aid (Cord et al., 2002; Kuk, 1996; Sommers, 1979). Cord et al. (2002) reported that common reasons for not using directional microphones are related to the patients' difficulty remembering the different programs in their hearing aids and/or how to use them. In the present study, the experimenter carefully controlled access to different microphone (and room) conditions, and listeners made clarity judgments only after toggling between directly paired conditions.

Another potential factor that may have confounded the determination of any real-world directional advantage in previous studies is related to the methodologies used in data collection. Some of these studies have required subjects to wear a switchable omnidirectional/directional hearing aid over a period of time, and at a later date to provide subjective responses regarding their

real-world experiences using survey and categorical-scaling procedures (Chasin, 1994; Cord et al., 2002; Walden et al., 2000). Because of the time delay between testing and responding, the validity and reliability of the listener's responses may be questionable. Paired comparisons were used in the present study to overcome this problem. Specifically, paired stimuli were presented sequentially and with minimal time delays between presentations, resulting in a cognitively simpler task (Fabry & Schum, 1994). Studebaker (1982) further suggested that judgments of small differences between stimuli are easier to make when performed in a comparative mode rather than in an isolated mode.

To simulate real-world environments, this study utilized living room and classroom environments for the recording of speech and noise stimuli. It also incorporated sound sources at distances and recording-microphone orientations that simulated real-world communication settings for typical listeners.

Experiment 1

In Experiment 1 of this study, question 1 was designed to determine which polar pattern listeners preferred in different real-world environments. For all three groups of listeners, preferences revealed that directional patterns were superior to the omnidirectional pattern in all three rooms tested. This finding is consistent with studies by Kuk (1996) and Surr et al. (2002), who also found that listeners preferred directional microphones under everyday listening conditions.

In addition, findings indicated that the preferred microphone pattern differed as a function of the acoustic environment (Table 3.1). Specifically, the

hypercardioid pattern was preferred in a sound-treated room and in a living room, while the cardioid pattern was preferred in a classroom condition.

The hearing aid used in this study was unvented. As a result, directivity was probably greater than it would have been with the same aid in a vented shell (Ricketts, 2000). It is possible that significant differences, or differences of the same degree, would not have been noted between the omnidirectional and both directional polar patterns if venting had been used. Until such empirical evidence is available, audiologists should consider selecting and fitting more than one polar pattern for patients who experience multiple acoustical environments in their everyday lives.

Question 2 of Experiment 1 addressed whether preferences for polar patterns differed across listener groups. For the most part, group preferences agreed very closely. For instance, each group judged directional patterns to provide better speech clarity than the omnidirectional polar pattern in all three listening environments. Preferences for the cardioid and hypercardioid patterns were highly similar within a given room for both hearing-impaired groups (see Figure 3.2). Based on these findings, it seems reasonable to conclude that experience with amplification is not a critical factor in determining microphone preference using speech-clarity judgments.

The data that addressed Question 2 also revealed an inverse relationship between RT and preference based on speech clarity. That is, as RT increased, clarity decreased. This outcome was anticipated based on previous studies that used objective test methods (e.g., Hawkins & Yacullo, 1984; Leeuw and

Dreschler, 1991; Madison & Hawkins, 1983). The fact that significant polar-pattern preferences were seen for rooms differing in RT by only a few hundred milliseconds is compelling. This suggests that microphone effects evaluated in a sound-treated room with a small RT, an environment used in many clinical settings, can differ from those that listeners experience in the real world. Because sound-treated rooms are known to range in RT between 50 and 600 ms (Madison & Hawkins, 1983; Nielsen & Ludvigsen, 1978; Punch et al., 1994; Studebaker et al., 1980), clinicians must recognize the potential acoustical impact of test conditions in their clinics if they are to make reasonable predictions of performance of their patients when aided in the real world. For rooms having short RTs, such as the sound-treated room used in this study, clinicians can assume that the ability to simulate the acoustical properties of everyday listening environments is poor.

The three rooms differed markedly in their RTs, which led to differing degrees of temporal smearing of the speech and noise. These differences were clearly visible in a spectrographic analysis of the stimuli (Figures 2.16-2.18). Apparently, these differences were also audible to listeners. It should be pointed out that the room acoustics differed in other ways, as well. Most notably, there were differences in the ambient noise levels and in the rooms' impact on the spectral characteristics of signals, as determined by RT characteristics.

Subjects in this study made speech-clarity judgments monaurally. It is possible that the results of the study would have been even stronger, and more clinically compelling, had listening been binaural. In fact, the literature suggests

that hearing aid comparisons made monaurally may reflect less sensitivity to differences among the electroacoustic characteristics (including directionality) of hearing aids (e.g., Hall & Fernandes, 1983; Hawkins & Yacullo, 1984; Naidoo & Hawkins, 1997). The complexities of this study precluded the use of binaural hearing aids and listening conditions. Had this study incorporated binaural listening, it seems reasonable to conjecture that findings might have resulted in greater differences in preferences across hearing-impaired groups, and possibly a clearer preference for one directional microphone over the other.

Experiment 2

Experiment 2 was undertaken to determine whether the ABN paradigm offers any substantive advantages over those produced by the more traditional AB procedure in the evaluation of paired-comparison judgments of directionality. This aspect of the study was motivated largely by findings reported by Punch and colleagues (2001), who found that the ABN procedure improved the reliability and sensitivity of preferred frequency-response slopes in a simulated programmable hearing aid. Although intrasession test-retest reliability for their group of normal-hearing listeners was similar for the AB and ABN procedures, as determined by Spearman *rho* correlation coefficients, the reliability of slopes ranked as top choices was notably greater for the ABN than for the AB procedure. In the present study on directionality, intrasession test-retest reliability was found to be very high when assessed with both the AB and ABN procedures

(all values at .97 or above). Further analysis of reliability of top choices was considered impractical, based on findings discussed below.

Whereas the earlier findings of Punch and colleagues (2001) revealed that the modified procedure (ABN) demonstrated greater statistical sensitivity (i.e., larger *F*-ratios) than the more traditional paired-comparison technique (AB), in this study, the AB and ABN methods yielded similar trends for microphone and room across groups. Findings of this study, therefore, reflected essentially equal statistical sensitivity for the two procedures. As a result, no significant increase in power was observed for ABN, which most probably occurred because of large perceptual differences among stimuli.

Question 2 of Experiment 2 addressed whether preference patterns between the ABN and AB procedures were similar. For the ANOVA main effects of microphone and room, and for the interaction effects of microphone-by-room and room-by-group, the answer is clearly yes (see Figures 3.6 – 3.9). Only slight differences in rank ordering were noted between the two psychophysical procedures, based on the Spearman *rho* correlation analyses and the interaction effects provided by the ANOVA analysis.

In question 3 of Experiment 2, the patterning of No-Preference responses associated with the ABN method was assessed. In their study, Punch et al. (2001) found No-Preference data to be informative. Specifically, they found that listeners were more likely to judge paired stimuli as equally good or equally poor when relatively flat frequency shaping was involved. An analysis of the No-Preference data in the present data was also found to be informative. No-

Preference data showed that listeners chose the N option only occasionally when comparisons involved a hypercardioid pattern. In fact, they demonstrated strong preferences for the hypercardioid pattern when it was available as one of the paired stimuli. Conversely, listeners judged the omnidirectional microphone to be equally desirable or equally undesirable more often, resulting in a greater number of N responses. Across room conditions, listeners were more likely to select N for stimuli recorded in a classroom than in a living room or sound-treated room. The latter finding suggests that longer RTs had an effect on listeners' ability to understand speech.

CHAPTER 4

CONCLUSIONS AND FUTURE DIRECTIONS

The results of Experiment 1 contribute to our understanding of listener preferences in real-world listening conditions. First, results established that listeners overwhelmingly preferred directional microphones over omnidirectional microphones under conditions that simulated real-world settings, even in rooms differing substantially in their reverberation times. This finding clearly indicates that directional microphones are likely to offer an everyday improvement in speech clarity over omnidirectional microphones. A related finding was that the most preferred microphone pattern differed across room environments.

The salience of this finding may be dampened somewhat by the fact that the hearing aid used in this study was unvented. In other words, the directivity of the hearing aid was likely greater than it would have been had the shell been vented (Ricketts, 2000). A follow-up study could be undertaken to determine if listener preferences for polar patterns differ when venting is used under conditions similar to those used in this study.

Hearing Aid Counseling

Previous studies have shown that listeners fitted with hearing aids having switchable microphones do not toggle adequately between microphone options (e.g., Cord et al., 2002, Kuk, 1996; Sommers, 1979). In a recent editorial, Jerger (2003) suggested that listeners might not toggle between microphone options

because of ineffective counseling on the part of the dispenser and unrealistic expectations on the part of the listener. In this study, subjects were required to toggle between hearing aid-processed stimuli differing in microphone and/or room conditions by means of buttons on a response box. The fact that normal-hearing and hearing-impaired listeners were capable of switching reliably between polar patterns, as indicated by the strong Spearman ρ correlation coefficients, suggests that listeners are able to switch to appropriate alternatives if given the proper counseling and sufficient listening experience. A reasonable future study might be done in which the effectiveness of various strategies to counsel listeners on the use and function of hearing aids having switchable microphones is assessed under everyday listening conditions.

Hearing Aid Fitting

A potential follow-up study might be to evaluate speech-recognition performance in noise for a fixed directional pattern and an adaptive directional system. Ricketts and Henry (2002b) found that an adaptive directional system provided significantly better speech-recognition performance in noise when compared to the fixed directional patterns, but only for a few specific listening conditions. Because of the greater sensitivity associated with the paired-comparison procedure over speech-recognition testing, a potential follow-up study might involve a comparison of listener preferences based on paired-comparison speech-clarity judgments, using a fixed-directional pattern and an adaptive directional system.

The fact that this study did not incorporate binaural hearing aids and did not allow for listener preferences under binaural listening conditions may also be considered a shortcoming. In fact, previous literature suggests that hearing aid comparisons made monaurally might reflect less sensitivity to differences among the electroacoustic characteristics (including directionality) of hearing aids (e.g., Hall & Fernandes, 1983; Hawkins & Yacullo, 1984; Naidoo & Hawkins, 1997). A replication of this study performed binaurally is one means by which to answer this question.

At the outset of this study, it was anticipated that Group 2E might perform differently from Group 2I. Such an effect was not observed. Experience with hearing aids, therefore, does not appear to be a critical factor in determining directional-microphone preferences. Were such differences to exist, it is highly likely that they would have been revealed by the paired-comparison method used in these experiments.

In this study, it was found that experience with amplification is not a critical factor in determining polar-pattern preferences. Ricketts and Mueller (1999b) found that audiometric slope, degree of high-frequency hearing loss, and speech-recognition performance in the omnidirectional mode were not predictive of the amount of directional benefit. A study could be undertaken to identify which variables—in addition to the environmental factors experienced by the listener— influence the optimal selection and fitting of directional characteristics.

ABN Method

In Experiment 2, it was hypothesized that a modified paired-comparison technique (ABN) could increase the sensitivity of speech-clarity judgments. Both the AB and ABN paired-comparison procedures showed excellent reliability. The significant difference in statistical sensitivity between AB and ABN, seen earlier by Punch et al. (2001) when they manipulated frequency-response slope in a simulated hearing aid, did not materialize in this study. This outcome can be explained by the fact that listeners in this study had strong preferences for specific polar patterns and rooms. Despite the fact that this study revealed no distinct differences between the normal-hearing and hearing-impaired groups, or between the two hearing-impaired groups, with regard to overall preference trends in the AB and ABN tasks, ABN was shown to provide a modest amount of additional information not available from the traditional paired-comparison method.

In comparing the two studies, both of which relied on listener judgments of speech clarity in a paired-comparison task, it is apparent that when the ABN task is applied to judgments of polar patterns, it does not offer an advantage similar to that found when it is applied to judgments of frequency-response patterns. Simply stated, reporting polar-pattern preferences, at least under conditions of the present investigation, appears to be an easier task for listeners than reporting preferences for different frequency-response patterns. As both studies were based on judgments of speech clarity, this difference may reflect the relative differences in effectiveness of using directional microphones and modifying

frequency-response patterns to alter speech intelligibility. When asked to indicate preferences based on directionality, listeners in this study often had a clear preference for one condition over another. The same was not true for listeners in the Punch et al. (2001) study, who were asked to indicate their preferences for changes in frequency response of a hearing aid. Clearly, further evidence is needed regarding the ABN method's psychophysical and statistical properties before it can be considered a fully viable research and clinical tool in the selection and fitting of hearing aids.

APPENDIX A
TYPES OF MICROPHONES

In this appendix, the characteristics of the omnidirectional hearing aid microphone are discussed, followed by a discussion of the design characteristics of single-microphone and dual-microphone directional hearing aids.

Omnidirectional Microphone

An omnidirectional microphone is essentially a closed box that is divided into two small volumes by a thin diaphragm (Figure A.1). Because it is designed with one sound inlet, all sounds that enter the inlet port are processed equally regardless of azimuth in an acoustic (free⁷ or sound⁸) field. This is achieved when sound pressure enters the microphone through the extension tubing, and then travels toward the front volume of the microphone. In the front volume, the sound pressure displaces the diaphragm. On the opposite side of the diaphragm, the back volume contains a metal plate coated with an electret material, which holds a permanent electrical charge. Movement of the diaphragm near this back plate creates a small electrical signal that is amplified and delivered to the ear. The omnidirectional microphone is considered a conventional design in hearing aids.

Directional Microphones

Directional microphones in hearing aids were commercially available in the United States in 1971 (Mueller, 1981, as reported in Ricketts and Mueller,

⁷ An area over which the sound distributed is not affected by reflections (Nicolosi, Harryman, & Kresheck, 1989).

⁸ An area over which the sound distributed is affected by reflections (Nicolosi et al., 1989).

1999a). At that time, hearing aids were configured with one directional microphone having two sound inlet ports. The two-port design consists of two sound inlets that are horizontally aligned along a line running in the direction faced by the user. These sound inlets lead to two separate cavities, the front and rear inlet ports, divided by a single diaphragm (Figure A.2). Sounds directed into the two inlet ports impinge on opposite sides of the diaphragm, and the net displacement of the diaphragm is dependent on the differences in acoustic pressure between the front and back volumes. Any sound arriving from behind the listener enters the rear inlet port first. Prior to reaching its side of the diaphragm, that sound is delayed by the use of fine-metal mesh materials. Such materials are placed in the rear inlet's sound path to create an acoustical resistance, which, in conjunction with the compliance of the volume of air in the sound path, effectively creates an internal time delay (Preves, 1997; Thompson, 2003).⁹ The same sound that enters the rear inlet port also enters the front inlet port and is routed to the opposite side of the diaphragm after a slight external delay that is controlled by inlet spacing. Sounds that originate in front of the listener arrive at the front port sooner than they arrive at the rear port. These time delays cause a small phase shift between the signals in the front and back volumes. This design allows cancellation, or partial cancellation, of sound from the rear by virtue of that sound's reaching both sides of the diaphragm at the same time. Such a cancellation effect reaches its maximum when the delay created by the damping screen in the rear port is equal to the delay created by

⁹ The amount of resistance used determines the polar pattern of the directional microphone. Polar patterns are discussed in Appendix B – Quantifying Directivity in the Laboratory.

inlet spacing, resulting in little or no difference in sound pressure on either side of the microphone diaphragm. The net effect, when speech or other desired signals come mostly from the front, and noise or other undesired signals come mostly from the rear, is an enhanced signal-to-noise ratio (SNR).

The more contemporary approach to achieving directivity, using either analog or digital circuitry, is through the use of two omnidirectional microphones, each with its own inlet port (Agnew & Block, 1997; Ricketts & Mueller, 1999a; Thompson, 2003). Typically, these microphones are positioned in a hearing aid such that one microphone is located at the front of the aid and the other microphone is located at the rear of the aid. Both microphone inlet ports are positioned horizontally in a line parallel to the ground. In this approach, sounds entering the rear microphone may be delayed electronically, in addition to the delay created by inlet spacing (Edwards, 2000). The delayed signal from the rear microphone is then subtracted from the signal processed at the front microphone (Valente, 2000) (Figure A.3). Specific directional patterns are achieved in this design by both electrical filtering and any delay circuit in the rear channel. Manufacturers use microphones that are closely matched in sensitivity. Typically, this matching is achieved by using matched pairs of microphones and adjusting the relative gain of the microphone amplifiers (Thompson, 2003).

In dual-microphone designs incorporating DSP, an analog-to-digital (A/D) converter samples and digitizes the output from each microphone, and the signal processor monitors the relative sensitivity of the two microphones. In principle, the processor can correct for gain and frequency response differences for one of

the microphones, as needed for near-perfect matching. The functioning of the dual-microphone design in DSP aids is virtually identical to that of analog designs. The *dynamic matching* that is possible with DSP, however, permits greater control of any relative drift in microphone sensitivity. As in the analog dual-microphone system, the output from the rear microphone is ultimately subtracted from sound processed at the front microphone. Edwards, Hou, Struck, and Dharan (1998) found that using an A/D converter provides greater precision in effecting the dynamic electronic delays needed to control the frequency response of the two microphones. They reported that the use of DSP to subtract the output of one microphone from the output of the other, and to monitor their matching characteristic, assures that the two microphones are closely matched. A mismatch in amplitude of 1-2 dB or a mismatch in phase between microphones can effectively transform a directional response to an omnidirectional response (Edwards et al., 1998). Furthermore, as the distance between microphones is decreased, the effect of mismatched microphones is increased. Thus such a mismatch might be more common with an ITE and smaller-style hearing aids than in BTE aids.

Omnidirectional and directional microphones also exhibit different frequency responses (Wolf, Hohn, Martin, & Powers, 1999). The frequency response of an omnidirectional microphone is relatively flat when compared to that of a directional microphone (Figure A.4). In the low frequencies, the time delay between the sounds reaching the front and back of the diaphragm in a dual-inlet design, or the two separate diaphragms in a two-microphone design, is

small compared to the period, regardless of the direction of the sound source (Dillon, 2001). The two waves are almost in phase and have only a small net effect in terms of diaphragm displacement. This results in greater cancellation in the low frequencies, in comparison to high frequencies, effectively producing a lower output voltage in the lower frequencies. This low-frequency sensitivity occurs because low-frequency sounds are more similar in phase than high-frequency sounds. With respect to frequency response, these differences yield a response slope of approximately +6 dB per octave. This effect results in directional roll-off (Ricketts & Henry, 2002a), as illustrated in Figure A.4. A compensatory electronic filter can be used to increase the amount of low-frequency gain, a process often referred to as *equalization*. The amount of directional roll-off also depends on the length of the extension tubes leading from the microphone inlet ports, as well as the spacing between microphone ports (Figure A.2). Sensitivity decreases for low frequencies when the separation between ports is smaller (Thompson, 2002).

The directional roll-off just described can have perceptual consequences. For some listeners, the unequal gain between omnidirectional and directional microphones in the low frequencies results in a noticeable difference in loudness when the user toggles between modes. Equalization may be used to reduce the difference in loudness of sound processed by omnidirectional and directional microphones. Preves et al. (1999), however, found that hearing-impaired listeners showed no significant differences in the amount of SNR necessary for 50% speech intelligibility in noise when the low-frequency gain of a directional

device was equalized, as opposed to unequalized. (The details of this study are reported in Chapter 1, Assessment of DMHAs Using Objective Methods.)

A potential consequence of equalizing the low-frequency gain in dual-microphone directional systems is an increase in the internal noise generated by the microphones (Ricketts & Henry, 2002a; Thompson, 2003). This may negatively affect sound quality for listeners in quiet, particularly those listeners with normal or near-normal low-frequency hearing sensitivity.

Summary: Types of Microphones

Hearing aids are equipped with different types of microphones. Omnidirectional microphones are designed with one sound inlet to process sounds equally from all directions. Directional microphones are designed with two inlets that effectively reduce sensitivity to sounds arriving from the sides and rear of the listener, when compared to that for sounds directly in front of the listener. Initially, directional-microphone hearing aids (DMHAs) were manufactured using a single-microphone design featuring two inlet ports, but more recently many of these aids are manufactured using a dual-microphone design.

APPENDIX B

QUANTIFYING DIRECTIVITY IN THE LABORATORY

The most common methods used to quantify microphone performance in the laboratory are discussed in this appendix. These methods include polar-pattern plots, and calculation of directivity factor (DF), distance factor, directivity index (DI), articulation-index directivity-index (AI-DI), and the unidirectional index (UI).

Polar Directivity Patterns

Polar directivity patterns, or polar plots, are a graphical representation of a microphone's sensitivity to signals presented from all directions, and at an equal distance in three-dimensional space (Ricketts & Mueller, 1999a; Ricketts, 2000). Specifically, the output of a hearing aid is measured and may be plotted as a function of azimuth and elevation. In the assessment of a hearing aid microphone, polar plots are typically measured only in the horizontal plane, with the findings presumed to generalize to the vertical plane (Beranek, 1954; Preves, 1997; Ricketts & Mueller, 1999a; Ricketts, 2000). According to Ricketts and Mueller (1999a), "two-dimensional polar plots may be adequate for analysis of directional hearing aids (even if symmetry is not assumed) because the talker's mouth and the two microphone inputs are generally in the same plane, that is, the assumption is that most listeners rotate and angle their heads to face the talker directly" (p.119).

The polar plot, as seen in Figure B.1, is a graph consisting of a set of concentric circles, one of which provides a reference of 0 dB. The 0-dB reference is typically based on the level obtained at 0° azimuth. Negative values on the plot

indicate a reduction in sensitivity with respect to the reference. In most such depictions, 0° azimuth is placed at the top of the circle, 90° azimuth is at the right-most portion, 180° azimuth at the bottom, and 270° azimuth at the left-most portion.

Polar plots are often derived for the frequencies of 500, 1000, 2000, and 4000 Hz. Ricketts and Mueller (1999a) report that measurements are often made at these frequencies to assess the directivity of a hearing aid differing at each frequency. These measurements can also be shown as an average polar plot across frequencies, tested in free field, sound field, or on a manikin situated in a free or sound field (Dittberner, 2003a). According to Ricketts and Mueller (1999a), averaging polar plots across frequencies provides “a more general indication of directivity for a broad band signal such as speech” (p. 119). Differences between measurements in free field (or sound field) and on KEMAR reflect the head-shadow effect created by the manikin, resulting in greater sensitivity for those azimuths closest to KEMAR’s aided side and lower sensitivity for azimuths opposite the aided ear. These effects are particularly notable for high-frequency sounds. Unless stated otherwise, microphone patterns described throughout this appendix are those derived under free-field conditions without a manikin.

For hearing aid microphones, five basic polar patterns are commonly seen. Of these five basic patterns, four are directional and the other is omnidirectional. These five polar patterns are described below.

Omnidirectional Polar Pattern

A hearing aid designed with an omnidirectional microphone is defined by the circular polar pattern seen in Figure B.2. (In actuality, these patterns are rarely perfectly circular.) These microphones provide virtually no reduction in sensitivity to sounds arriving from any direction in free field (Preves, 1997). The solid line superimposed upon the 0-dB concentric reference line illustrates this effect.

Cardioid Polar Pattern

A cardioid directional microphone, illustrated in Figure B.3, shows a progressive decrease in sensitivity as the source moves away from 0° in either direction, with a null at 180° (Preves, 1997; Ricketts & Mueller, 1999a; Valente, 2000).

Hypercardioid Polar Pattern

Directional microphones can also be designed with a hypercardioid polar pattern (Figure B.4). The plot for this microphone's sensitivity shows progressively less sensitivity to sounds at azimuths on either side of 0° , with minimal sensitivity at azimuths around 110° and 250° , resulting in nulls at those points (Preves, 1997; Ricketts & Mueller, 1999a; Valente, 2000). A secondary lobe is present for sound sources behind these null points, with an increase in sensitivity to sounds at 180° azimuth. This secondary lobe shows the hypercardioid polar pattern to be somewhat more sensitive than the cardioid polar pattern to sounds that arrive from behind.

Supercardioid Polar Pattern

A supercardioid polar pattern is shown in Figure B.5. As with the cardioid and hypercardioid patterns, its sensitivity progressively decreases as the source moves to either side of 0° azimuth. The microphone's sensitivity is sharply reduced between azimuths of 90° and 270° , with nulls present around 130° and 230° azimuths (Preves, 1997; Ricketts & Mueller, 1999a; Valente, 2000). A small secondary lobe is present between these nulls, for which the greatest sensitivity to sound is at 180° azimuth. This smaller secondary lobe, and the location of the nulls, constitute the major distinctions between the supercardioid and hypercardioid patterns.

Bidirectional Polar Pattern

As illustrated in Figure B.6, a polar pattern having symmetrical primary lobes in the front and rear directions, and having nulls at azimuths around 90° and 270° , is classified as being bidirectional (Preves, 1997; Ricketts & Mueller, 1999a; Valente, 2000).

Directivity Factor (DF)

According to Beranek (1954), "The directivity factor is the ratio of the intensity on a designated axis of a sound radiator at a stated distance to the intensity that would be produced at the same position by a point source if it were radiating the same total acoustic power as the radiator" (p.109). Stated differently, the directivity factor (DF) is a ratio of the microphone's sensitivity for a

sound presented at 0° azimuth relative to the same microphone's sensitivity to sounds from all other directions (i.e., diffuse). It is calculated, therefore, from polar-pattern data points. To derive a two-dimensional DF, the following equation from Beranek (1954) is used:

$$DF = \frac{8\pi \times 57.3^\circ}{2\pi \sum_{n=1}^{36} |p(\theta_n)/p_{ax}|^2 \sin \theta_n \times 10^\circ} \quad (B.1)$$

where 57.3° refers to a radian, $p\theta_n$ represents the intensity of a signal for a given angle other than 0° , p_{ax} represents the intensity of the signal at 0° azimuth, and 10° represents the angular measurement step size. DF measurements are often performed at the frequencies of 500, 1000, 2000, and 4000 Hz.

Distance Factor

The distance factor is the square root of the DF (Preves, 1997). This measurement indicates how much farther a directional device can be from the sound source than an omnidirectional device in the presence of a diffuse field, without changing the SNR.

Directivity Index (DI)

The directivity index (DI) is the DF converted to decibels (Preves, 1997). That is, based on the DF, DI is calculated as follows (Beranek, 1954):

$$DI = 10 \log_{10} DF \quad (B.2)$$

$$DI = 10 \log_{10} DF \quad (B.2)$$

Equation B.2 states that DI is 10 times the logarithm to the base 10 of the DF. This derived value represents the microphone's overall sensitivity based on its polar pattern. For instance, an ideal omnidirectional pattern is defined as having equal sensitivity for a sound presented at 0° azimuth compared to the same microphone's sensitivity to sounds from all other directions. As a result, its associated DI will be 0 dB. Conversely, if the sensitivity of the microphone at the hearing aid's output is greater at 0° than at other angles, then the DI will be greater than 0 dB. In the event that the sensitivity of the microphone is reduced at 0° compared to other angles, then the DI will be less than 0 dB.

Articulation Index-Directivity Index (AI-DI)

In an attempt to provide a reasonable estimate of directionality on speech intelligibility, Soede and Killion, as reported in Killion et al. (1998), developed a means by which speech intelligibility can be estimated under different directivity conditions. Based on speech weighting for monosyllabic words, as used in the Mueller and Killion (1990) count-the-dot audiogram, frequency-importance functions of 0.20, 0.23, 0.33, and 0.24 are assigned to the frequencies of 500, 1000, 2000, and 4000 Hz, respectively. This modification has been termed the Articulation Index-Directivity Index (AI-DI) and is calculated using the equation:

$$AI-DI = (0.20 \times DI_{500}) + (0.23 \times DI_{1000}) + (0.33 \times DI_{2000}) + (0.24 \times DI_{4000}) \quad (B.3)$$

The AI-DI is based on the frequency-specific DI values. Reports suggest little difference between the unweighted DI value and the AI-weighted DI value (Amlani, Punch, & Ching, 2002; Ricketts & Dittberner, 2002). Any difference between the weighted and unweighted DI methods is the result of the greater importance given to the 2000 Hz region. The difference between an unweighted DI and the AI-DI is expected to be no more than 0.2 dB (Dittberner, 2003a, b).

Unidirectional Index (UI)

The UI is defined as the ratio of sound energy originating in the front hemisphere (extending from 270° to 90°) to sound energy originating from the rear hemisphere (extending from 90° to 270°), with both hemispheres centered on the microphone (Beranek, 1954). The UI expresses the relationship between output signals in the front and rear hemispheres, as calculated from the polar pattern of a microphone. Like the DI, an ideal omnidirectional pattern will result in a UI of 0 dB. If the sensitivity of the microphone is greater at 0° than at other angles, then the UI will be greater than 0 dB. In the event that the sensitivity of the microphone is reduced at 0° compared to other angles, then the UI will be less than 0 dB. Ricketts and Mueller (1999a) state that the UI “is not [an] ideal [measurement of directivity] if it is assumed that the listener usually faces the talker directly and that noise may originate in the ‘front’ hemisphere” (p. 122).

Summary: Quantifying Directivity in the Laboratory

To quantify the amount of directivity provided by DMHAs under laboratory conditions, several methods have been developed. First, polar patterns quantify the output of a hearing aid at various angles for a given input source. The directivity factor (DF) is a second method, and is derived from polar-pattern data points. The DF is the ratio of the microphone's sensitivity to sounds presented from directly in front (0° azimuth) compared to the same microphone's sensitivity to sound from all other directions. The distance factor is a third method used to quantify the directivity of a DMHA. It is formulated from the DF, and is an indicator of how much farther a directional device can be from the sound source than an omnidirectional device in the presence of a diffuse field, without changing the SNR. A fourth method, the directivity index (DI), converts the DF to decibels. Fifth, the articulation index-directivity index (AI-DI) is an attempt to provide a reasonable estimate of the effects of directionality on speech intelligibility. It uses speech weighting from the Mueller and Killion (1990) count-the-dot audiogram, which is applied to the manufacturer-reported frequency-specific DI values. Lastly, the unidirectional index (UI) quantifies the directivity of a DMHA by comparing the hearing aid's output for sounds in the front and rear hemispheres.

APPENDIX C

QUANTIFYING DIRECTIVITY IN THE CLINIC

Because of time, space, cost, and convenience constraints, laboratory measures of directivity are not practical in clinical practice, and therefore, are rarely performed in audiology clinics. Because of these constraints, alternative means of quantifying directivity have been developed for clinical use. In this appendix, the clinical means of determining directivity through hearing aid test box measurements and audiometric sound-treated rooms are described, followed by a discussion of the front-to-back ratio (FBR).

Hearing Aid Test Box

The physical and acoustic constraints of conventional hearing aid test boxes preclude hearing aid manufacturers and audiologists from using those systems in measurements of directional effects. Using a conventional hearing aid test box, one can obtain only a rough approximation of the directional characteristics of a DMHA (Preves, 1975). A major limiting factor in measuring DMHAs is that the test box provides a relatively uniform sound pressure level (Brey, Caustin, & McPherson, 1977). This uniform sound pressure level is appropriate for omnidirectional microphones, which have equal sensitivity to sound from all azimuths, but is problematic for the measurement of directional devices because it fails to provide a definable directional input signal for testing directional patterns of a DMHA. As a result, attempts to measure directivity are rendered invalid by an inability to effect meaningful changes in the orientation of the signal with respect to the aid.

To control the orientation of the input source with respect to the microphone, DI measurements are typically made in an anechoic environment. Because directionality is reduced under reverberant conditions (e.g., Hawkins & Yacullo, 1984; Madison & Hawkins, 1983; Nielsen & Ludvigsen, 1978; Ricketts & Dhar, 1999; Studebaker, Cox, & Formby, 1980), the use of an anechoic room for these measurements is preferred (Preves, 1975). Such a room is seldom available in ordinary audiology clinics, however, and only rarely available in hearing aid laboratory facilities, because of the special construction requirements.

Audiometric Sound-Treated Room

Brey et al. (1977) attempted to measure the directional characteristics of hearing aids in a sound-field environment (RT not reported) without the use of a hearing aid test box. They attached a hearing aid (make and model unspecified) to a 2-cc coupler in the sound field, and sent its response to a 1-inch condenser microphone. The output from the condenser microphone was delivered to a microphone amplifier, and then to a graphic level recorder. Sounds were presented to the hearing aid from a loudspeaker positioned 12 in from the aid. The loudspeaker delivered a sweep-frequency signal between 250 and 5000 Hz, which was generated by a sine-random generator. Measurements were made with the loudspeaker positioned at 0° and 180° azimuth with respect to the hearing aid. Directivity was determined by comparing the output in the front and back positions. This procedure was also carried out in an anechoic chamber so

that a comparison could be made between directivity determined in the sound-treated room and anechoic room. Findings indicated essentially equivalent outcomes in the two rooms.

As part of a larger study on the effects of test-room acoustics on directivity, Studebaker et al. (1980) investigated differences in directional performance of an omnidirectional-microphone behind-the-ear (BTE) hearing aid and three directional-microphone BTE hearing aids in a sound-treated room and an anechoic chamber. The authors did not specify the models of hearing aids used in their study. The BTE devices were fitted on the right ear of KEMAR. A broad-band thermal noise was presented from directly in front and at a distance of 1 m, and the output of each hearing aid was measured at azimuths of 0° , 90° , 180° , and 270° in each room. For the directional hearing aids, the effective directivity was decreased in the sound-treated room when compared to the anechoic chamber. According to Studebaker et al. (1980, p. 104), "...the audiometric test room with perforated metal walls normally used for hearing aid evaluations..., are unique places, These results suggest that the unique characteristics of the audiometric test environment may be especially troublesome in the evaluation of directional hearing aids, particularly if competing signals presented from rearward or other azimuths are made a part of the evaluation procedure."

Front-to-Back Ratio (FBR)

Because most clinics do not have an anechoic chamber, the front-to-back ratio (FBR) provides a means to measure the directivity characteristics of a hearing aid in a typical clinical setting. FBR is broadly defined as the ratio of the microphone sensitivity when a signal is presented from in front to the sensitivity of the same microphone when a signal is presented from behind (Mueller & Johnson, 1979). Mueller and Hawkins (1992) point out that FBR measurements can be made in both the clinic and laboratory with probe-microphone equipment, using the differences between the real-ear aided gain (REAG) values obtained when the signal source is directly in front and in back of the listener. For an omnidirectional microphone measured in a sound field, the REAG curve measured from in front will typically match, or nearly match, the REAG curve measured from behind. Such a result is to be expected, based on the omnidirectional microphone's equal sensitivity to sounds originating from all azimuths.

In the case of a directional microphone, the REAG for signals presented from behind will be lower than the REAG obtained for signals presented from in front. In fact, studies on DMHAs have reported FBRs ranging from 10 to 30 dB in the 500 to 4000 Hz range (Mueller & Johnson, 1979; Hawkins & Yacullo, 1984; Agnew & Block, 1997). For single-microphone-directional devices, the FBR demonstrates its greatest value in the low-frequency region, and this front-to-back difference is noticeably reduced around 2000 Hz (Valente, 2000). In dual-

microphone devices, the magnitude of the FBR will be greater than that measured for a single-microphone directional device (Valente, 2000).

Despite the relative convenience of FBR measurements for clinical applications, caution must be exercised when predicting real-world performance from this electroacoustic measure. According to Dillon (2001), the FBR is misleading in that it fails to indicate the effectiveness of the hearing aid in suppressing noise from directions other than precisely behind the listener. In addition, the FBR fails to represent the type of polar directivity pattern of the hearing aid tested. For instance, a hearing aid with a cardioid polar pattern (i.e., null at 180° azimuth) would demonstrate an excellent FBR. In the real world, however, when the listener is surrounded by noise sources, the directional advantage of the cardioid pattern would be lower than that with hypercardioid or supercardioid microphones, which demonstrate smaller FBRs (Ricketts & Mueller, 1999a).

Summary: Quantifying Directivity in the Clinic

Clinical applications of quantifying directivity have been developed because of time, space, cost, and convenience constraints associated with laboratory methods. Hearing aid test boxes are commonly used in this regard. Use of this equipment to measure directionality, however, is unreliable and susceptible to large differences in measurement because of difficulties in creating a truly directional input-signal source. Measurements performed in a sound-treated room have also been proposed, but have failed largely because of the unique

characteristics of such rooms. Another commonly used clinical procedure, the front-to-back ratio (FBR), has been reported to be a poor indicator of real-world performance because of its inability to indicate the degree of suppression of noise from directions other than behind the listener.

APPENDIX D
SCREENING FORM

Screening Form

PAIRED-COMPARISON PREFERENCES FOR POLAR DIRECTIVITY

PATTERNS IN DIFFERENT LISTENING ENVIRONMENTS

Subject: _____ Ss #: _____ Date: _____ Time: _____

DOB: _____ Gender: ☐ Male ☐ Female Test Ear: ☐ Right ☐ Left

Group: ☐ NH ☐ HI (Experienced) ☐ HI (Inexperienced)

History	Yes	No
Recent onset of hearing loss?		
Active upper respiratory infection?		
Vertigo?		
Tinnitus?		
Otologic surgery?		
Previous hearing aid user?		
<i>If yes, $\geq$ 12-month period?</i>		
<i>If no, trial period with hearing aids attempted?</i>		

Informed Consent Form Signed? ☐ Yes ☐ No

Audiometric Test Results

Pure-Tone Air Conduction Thresholds (dB HL)						
	Frequency (Hz)					
Ear	250	500	1000	2000	4000	8000
R						
L						

Tympanogram		Ipsilateral Reflex Thresholds	
Ear	Type	500 Hz	1000 Hz
R			
L			

Audiometer: _____ Immittance Bridge: _____

APPENDIX E
INFORMED-CONSENT FORM

Consent Form

PAIRED-COMPARISON PREFERENCES FOR POLAR DIRECTIVITY PATTERNS IN DIFFERENT LISTENING ENVIRONMENTS

1. The aim of the project is to determine the effect of different rooms on listening preferences when speech and competing noise are recorded through a hearing aid having different types of microphones. Through an insert earphone placed in your preferred ear, you will hear 2 pre-recorded speech passages against a noise background and processed through differing microphones. These passages will be presented at a comfortable level. Using a response box, your task will be to toggle between the passages and judge which of the two provides better speech understanding and to indicate your preferences using the response box.
2. Your participation will take place over a single test session that will last 120-150 minutes, including breaks.
3. Stimulus levels will not be uncomfortable loud. There are no foreseeable risks and/or discomforts to you, other than possible minor fatigue from participation.
4. Your participation in this study is voluntary and you may request to withdraw yourself at any time without penalty or loss of benefits to which you are otherwise entitled.
5. All results will be treated with strict confidence and each subject will remain anonymous in any reporting of the findings. Your identity will be kept confidential to the maximum extent provided by law.
6. You should be aware that you may not personally or directly benefit from any of the procedures administered or from the outcomes of the study.
7. For your time, you will be compensated \$20. Partial payment will be made if you withdraw before the completion of data collection.
8. If you have any questions or concerns regarding your participation in this study, you may contact Jerry L. Punch, Professor, at (517) 353-8656, Brad Rakerd, Professor, at (517) 353-8788, or Amyn Amlani, Doctoral (Ph.D.) Candidate, at (517) 432-1646. If you have any questions about your rights as a research subject, you may contact Ashir Kumar, Chair of the University Committee on Research Involving Human Subjects (UCRIHS) at (517) 353-2976.

9. If you are injured as a result of your participation, in this project, Michigan State University will provide emergency medical care if necessary. If the injury is not caused by the negligence of the University, you are personally responsible for the expense of this emergency and any other medical expenses incurred as a result of the injury.

10. This study has been explained to me and I freely consent to participate.

Signed _____

Date _____

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APPENDIX F

MCL FORM

MCL Form

<i>Most Comfortable Loudness (MCL) Level</i>								
Level (dB HL)	1		2		3		4	
	A	D	A	D	A	D	A	D
90								
87.5								
85								
82.5								
80								
77.5								
75								
72.5								
70								
67.5								
65								
62.5								
60								
57.5								
55								
52.5								
50→								
MCL Level = dB HL								

Rating Scale:

- 7 → Uncomfortably Loud
- 6 → Loud, But OK
- 5 → Comfortable, But Slightly Loud
- 4 → Comfortable
- 3 → Comfortable, But Slightly Soft
- 2 → Soft
- 1 → Very Soft

Procedure: Begin at 50 dB HL, and if the rating is below 4, ascend in 2.5 dB steps; when the rating is 5 or above, descend in 5 dB steps. Repeat this procedure until two-out-of-three ratings of 4 are obtained in the ascending mode at the same intensity. Record this response intensity as the Most Comfortable Loudness (MCL) Level. If ratings of 4 occur at more than one level on ascending trials, record MCL as the higher of these levels.

APPENDIX G

SUBJECT INSTRUCTIONS – AB TASK

SUBJECT INSTRUCTIONS – AB TASK

PAIRED-COMPARISON PREFERENCES FOR POLAR DIRECTIVITY PATTERNS IN DIFFERENT LISTENING ENVIRONMENTS

In this task you are to listen to 30-second passages of speech, along with a background noise and echo, amplified by a hearing aid. The pairs are referred to as A and B. You are to indicate which of the passages results in greater speech intelligibility. Think of intelligibility as the percentage of spoken words you can understand. Try to ignore the loudness of the speech, any unpleasantness in sound quality (i.e., tinniness or too much bass), as well as the background noise and echo, and concentrate only on which of the pair, A or B, results in improved speech understanding.

When you are ready to listen, flip the toggle switch of the response box to ON. This action will cause all lights to come on for a couple of seconds and signal you to listen carefully. The listening task will begin randomly with either A or B. Listen to that condition for a few seconds and then press the other button for a few seconds. The light above A or B will indicate the current listening condition. Feel free to press the A or B buttons alternately as many times as you wish during the 30-second time period.

When you are ready to respond, flip the toggle switch of the response box to OFF, and then press A or B to indicate your preference. In the event that you need all 30 seconds to make a decision, the passage of speech and noise will stop automatically and all the lights will come on. This indicates the need for you to respond. Flip the toggle switch to OFF, and then press A or B to indicate your preference. Remember that you will need to toggle the switch to ON to listen, and OFF to respond.

APPENDIX H
SUBJECT INSTRUCTIONS – ABN TASK

SUBJECT INSTRUCTIONS – ABN TASK

PAIRED-COMPARISON PREFERENCES FOR POLAR DIRECTIVITY PATTERNS IN DIFFERENT LISTENING ENVIRONMENTS

In this task you are to listen to 30-second passages of speech, along with a background noise and echo, amplified by a hearing aid. The pairs are referred to as A and B. You are to indicate which of the passages results in greater speech intelligibility, or that you have No Preference, which is denoted by the letter N. Think of intelligibility as the percentage of spoken words you can understand. Try to ignore the loudness of the speech, any unpleasantness in sound quality (i.e., tinniness or too much bass), as well as the background noise and echo, and concentrate only on which of the pair, A or B, results in improved speech understanding.

When you are ready to listen, flip the toggle switch of the response box to ON. This action will cause all lights to come on for a couple of seconds and signal you to listen carefully. The listening task will begin randomly with either A or B. Listen to that condition for a few seconds and then press the other button for a few seconds. The light above A or B will indicate the current listening condition. Feel free to press the A or B buttons alternately as many times as you wish during the 30-second time period.

When you are ready to respond, flip the toggle switch of the response box to OFF, and then press A or B to indicate your preference. If A and B sound the same to you, or if you perceive a difference, but don't have a preference for either, press N. In the event that you need all 30 seconds to make a decision, the passage of speech and noise will stop automatically and all the lights will come on. This indicates the need for you to respond. Flip the toggle switch to OFF, and then press A, B, or N to indicate your preference. Remember that you will need to toggle the switch to ON to listen, and OFF to respond.

APPENDIX H

TABLES

Table 1.1. Summary of studies that have used various objective methods for assessing behavioral performance with single- and dual-microphone devices. See text for further details.

Study	Subjects	Environment (RT in sec)	Aid (Polar Pattern)	Fitting/ Procedure	Task/Conditions
Lentz (1972)	20 HI children/ adults (11-87 yrs); mild/mod sev SNHL; experienced w/HAS	SR (RT NR)	BTE1 (mfr & model NR), OD; Maico M-100 BTE; single DM (NR)	Monaural/ half-gain; OD, DM	Percent correct (fixed SNR); CID W-22 at 62 dB SPL (0°); quiet, WN at 0 dB and -6 dB SNR (180°)
Frank and Gooden (1973)	3 groups of 20 NH adults (age NR)	SR (RT NR)	BTE (mfr & model NR); OD, single DM (NR)	Monaural right/E; OD, DM	Percent correct (fixed SNR); PAL PB-50 at 55 dB SPL (45°); MTB at +6, 0, -6, -12, and -18 dB SNR (Exp 1 - 0°, Exp 2 - 180°, Exp 3 - 0°, 180°)
Nielsen (1973)	22 HI children/ adults (17-68 yrs) (HL NR); experienced w/HAS	SR (RT NR)	Oticon 568 BTE; OD, single DM (NR)	Binaural/E; OD, DM	Percent correct (fixed SNR); PB words (type NR) at 55 dB SPL (0°); CFN at +5, +10, +15, +20 dB SNR (90°, 180°, 270°)
Sung et al. (1975)	32 HI adults (18- 69 yrs); mild/ mod SNHL; experienced w/monaural HAS	SR (RT NR)	BTE1 (mfr & model NR), OD; BTE2, 3, & 4 (mfr & model NR), single DM (NR)	Monaural/E; OD, DM	Percent correct (fixed SNR); CID W-22 at 62 dB SPL (45°); CPN at 62 dB SPL (225°)

Table 1.1. Continued.

Study	Subjects	Environment (RT in sec)	Aid (Polar Pattern)	Fitting/ Procedure	Task/Conditions
Madison and Hawkins (1983)	12 NH young adults (age NR)	AR (RT = 0.0) RR (RT = 0.6)	Oticon E24V (style NR); OD, single DM (NR)	Monaural KEMAR/E; OD, DM	Adaptive SNR - 50% correct performance, NU-6 varied in 2.5-dB steps (0°); babble (type, NR) at 65 dB SPL (180°)
Hawkins and Yacullo (1984)	12 NH young adults (age NR); 11 HI adults (34-76 yrs); mild-mod SNHL; 10 experienced w/Has	RR (RT = 0.3) RR (RT = 0.6) RR (RT = 1.2)	Oticon E24V ITE; OD, single DM (NR)	Monaural & binaural KEMAR/E; OD, DM	Adaptive SNR - 50% correct performance, NU-6 at 65 dB SPL (NH) (0°); NU-6 at MCL (HI) (0°); 12-talker babble (SPIN test) varied in 2-dB steps (180°)
Leeuw and Dreschler (1991)	12 NH children/adults (14-44 yrs)	RR (RT = 0.156) RR (RT = 0.883)	Bosch Star 33 PP-CTC BTE; OD, single DM (NR)	Monaural right/E; OD, DM	Adaptive SNR - 50% correct performance; Danish sents varied (step-size NR) (0°); BN at 56 dBA SPL (180°)
Chasin (1994)	10 HI adults (age NR); flat mod SNHL (500-4000 Hz); experienced w/monaural HAs	SR (RT NR)	Beltone ITE (model NR); OD, dual DM (NR)	Monaural/E; OD, DM	Adaptive SNR - 50% correct performance, NU-6 at 65 dB SPL (0°); SWN varied (step-size NR) (180°)
Voss (1997)	13 HI adults (29-82 yrs); mild/mod sev SNHL; experienced w/binaural HAs	SR (RT NR)	Phonak Piconet 232X AZ BTE; OD, dual DM (NR ¹)	Binaural/ Basic - half-gain (OD); Party - mfr (OD, DM)	Percent correct (fixed SNR); DANTALE sents at 65 dB SPL (0°); DANTALE babble at 0, -10, -15 dB SNR (45°, 135°, 225°, 315°)

Table 1.1. Continued.

Study	Subjects	Environment (RT in sec)	Aid (Polar Pattern)	Fitting/ Procedure	Task/Conditions
Larsen (1998)	19 HI adults (57-75 yrs) (HL NR); experienced w/binaural HAS	SR (RT NR)	Digital BTE (mfr & model NR); OD; Phonak Piconet2 AZ BTE; dual DM (NR ¹)	Binaural/ NAL-R (OD); mfr's best fit (DM)	Adaptive SNR - 50% correct performance; DANTALE sents (level NR) (0°); ICRA noise varied (step-size NR) (45°, 135°, 225°, 315°)
Valente et al. (1995)	50 HI adults (20-83 yrs); mild/mod sev SNHL (2 sites); experienced w/binaural HAS	SR (RT NR)	Phonak PICS AZ BTE; OD; dual DM (NR ¹)	Binaural/ Basic - REIG approx NAL-R (OD, DM); Party -mfr (OD, DM)	Adaptive SNR - 50% correct performance; HINT sents varied in 2-dB steps (0°); HINT noise at 65 dBA SPL (180°)
Agnew and Block (1997)	20 HI adults (age NR); mild/mod sev SNHL; experience w/HAS NR	SR (RT NR)	Starkey BTE (model NR); OD, dual DM (NR)	Binaural/ REIG approx NAL-R (OD, DM)	Adaptive SNR - 50% correct performance; HINT sents varied in 2-dB steps (0°); HINT noise at 65 dBA SPL (180°)
Preves et al. (1999)	10 HI adults (mean age = 66 yrs); mild/mod sev SNHL; inexperienced w/HAS	SR (RT NR)	Micro-Tech Persona ITE; OD, dual DM (SD; DI = 4.7 dB)	Binaural/ NAL-R (OD); NAL-R EVC target (Exp 1) UEVC target (Exp 2) (DM)	Adaptive SNR - 50% correct performance; HINT sents varied in 2-dB steps (0°); UC SWN at 65 dB SPL (115°, 245°)
Gravel et al. (1999)	20 HI children (4-11 yrs); mild/mod sev SNHL; experienced w/binaural HAS	SR (RT NR)	Phonak PICS 332X AZ BTE; OD, dual DM (NR ¹)	Binaural/ DSL - RECD (OD, DM)	Adaptive SNR - 50% correct performance; PSI words and sents at 50 dB HL (0°); MTB varied in 2-dB steps (72°, 144°, 216° and 288°)

Table 1.1. Continued.

Study	Subjects	Environment (RT in sec)	Aid (Polar Pattern)	Fitting/ Procedure	Task/Conditions
Walden et al. (2000)	40 HI adults (52-76 yrs); mild/mod sev SNHL; experienced w/ binaural HAs	SR (RT NR)	GN Resound BZ5 BTE; OD, dual DM (HD)	Binaural/ mfr (OD, DM, DM + noise reduction)	Percent correct (fixed SNR); CST in (1) speech = 50 dBA (0°), noise = 40 dBA (90°), 180°, 270°; (2) speech = 60 dBA in simulated RT = 0.78 s (0°), (3) speech = 60 dBA (0°), 75 dBA; two-talker babble at 60 dBA, six-talker babble at 73 dBA (90°, 180°, 270°)
Ricketts and Dhar (1999)	12 HI adults (age NR); mild/mod sev SNHL; experience w/HAs NR	AR (RT = 0.0); LR (RT = 0.642)	Phonak P2 AZ BTE, OD, dual DM (NR ²); Siemens Prisma BTE, OD, dual DM (NR ²); Widex Senso C9 BTE, OD, dual DM (NR ²)	Binaural/ mfr	Adaptive SNR - 50% correct performance; HINT sentis; UC CFN at 65 dBA SPL (90°, 135°, 180°, 270°)
Wouters et al. (1999)	10 HI children/adults (12-77 yrs); mild/mod SNHL; experienced w/HAs	Office (RT = 0.45)	Phonak PICS 232 AZ (style NR); OD, dual DM (NR ¹)	Binaural/ POGO II (OD); mfr + RT (DM)	Adaptive SNR - 50% correct performance; BLU words varied in 2-dB steps; sentis varied in 3-dB steps (0°); SWN, TFN, MTB at 65 dBA SPL (90°)

Table 1.1. Continued.

Study	Subjects	Environment (RT in sec)	Aid (Polar Pattern)	Fitting/ Procedure	Task/Conditions
Ricketts et al. (2001)	47 HI adults (36-94 yrs); mild/mod sev SNHL (2 sites); 29 experienced w/HAs	RR (RT = 0.371) Site I; RR (RT = 0.456) Site II	BTE (mfr/model NR) (OD), dual DM (NR); ITE1 (mfr/model NR) (OD), dual DM (NR); ITE2 (mfr/model NR) (OD), dual DM (NR); ITE3 (mfr/model NR) (OD), single DM (NR); ITE4 (mfr/model NR) (OD), single DM (NR)	Binaural/ NAL-NL1 (OD, DM)	Adaptive SNR - 50% correct performance; HINT sents varied in 2-dB steps (0°); UC CFN at 65 dBA (30°, 105°, 180°, 255°, 330°); percent correct (fixed SNR); CST at +4 dB (Site I); -1 dB (Site II) (0°); UC CFN at 65 dBA (30°, 105°, 180°, 255°, 330°)
Ricketts and Henry (2002b)	20 HI adults (age NR) - mild/mod sev SNHL; experience w/HAs NR	RR (RT = 0.371)	Phonak Claro 211 dAZ BTE (OD), dual DM (Adaptive), dual DM (Static-CD & HD)	Binaural/mfr (OD, DM)	Adaptive SNR - 50% correct performance; HINT sents varied in 2-dB steps (0°); UC CFN at 65 dBA (30°, 105°, 180°, 255°, 330°); percent correct (fixed SNR) -CST at +2 dB (0°); (1) UC CFN at 65 dBA (30°, 105°, 180°, 255°, 330°); (2) UC CFN at 65 dBA (160°, 200°); (3) UC CFN at 65 dBA (70°, 110°); (4) UC CFN at 65 dBA (panning)

Table 1.1. *Continued.*

AR = anechoic room; aRT = adaptive recovery time; BN = background noise; BTE = behind-the-ear; CD = cardioid; CFN = cafeteria noise; CPN = cocktail party noise; DM = directional microphone; E = equalized frequency response; Exp = experiment; HAs = hearing aids; HD = hypercardioid; HI = hearing impaired; ITE = in-the-ear; LR = living room; MFR = manufacturer; Mod = moderate; Mod Sev = moderately severe; MTB = multitalker babble; NH = normal hearing; NR = not reported; NR¹ = not reported – mfr reports CD; NR² = not reported – mfr reports SD; OD = omnidirectional; RR = reverberant room; RT = reverberation time; SD = supercardioid; SENTs = sentences; SNHL = sensorineural hearing loss; SNR = signal-to-noise ratio; SR = sound-treated room; SWN = speech-weighted noise; TFN = traffic noise; UC = uncorrelated; UE = unequalized frequency response; WN = white noise

Table 1.2. Summary of studies that have used various subjective methods for assessing behavioral performance with single- and dual-microphone devices. See text for further details.

Study	Subjects	Environment	Aid (Polar Pattern)	Fitting/ Procedure	Task/Conditions
Mueller et al. (1983)	24 HI adults (age & HL NR); inexperienced w/HAs	Daily listening	BTE (mfr/model NR); OD, single DM (NR)	Monaural/NR	Questionnaire; differences between OD/DM in quiet and in noise
Mueller et al. (1983)	30 HI adults (age & HL NR); inexperienced w/HAs	Daily listening	BTE (mfr/model NR); OD, single DM (NR)	Binaural/MR	Questionnaire; differences between OD/DM in four everyday listening conditions (optimum to extremely adverse) for noise and reverberation
Sommers (1979)	NR	NR	BTEs (mfr/model NR); OD, single DM (NR)	NR/NR	Questionnaire; use of mode (OD vs. DM)
Kuk (1996)	100 HI adults (HL NR); experience w/HAs NR	Daily listening	Phonak Piconet 232 AZ; OD, DM (NR ¹)	NR/NR	Questionnaire; ratings of preferences between OD/DM in several quiet and noisy environments
Kuk et al. (1999)	20 HI children (7 yrs 6 mos-13 yrs 8 mos); 9 mild/mod sev SNHL; 11 mod/sev SNHL	Daily listening	Widex Senso C9; OD, dual DM (SD); Widex Senso C19; OD, dual DM (CD)	Binaural/mfr (OD, DM)	Questionnaire; ratings of preferences between own HA and DSP aid with OD/DM capabilities using teacher's (LIFE) and parental (diary) perceptions

Table 1.2. Continued.

Study	Subjects	Environment	Aid (Polar Pattern)	Fitting/ Procedure	Task/Conditions
Chasin (1994)	10 HI adults (age NR); flat mod SNHL (500- 4000 Hz); experienced w/monaural HAS (data used for 8 subjects)	Daily listening	Belitone ITE (model NR); OD, dual DM (NR)	Monaural/E; OD, DM	Category scaling; 7-point scale of OD/DM preference in (1) quiet, (2) ease of listening w/noise, (3) difficult listening w/noise
Walden et al. (2000)	40 HI adults (52- 76 yrs); mild/ mod sev SNHL; experienced w/ binaural HAS	SR (RT NR)	GN Resound BZ5 BTE; OD, dual DM (HD)	Binaural/ mfr (OD, DM, DM + noise reduction)	Category scaling; 11-point scale used to rate speech clarity, sound comfort, sound quality/naturalness
Cord et al. (2002)	48 HI adults (45- 91 yrs) (HL NR); experienced w/HAS	Daily listening	Mfr & model (NR); OD, DM (NR)	NR	Category scaling; MPQ (31- item, 7-point scale) used to elicit responses for presence/ absence of noise, amount of reverberation, location of signal/noise, distance of the listener relative to signal
Surr et al. (2002)	11 HI adults (56- 77 yrs); mild/ mod sev SNHL; experienced w/binaural HAS	Daily listening	GN Resound Canta 7 BTE; OD, DM (adaptive)	Binaural/mfr; OD, DM	Category scaling; 6-point scale for rating preferences OD/DM; scale for estimating speech understanding in percent (OD/DM)

Table 1.2. Continued.

Study	Subjects	Environment	Aid (Polar Pattern)	Fitting/ Procedure	Task/Conditions
Nielsen (1973)	22 HI children/ adults (17-68 yrs) (HL NR); experienced w/HAs	SR (RT NR)	Oticon 568 BTE; OD, single DM (NR)	Binaural/E (OD,DM)	Paired comparisons (OD/DM); male voice (type and level NR) (0° azimuth); young female voice (90°), CFN (180°); older female voice (270°) (level NR)
Nielsen (1973)	22 HI children/ adults (17-68 yrs) (HL NR); experienced w/HAs	Daily listening	Oticon 568 BTE; OD, single DM (NR)	Binaural/E (OD,DM)	Paired comparisons (OD/DM)
Preves et al. (1999)	10 HI adults - mild/mod sev SNHL; inexperienced w/HAs	SR (RT NR)	Micro-Tech Persona ITE; OD, dual DM (SD)	Binaural/ NAL-R (OD); NAL-R EVC target (Exp 1) UEVC target (Exp 2) (DM)	Paired comparisons for clarity, quality, background noise, and overall impression (OD/DM); connected speech (male) at 65 dB SPL (0°); (1) quiet, (2) MTB at 57 dB SPL (115°, 245°)

BTE = behind-the-ear; CD = cardioid; CFN = cafeteria noise; DM = directional microphone; DSP = digital signal processing; E = equalized frequency response; EXP = experiment; HAs = hearing aids; HD = hypercardioid; HI = hearing impaired; HL = hearing loss; ITE = in-the-ear; Mfr = manufacturer; MOD = moderate; MOD SEV = moderately severe; MTB = multitalker babble; NR = not reported; NR¹ = not reported – mfr reports CD; OD = omnidirectional; RT = reverberation time; SD = supercardioid; SEV = severe; SNHL = sensorineural hearing loss; SR = sound-treated room; UE = unequaled frequency response; VC = volume control

Table 2.1. Age, gender, audiometric data, and immittance data for Group 1. All diagnostic values are reported in dB HL.

Subject	Age	Gender	Ear	Tympanic Type	Acoustic Reflex		Frequency (Hz)						
					500 Hz	1000 Hz	250	500	1000	2000	4000	8000	
AB	21	F	R*	A	85	90	0	0	0	0	0	5	
SP	25	F	L	A	85	90	5	0	5	0	0	5	
			R*	A	85	85	0	0	0	0	0		
EB	22	F	L	A	90	85	0	0	0	5	0	0	
			R	A	95	95	0	0	5	15	0	0	
BH	22	F	L*	A	95	95	0	5	0	5	0	0	
			R*	A	95	95	0	0	0	0	0	0	
AA	29	F	L	A	95	90	0	0	0	0	0	0	
			R*	A	85	85	5	5	0	0	0	0	
LK	22	F	L	A	85	95	10	0	0	0	0	0	
			R*	A	85	95	0	5	0	0	0	15	
RJ	21	F	L	A	85	85	5	0	0	0	0	0	
			R*	A	75	85	5	5	0	0	5	15	
BM	26	F	L	A	90	100	15	0	0	5	0	5	
			R*	A	95	95	0	0	0	0	0	0	
CK	22	F	L	A	95	85	0	0	0	0	0	0	
			R*	A	85	85	0	0	0	5	5	0	
EJ	21	F	L	A	75	85	0	0	0	0	5	5	
			R*	A	85	90	0	0	0	0	0	5	
RA	29	M	L	A	85	90	0	0	5	0	5	0	
			R*	A	90	90	0	0	0	0	0	5	
DK	35	M	L	A	90	95	5	0	5	0	0	0	
			R*	A	80	85	0	0	0	0	0	10	
Mean	24.6	F = 10 M = 2	L = 1	A	85	90	5	0	0	0	5	15	
			R = 11	A	87.4	90.0	2.2	1.0	0.9	1.5	0.9	3.0	
SD	4.4				6.0	4.8	3.9	2.1	1.9	3.5	1.9	4.7	

SD = standard deviation, * Denotes experimental test ear

Table 2.2. Age, gender, audiometric data, and immittance data for Group 2E. All diagnostic values are reported in dB HL.

Subject	Age	Gender	Tympanic Type	Acoustic Reflex				Frequency (Hz)							
				500 Hz	1000 Hz	250	500	1000	2000	4000	8000				
BW	77	F	A	100	100	50	50	50	60	70	80				
			L*	100	105	45	45	45	60	70	80				
MP	88	F	A	85	90	25	30	45	50	55	80				
			L	90	95	20	45	50	50	50	80				
BM	67	M	A	90	100	40	35	35	45	65	65				
			L*	90	105	35	25	30	55	65	60				
SA	78	F	A	85	95	40	45	50	60	70	80				
			L	90	95	40	45	55	60	75	80				
HW	67	M	A	90	90	25	35	50	50	65	80				
			L*	90	NR	20	30	35	45	50	80				
DS	74	M	A	95	100	20	35	40	45	55	75				
			L*	100	100	20	30	40	45	60	80				
RV	64	M	A	80	85	25	25	35	55	60	80				
			L	80	80	25	25	35	50	60	80				
BH	22	M	A	100	NR	45	55	60	65	60	60				
			L	100	NR	45	50	60	70	65	60				
JO	25	F	A	100	100	20	40	40	45	50	60				
			L*	100	100	20	40	40	50	55	55				
RM	77	M	A	85	90	25	35	50	40	65	70				
			L*	90	95	30	40	50	45	60	70				
TC	48	M	A	85	105	20	25	35	55	60	80				
			L	85	100	25	25	35	45	55	80				
RA	55	M	A	80	85	20	25	35	45	55	55				
			L	85	90	25	25	35	45	50	55				
Mean	61.8	F = 3	L = 6	90.9	95.8	29.4	36.0	43.1	51.5	60.2	71.9				
SD	20.9	M = 9	R = 6	7.2	7.1	10.1	9.7	8.7	7.7	7.1	10.1				

SD = standard deviation, * Denotes experimental test ear

Table 2.3. Age, gender, audiometric data, and immittance data for Group 21. All diagnostic values are reported in dB HL.

Subject	Age	Gender	Ear	Tym Type	Acoustic Reflex		Frequency (Hz)							
					500 Hz	1000 Hz	250	500	1000	2000	4000	8000		
LJ	67	F	R	A	75	80	20	30	35	35	40	55		
			L*	A	80	85	20	30	35	40	45	55		
JN	72	M	R	A	90	80	20	30	45	50	55	65		
			L*	A	80	90	20	35	45	55	60	70		
GS	66	M	R*	A	70	75	25	30	35	45	45	55		
			L	A	80	85	25	45	35	45	45	55		
BS	73	F	R*	A	80	80	20	25	30	30	65	55		
			L	A	85	80	20	25	30	35	60	55		
JS	72	M	R*	A	85	80	20	25	30	50	60	80		
			L	A	80	80	30	25	30	50	60	75		
RR	41	M	R*	A	100	NR	30	35	55	60	70	75		
			L	A	100	NR	40	45	60	60	75	80		
ER	64	M	R	A	85	85	30	30	30	45	70	70		
			L*	A	90	85	35	35	35	55	75	80		
DD	63	M	R*	A	90	95	20	25	40	55	70	65		
			L	A	85	90	20	25	55	65	70	75		
RM	68	M	R	A	80	80	20	25	30	45	75	80		
			L*	A	85	80	20	25	35	45	75	80		
AM	79	F	R*	A	85	90	25	30	30	40	65	70		
			L	A	85	95	25	30	30	35	70	70		
SM	34	F	R*	A	80	85	20	30	40	45	55	55		
			L	A	80	90	25	25	50	45	45	60		
JD	82	M	R*	A	95	90	25	25	45	55	65	80		
			L	A	100	100	25	25	40	75	75	80		
Mean	65.1	F = 4	L = 4		84.6	84.8	24.2	29.6	38.5	48.3	62.1	68.3		
SD	14.2	M = 8	R = 8		7.2	5.6	5.5	5.9	9.1	10.5	11.3	10.3		

SD = standard deviation, * Denotes experimental test ear

Table 2.4. *Electroacoustic characteristics of the Nexus device, as reported by the manufacturer and as measured before and after the experiment.*

Electroacoustic Measure	Mfr Reported	Pre-Experiment	Post-Experiment
Max. OSPL90 (Freq)	104.7 dB (3150 Hz)	105.1 dB (3250 Hz)	104.9 dB (3250 Hz)
HF Avg. OSPL90	88.7 dB	89.1 dB	88.9 dB
HF Avg. FOG	29.7	30.2 dB	30.1 dB
RTG	14.9 dB	14.9 dB	14.9 dB
Response Limit	DNT	DNT	DNT
F1/F2	DNT	DNT	DNT
THD 500 Hz	3.1%	2.9%	3.2%
THD 1000 Hz	1.6%	1.3%	1.1%
THD 1600 Hz	0.5%	3.3%	2.3%
EIN	29.0 dB	28.2 dB	28.5 dB
Attack Time	40 ms	41 ms	41 ms
Release Time	190 ms	198 ms	196 ms

OSPL90 = Output sound pressure level, with 90-dB SPL input level; HF = High-frequency; RTG = Reference test gain; F1/F2 = Low- and high-cutoff frequencies; THD = Total harmonic distortion; EIN = Equivalent input noise level; DNT = Did not test.

Table 2.5. *Passage topic and number, as found in Table 1 of Speaks et al. (1994), for the 12 most homogeneous RSIR passages used in this study.*

Passage Topic	RSIR Number
Leg	7
Cotton	9
Lawn	12
Woodpecker	13
Eye	24
Eagle	28
Guitar	40
Ice	48
Dictionary	54
Dice	55
Lettuce	56
Nails	64

Table 2.6. Dimensions for the sound-treated room, simulated living room, and classroom.

Room	Scale	Length	Width	Height	Volume (cubic)
Sound-treated Room	Feet	9.0	8.3	6.7	495.0
	Meters	2.7	2.5	2.0	14.0
Living room	Feet	19.3	11.6	9.0	2006.8
	Meters	5.9	3.5	2.7	56.8
Classroom	Feet	27.5	24.0	10.0	6600.0
	Meters	8.4	7.3	3.1	186.9

Table 2.7. Ambient-noise levels across frequency and Leq for each of the rooms.

Room	Frequency (Hz)							
	125	250	500	1000	2000	4000	8000	Leq*
Sound-treated room	5.5	8.1	-0.9	-2.4	-1.3	1.1	2.6	30.1
Living room [†]	33.5	28.3	22.8	19.5	16.1	7.1	2.2	52.5
Classroom	28.9	17.5	5.4	-0.4	2.6	1.6	3.0	46.4

* 60-s time window

[†] Ventilation system on

Table 2.8. Estimated and actual reverberation times and critical distances for the sound-treated room, simulated living room, and classroom.

Room	Volume (m ³)*	Est. RT (s)	Est. CD (m)	Distance Used (m)	Actual RT (s)	Actual CD (m)
Sound-treated room	14.02	0.05	3.35	1.00	0.05	3.19
Living room	56.83	0.25	3.02	3.50	0.30	2.75
Classroom	186.89	0.35	4.62	5.00	0.42	4.22

* Data from Table 2.6.

Table 2.9. Reverberation times across frequencies for the sound-treated room, simulated living room, and classroom.

Room	Run #	Frequency (Hz)				RT (s)
		500	1000	2000	4000	
Sound-treated room						
	1	0.066	0.038	0.031	0.082	0.054
	2	0.053	0.039	0.041	0.079	0.053
	3	0.056	0.039	0.046	0.084	0.056
	4	0.058	0.040	0.035	0.081	0.054
	5	0.061	0.037	0.038	0.082	0.055
	Average (s)	0.059	0.039	0.038	0.082	0.054
Living room						
	1	0.349	0.255	0.212	0.178	0.249
	2	0.345	0.248	0.208	0.183	0.246
	3	0.347	0.251	0.204	0.188	0.248
	4	0.335	0.244	0.211	0.167	0.239
	5	0.338	0.243	0.215	0.173	0.242
	Average (s)	0.343	0.248	0.210	0.178	0.245
Classroom						
	1	0.545	0.476	0.383	0.289	0.423
	2	0.551	0.468	0.392	0.271	0.421
	3	0.575	0.455	0.368	0.266	0.416
	4	0.564	0.461	0.375	0.277	0.419
	5	0.558	0.465	0.382	0.269	0.419
	Average (s)	0.559	0.465	0.380	0.274	0.420

Table 2.10. Pilot data on three normal-hearing listeners for determining the fixed signal-to-noise ratio.

Subject	Speech (dB)	Free Field Level (dB)	
		Noise (dB)	SNR (dB)
1	68.0	73.0	-5.0
2	68.0	72.4	-4.4
3	68.0	73.7	-5.7
Mean	--	73.0	-5.0
SD	--	0.65	0.65

Table 2.11. Example case for the AB task, showing total number of wins as preferred cells (rows) over compared cells (columns) and rank order of preferences.

Preferred Cell	<u>Compared Cell</u>									Wins	Rank
	1	2	3	4	5	6	7	8	9		
1	-	0	0	0	0	0	0	0	0	0	9
2	1	-	0	0	0	0	1	0	0	2	7
3	1	1	-	1	0	0	1	1	0	5	4
4	1	1	0	-	0	0	1	0	0	3	6
5	1	1	1	1	-	0	1	0	0	5	4
6	1	1	1	1	1	-	1	1	0	7	2
7	1	0	0	0	0	0	-	0	0	1	8
8	1	1	0	1	1	0	1	-	0	5	4
9	1	1	1	1	1	1	1	1	-	8	1
Total	8	6	3	5	3	1	7	3	0	36	

Table 2.12. Example case for the ABN task using AB data only (ABN Preference), showing total number of wins as preferred cells (rows) over compared cells (columns) and rank order of preferences.

	<u>Compared Cell</u>										Rank
	1	2	3	4	5	6	7	8	9	Wins	
1	-	0	0	0	0	0	0	0	0	0	9
2	1	-	0	0	0	0	0	0	0	1	8
3	1	1	-	1	1	0	0	0	0	4	3.5
4	1	1	0	-	0	0	0	0	0	2	7
5	1	1	0	1	-	0	1	0	0	4	3.5
6	1	1	1	1	1	-	1	1	0	7	1.5
7	1	1	0	0	0	0	-	1	0	3	5.5
8	1	1	0	1	0	0	0	-	0	3	5.5
9	1	1	1	1	1	0	1	1	-	7	1.5
Total	8	7	2	5	3	0	3	3	0	31	

Table 2.13. Example case for the ABN task using N (No Preference) data only, showing total number of ties.

Referenced Cell	<u>Compared Cell</u>									Ties
	1	2	3	4	5	6	7	8	9	
1	-	0	0	0	0	0	0	0	0	0
2		-	0	0	0	0	0	0	0	0
3			-	0	0	0	1	1	0	2
4				-	0	0	1	0	0	1
5					-	0	0	1	0	1
6						-	0	0	1	1
7							-	0	0	0
8								-	0	0
9									-	0
Total	0	0	0	0	0	0	2	2	0	5

Table 3.1. Rankings of most preferred cell across groups for the AB task.

Cell (Conditions)	Overall Rankings		
	Group 1	Group 2E	Group 2I
1 (OD, CR)	9	9	9
2 (OD, LR)	8	8	8
3 (OD, SR)	5	5	5
4 (CD, CR)	7	7	7
5 (CD, LR)	3	4	3
6 (CD, SR)	2	1	1
7 (HD, CR)	6	6	6
8 (HD, LR)	4	3	4
9 (HD, SR)	1	2	2

OD = omnidirectional, CD = cardioid, HD = hypercardioid, CR = classroom, LR = living room, SR = sound-treated room

Table 3.2. Most preferred cell across room-by-group conditions for the AB task, with total number of wins reflected in parentheses.

	AB		
	Group 1	Group 2E	Group 2I
Sound-treated room	9 (187)	6 (175)	6 (174)
Living room	5 (114)	8 (125)	5 (116)
Classroom	7 (74)	7 (71)	7 (77)

Table 3.3. Rank-order correlation coefficients (Spearman rho) for preferences among the tasks for the three groups of subjects.

	AB Run 1 vs. Run 2
Group 1	0.98*
Group 2E	1.00*
Group 2I	0.97*

*Statistically significant at the .01 level (two-tailed)

Table 3.4. Rank-order correlation coefficients (Spearman rho) for preferences among the nine different microphone-by-room comparisons across group task.

	AB		
	CR	LR	SR
Group 1	1.00*	1.00*	1.00*
Group 2E	1.00*	1.00*	0.87
Group 2I	1.00*	1.00*	0.50

*Statistically significant at the .01 level (two-tailed)

Table 3.5. Results of the multivariate three-way repeated-measures analysis of variance (ANOVA) for the AB task.

Source	Hypothesis df	Error df	F	p
Within Subjects				
Microphone	2	32	271.92	.000*
Microphone x Group	4	66	0.76	.558
Room	2	32	613.37	.000*
Room x Group	4	66	2.80	.033*
Microphone x Room	4	30	6.79	.001*
Microphone x Room x Group	8	62	2.23	.037*
Between Subjects				
Group	2		0.0	1.000

*Statistically significant at the .05 level

Table 3.6. Rankings of most preferred cell across groups for the ABN Preference task.

Cell (Conditions)	Overall Rankings		
	Group 1	Group 2E	Group 2I
1 (OD, CR)	9	9	9
2 (OD, LR)	8	8	8
3 (OD, SR)	3	5	5
4 (CD, CR)	7	6	7
5 (CD, LR)	4	3	4
6 (CD, SR)	2	2	2
7 (HD, CR)	6	7	6
8 (HD, LR)	5	4	3
9 (HD, SR)	1	1	1

OD = omnidirectional, CD = cardioid, HD = hypercardioid, CR = classroom, LR = living room, SR = sound-treated room

Table 3.7. Most preferred cell across room-by-group conditions for the ABN Preference task, with total number of wins reflected in parentheses.

	ABN Preference		
	Group 1	Group 2E	Group 2I
Sound-treated room	9 (169)	9 (161)	9 (151)
Living room	5 (89)	5 (110)	8 (98)
Classroom	7 (50)	4 (47)	7 (51)

Table 3.8. Rank-order correlation coefficients (Spearman rho) for preferences among the tasks for the three groups of subjects.

	ABN Preference Run 1 vs. Run 2
Group 1	0.98*
Group 2E	0.97*
Group 2I	0.98*

*Statistically significant at the .01 level (two-tailed)

Table 3.9. Rank-order correlation coefficients (Spearman rho) for preferences among the nine different microphone-by-room comparisons across groups.

	ABN Preference		
	CR	LR	SR
Group 1	1.00*	1.00*	1.00*
Group 2E	0.87	1.00*	1.00*
Group 2I	1.00*	1.00*	1.00*

*Statistically significant at the .01 level (two-tailed)

Table 3.10. Results of the multivariate three-way repeated-measures analysis of variance (ANOVA) for the ABN Preference task.

Source	Hypothesis df	Error df	F	p
Within Subjects				
Microphone	2	32	426.15	.000*
Microphone x Group	4	66	3.69	.009*
Room	2	32	616.25	.000*
Room x Group	4	66	4.04	.005*
Microphone x Room	4	30	20.79	.000*
Microphone x Room x Group	8	62	1.90	.077
Between Subjects				
Group	2		1.57	.224

*Statistically significant at the .05 level

Table 3.11. Results of the multivariate three-way repeated-measures analysis of variance (ANOVA) for the No-Preference task.

Source	Hypothesis df	Error df	F	<i>p</i>
Within Subjects				
Microphone	2	32	79.83	.000*
Microphone x Group	4	66	0.41	.801
Room	2	32	7.39	.002*
Room x Group	4	66	0.49	.742
Microphone x Room	4	30	2.33	.078
Microphone x Room x Group	8	62	0.73	.662
Between Subjects				
Group	2		1.57	.224

* Statistically significant at the .05 level

APPENDIX J

FIGURES

Figure 2.1. Audiometric range and target thresholds for hearing-impaired subjects.

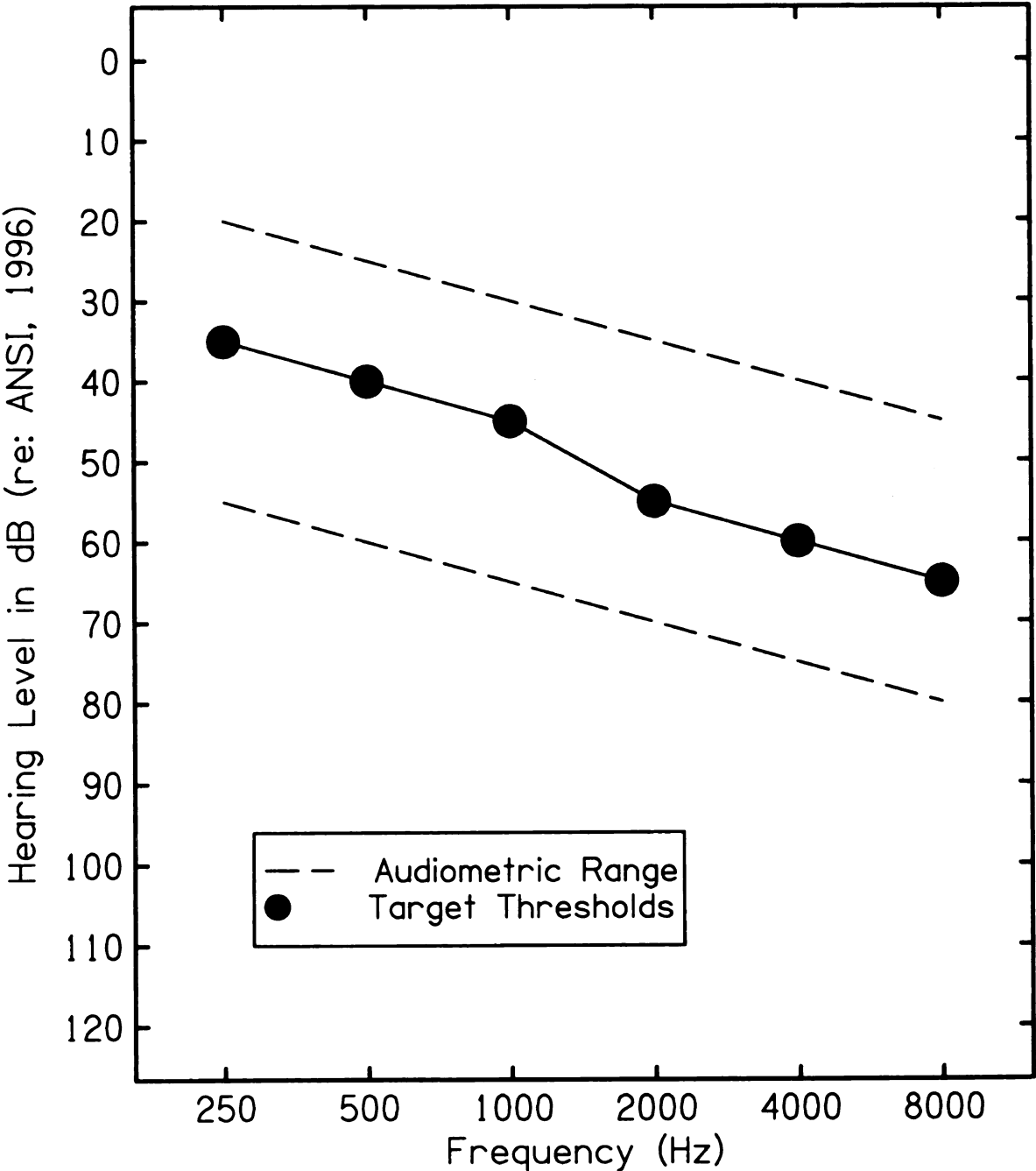


Figure 2.2. Diagram of equipment setup for polar-plot measures in the anechooic chamber.

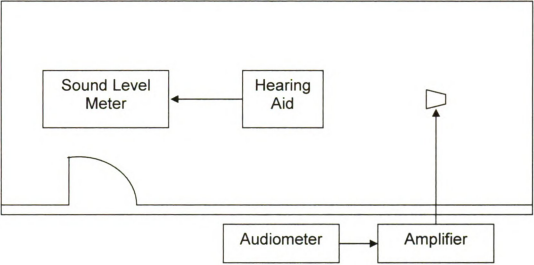


Figure 2.3. Polar plot depicting the omnidirectional pattern measured in free field at 2000 Hz on the Nexus device used in this study.

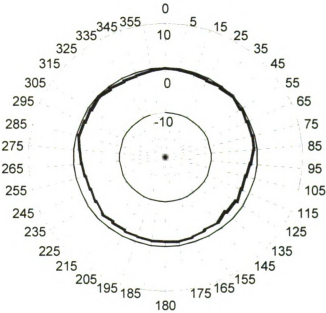


Figure 2.4. Polar plot depicting the cardioid pattern measured in free field at 2000 Hz on the Nexus device used in this study.

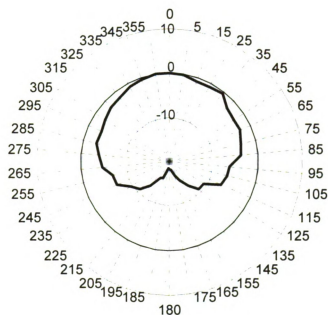


Figure 2.5. Polar plot depicting the hypercardioid pattern measured in free field at 2000 Hz on the Nexus device used in this study.

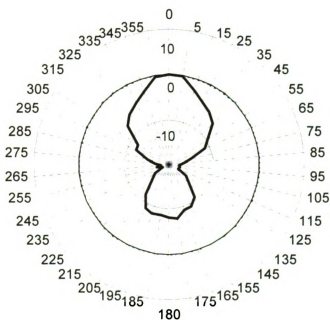


Figure 2.6. Frequency response of the Nexus hearing aid for the omnidirectional condition programmed using the target audiogram in Figure 2.1.

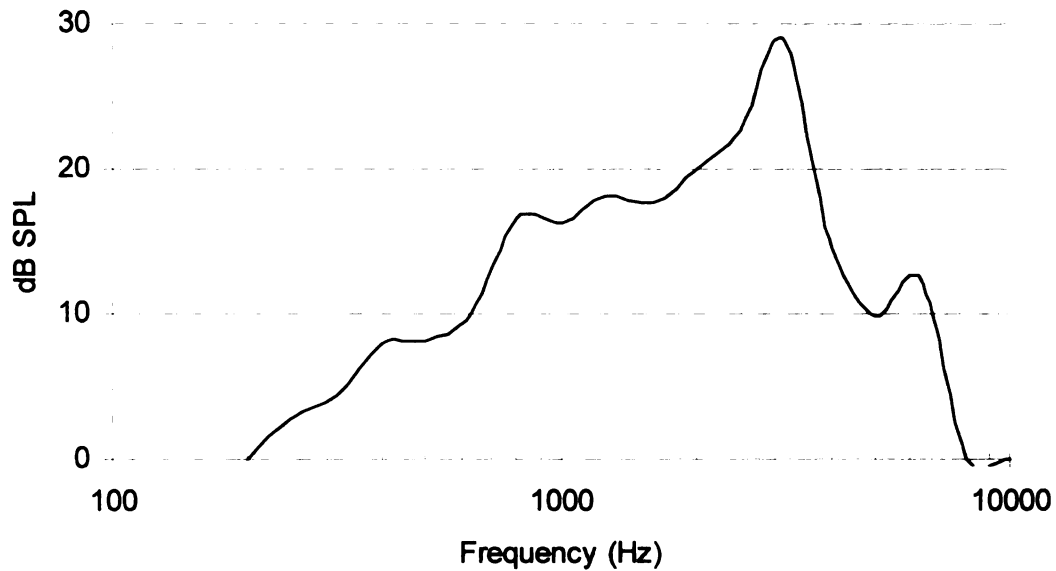


Figure 2.7. Long-term average spectra of 12 experimental speech passages and competing noise used in this study.

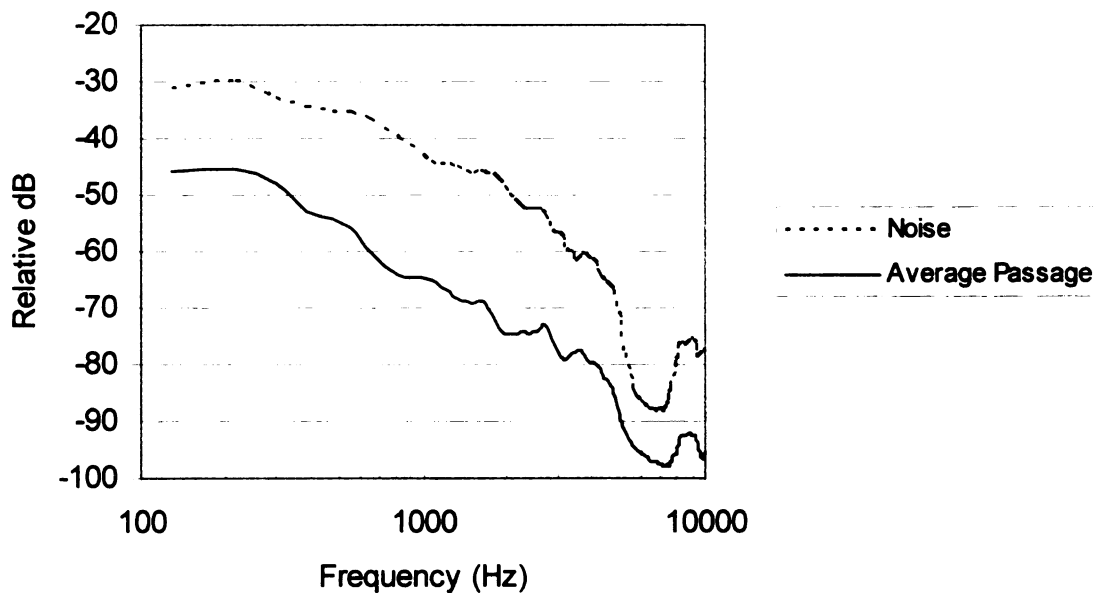


Figure 2.8. Frequency response of the four Realistic Minimus-3.5 loudspeakers.

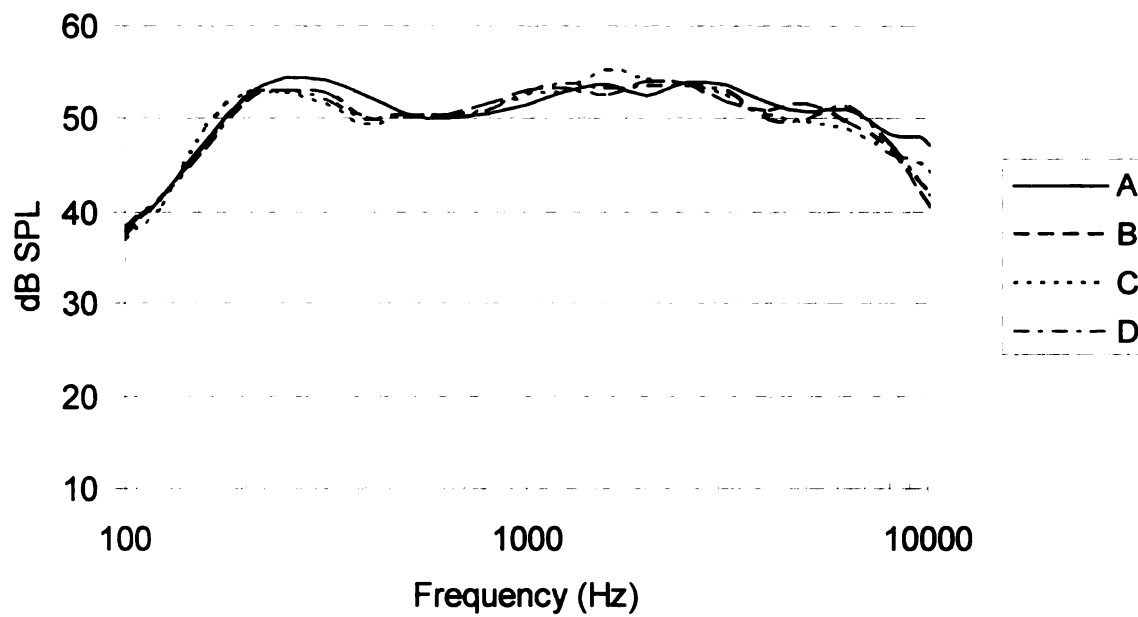


Figure 2.9. Equipment diagram used for determining the signal-to-noise ratio of the RSIR passages in noise.

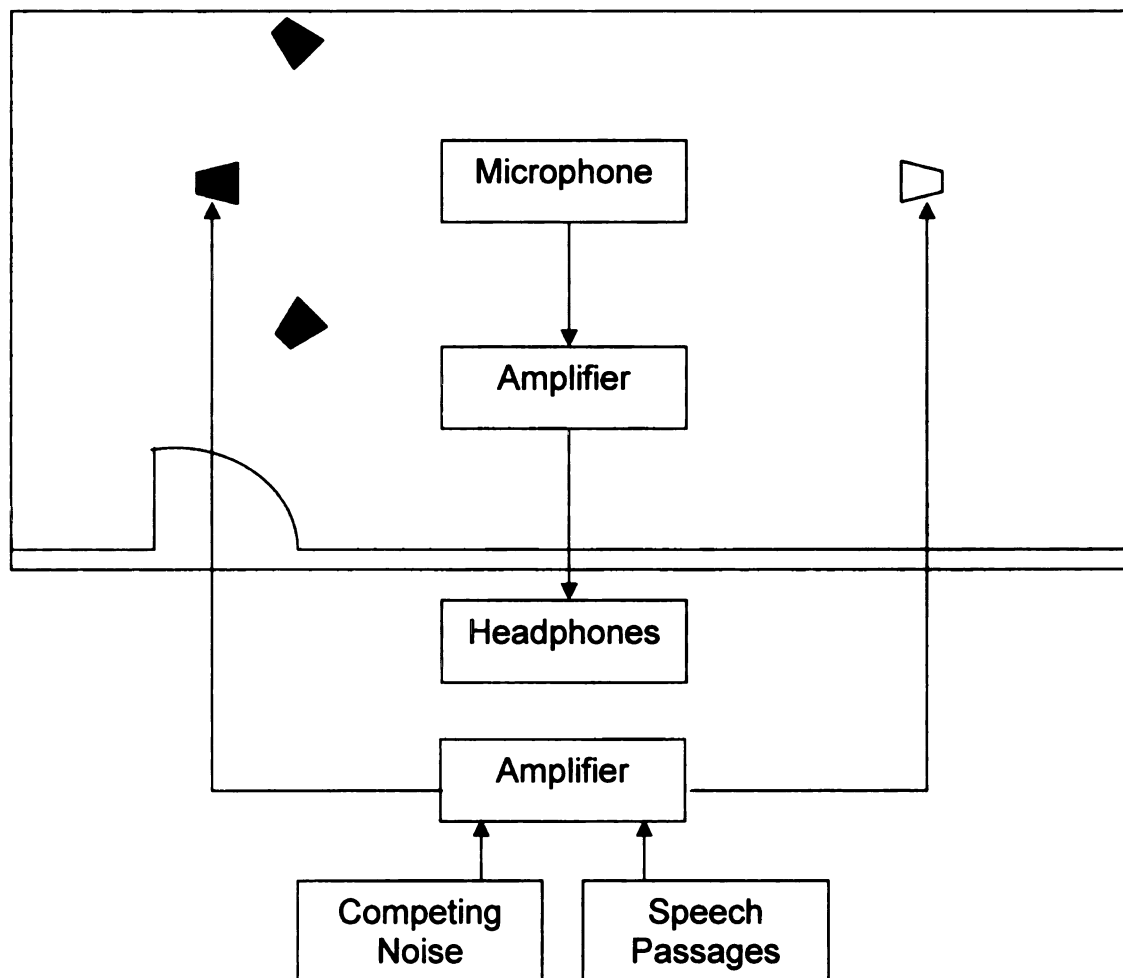


Figure 2.10. Schematic diagram of setup for recording in the sound-treated room.

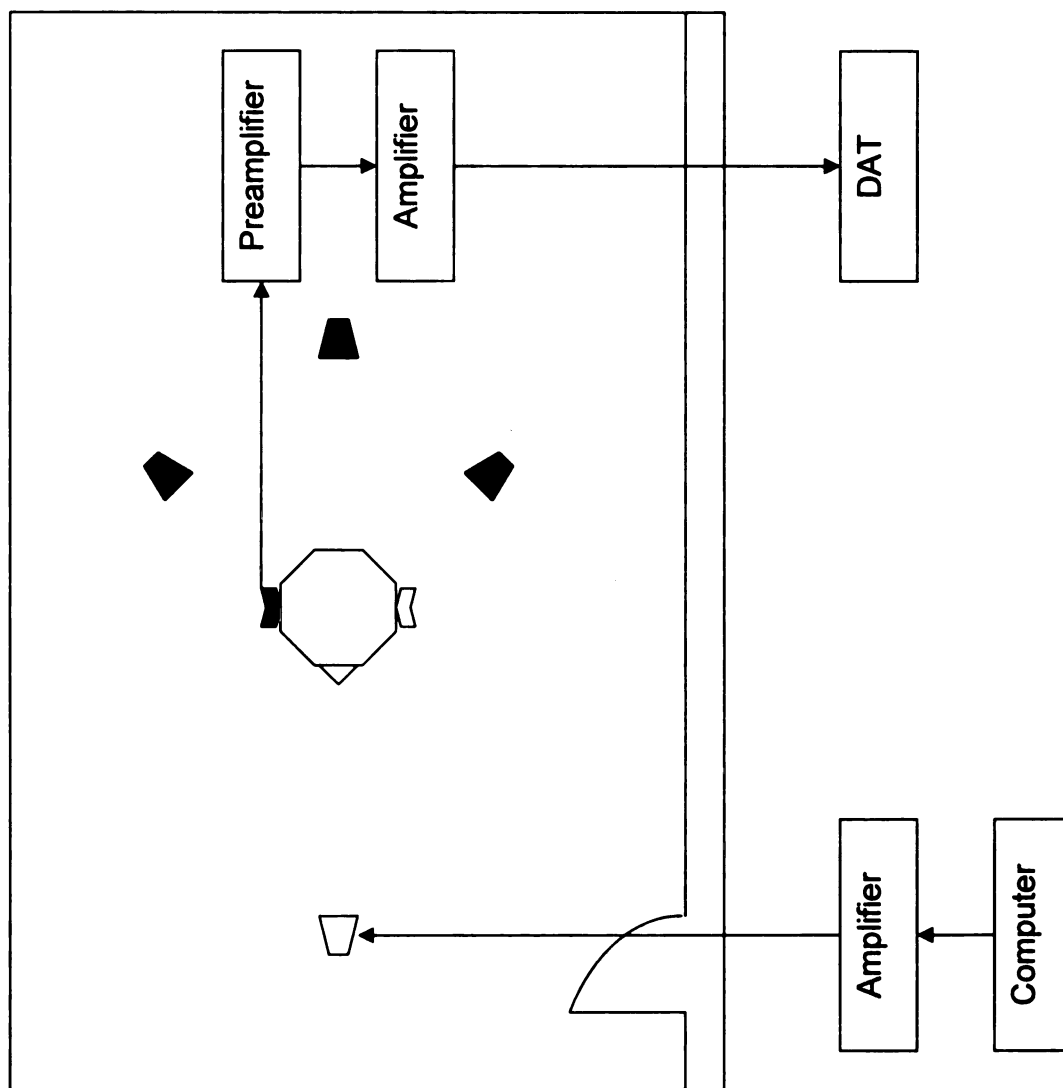


Figure 2.11. Schematic diagram of setup for recording in the simulated living room.

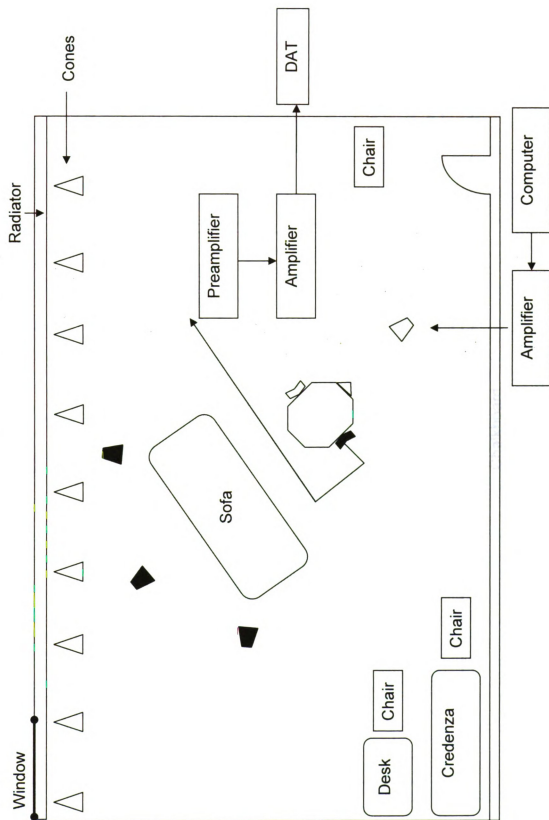


Figure 2.12. Schematic diagram of setup for recording in the classroom.

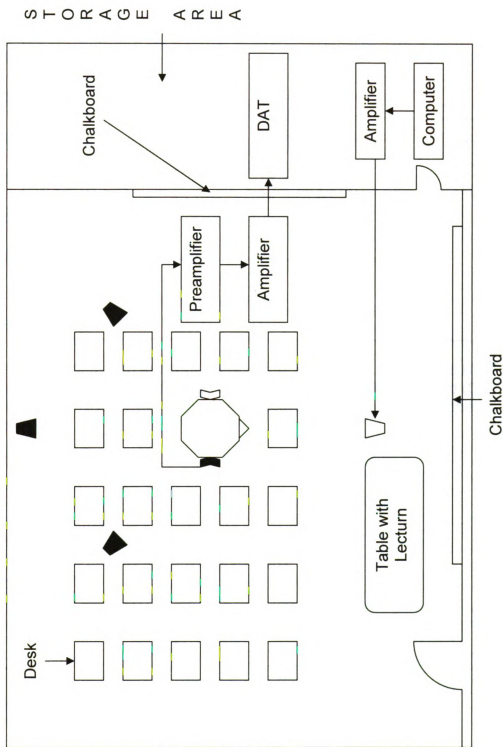


Figure 2.13. Long-term average speech-in-noise spectra for a single RSIR passage (#12) processed through the omnidirectional (OD), cardioid (CD), and hypercardioid (HD) microphones of the experimental hearing aid in the sound-treated room.

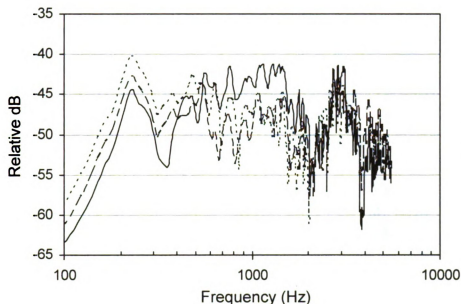


Figure 2.14. Long-term average speech-in-noise spectra for a single RSIR passage (#12) processed through the omnidirectional (OD), cardioid (CD), and hypercardioid (HD) microphones of the experimental hearing aid in the simulated living room.

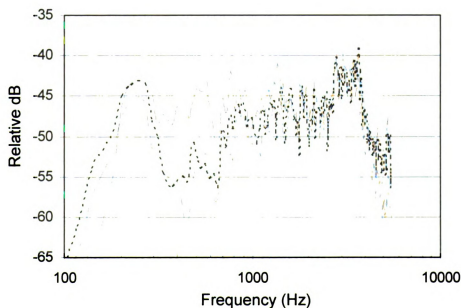


Figure 2.15. Long-term average speech-in-noise spectra for a single RSIR passage (#12) processed through the omnidirectional (OD), cardioid (CD), and hypercardioid (HD) microphones of the experimental hearing aid in the classroom.

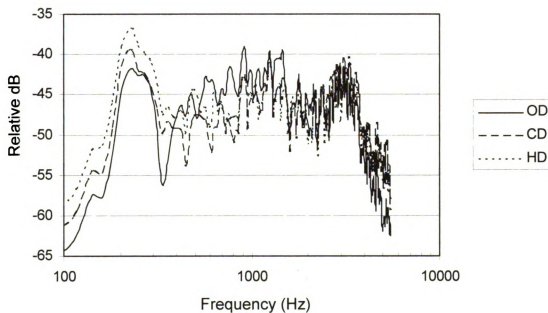


Figure 2.16. Spectrograms of the word *ground* processed through the omnidirectional (OD), cardioid (CD), and hypercardioid (HD) microphones of the experimental hearing aid in the sound-treated room (SR).

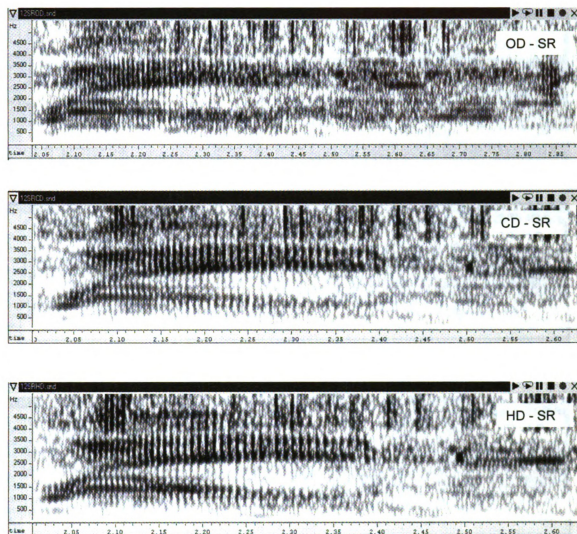


Figure 2.17. Spectrograms of the word *ground* processed through the omnidirectional (OD), cardioid (CD), and hypercardioid (HD) microphones of the experimental hearing aid in the simulated living room (LR).

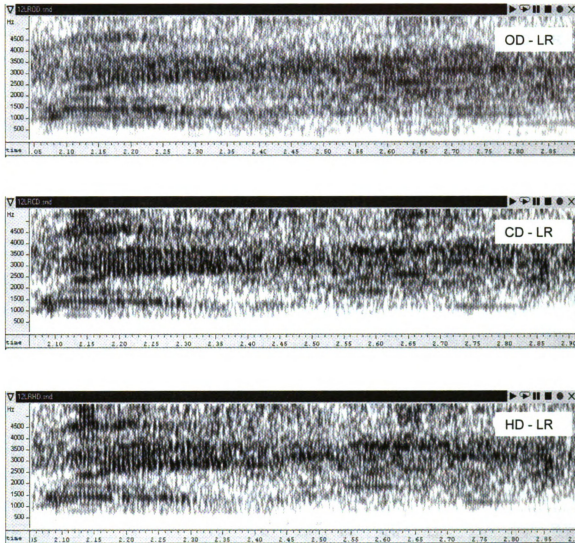


Figure 2.18. Spectrograms of the word *ground* processed through the omnidirectional (OD), cardioid (CD), and hypercardioid (HD) microphones of the experimental hearing aid in the classroom (CR).

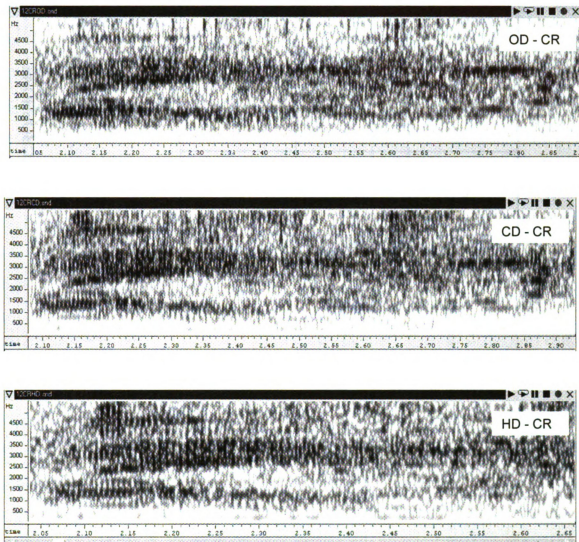


Figure 2.19. Experimental matrix created for room-by-microphone conditions. Numbers 1-9 are nominal values used to label conditions.

MICROPHONE	Omnidirectional	1	2	3
	Cardioid	4	5	6
	Hypercardioid	7	8	9
		Classroom	Living Room	Sound-treated Room
		ROOM		

Figure 2.20. Schematic of instrumentation required for stimulus playback during data collection for Group 1. See text for description of equipment.

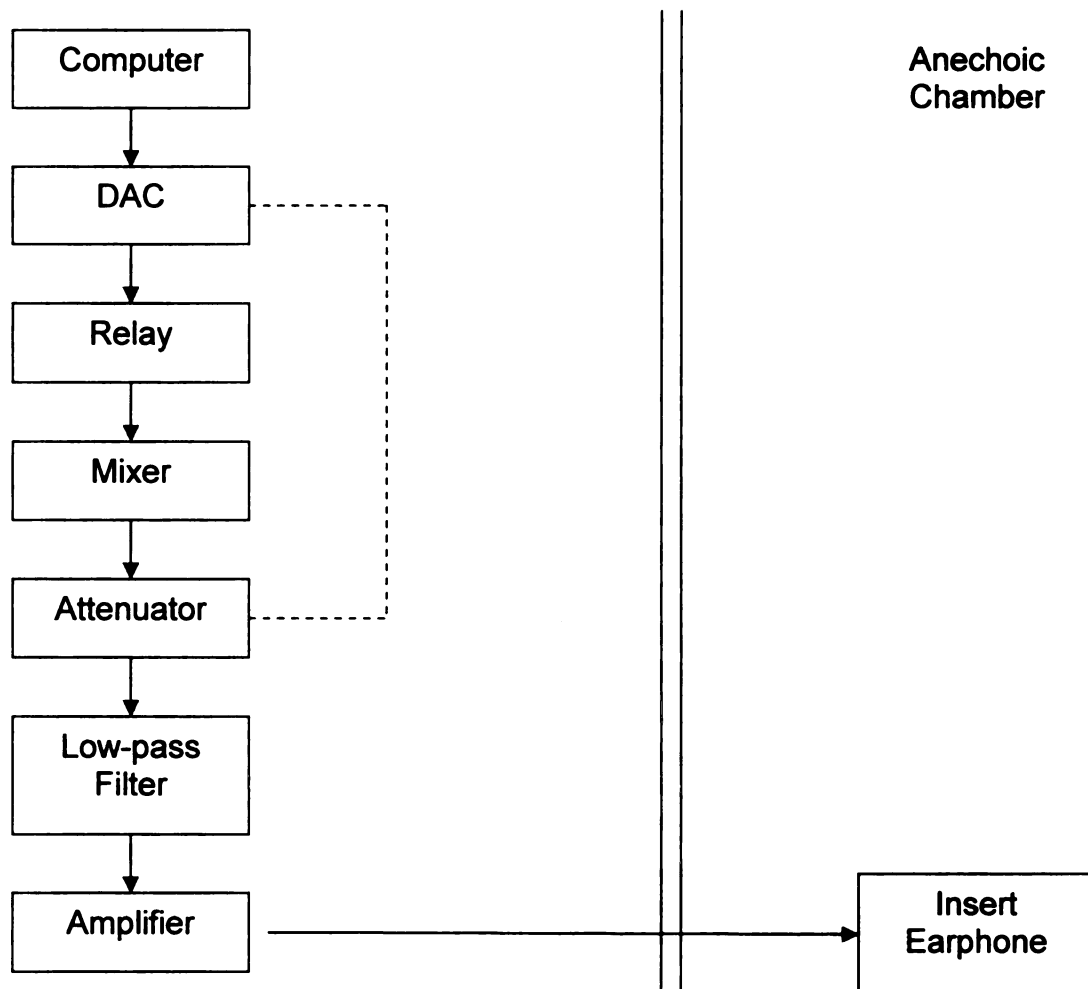


Figure 2.21. Schematic of instrumentation required for stimulus playback during data collection for Groups 2E and 2I. See text for description of equipment.

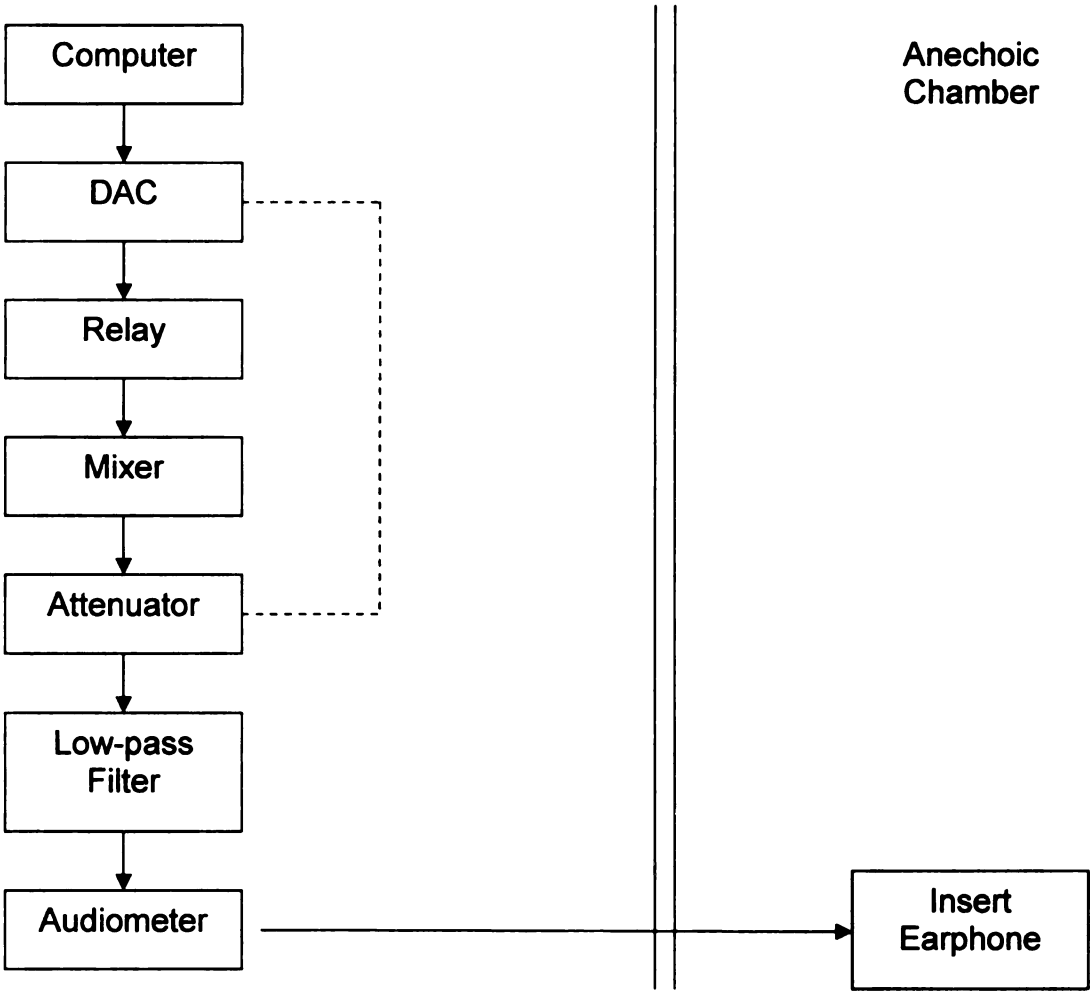


Figure 3.1. Mean preferences and Bonferroni-corrected 95-percent confidence intervals (CI_{95}), indicated by error bars, across microphones using the AB procedure.

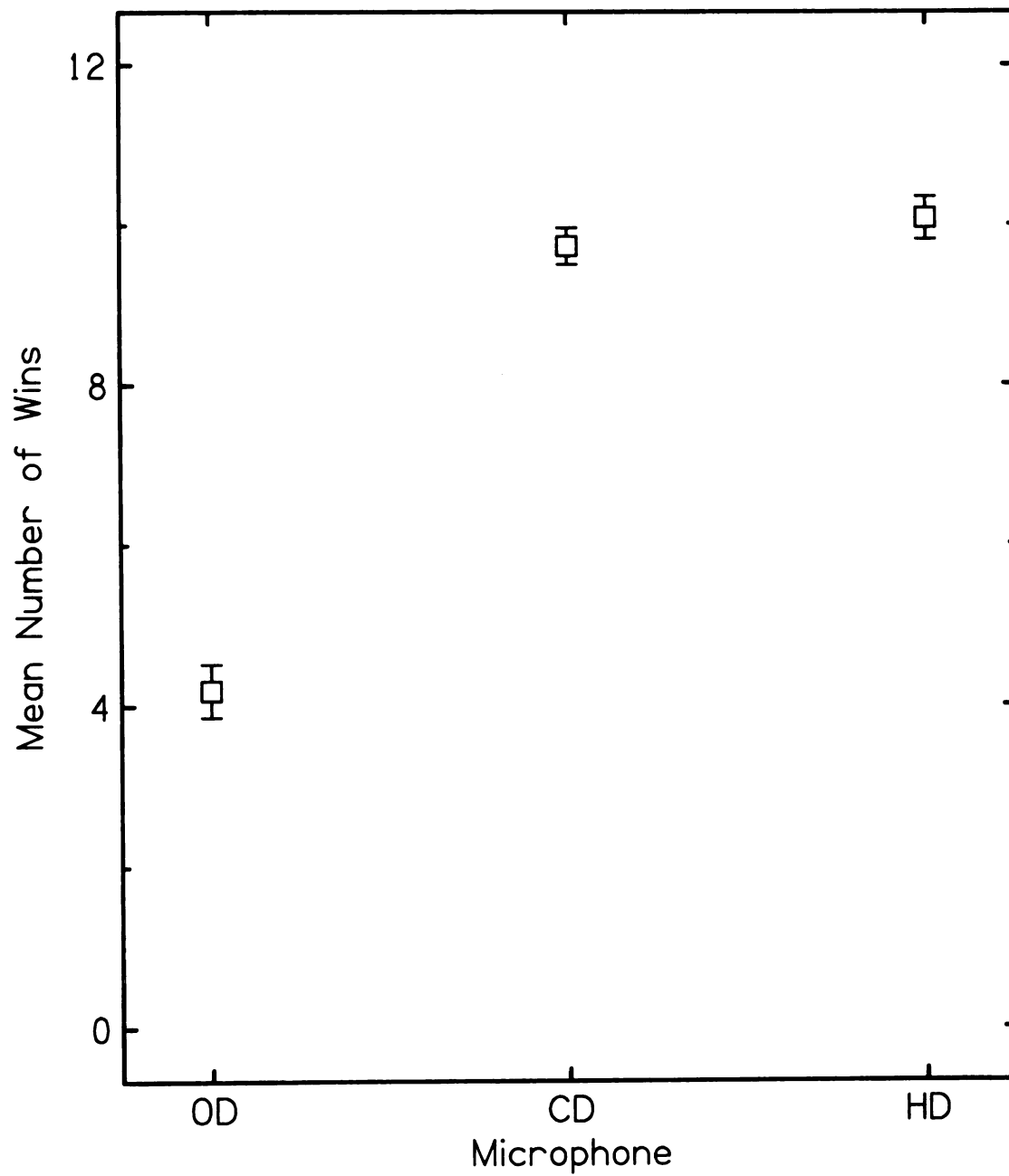


Figure 3.2. Mean preferences and Bonferroni-corrected 95-percent confidence intervals (CI_{95}), indicated by error bars, across rooms using the AB procedure.

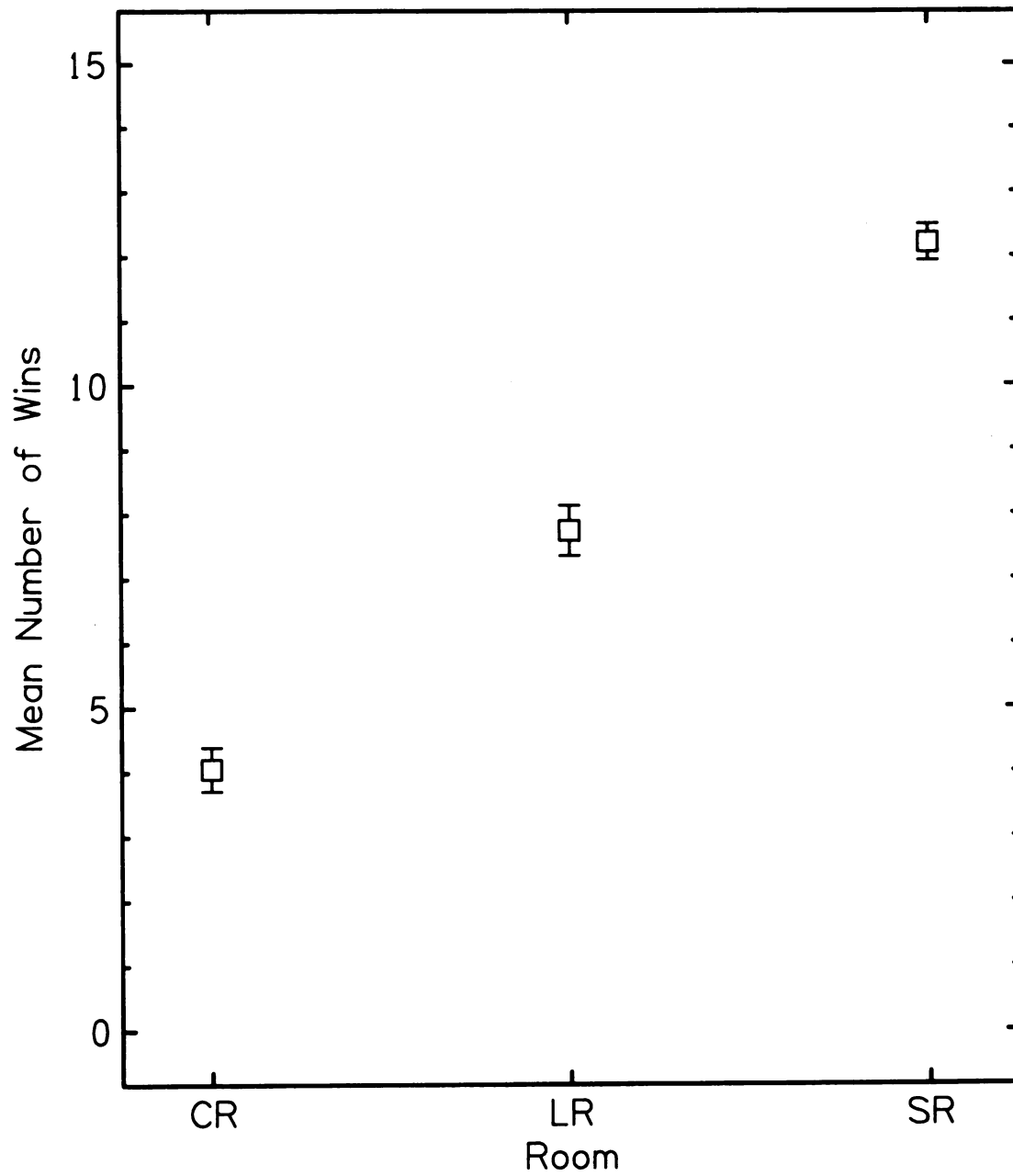


Figure 3.3. Mean preferences in the AB procedure across microphones and rooms.

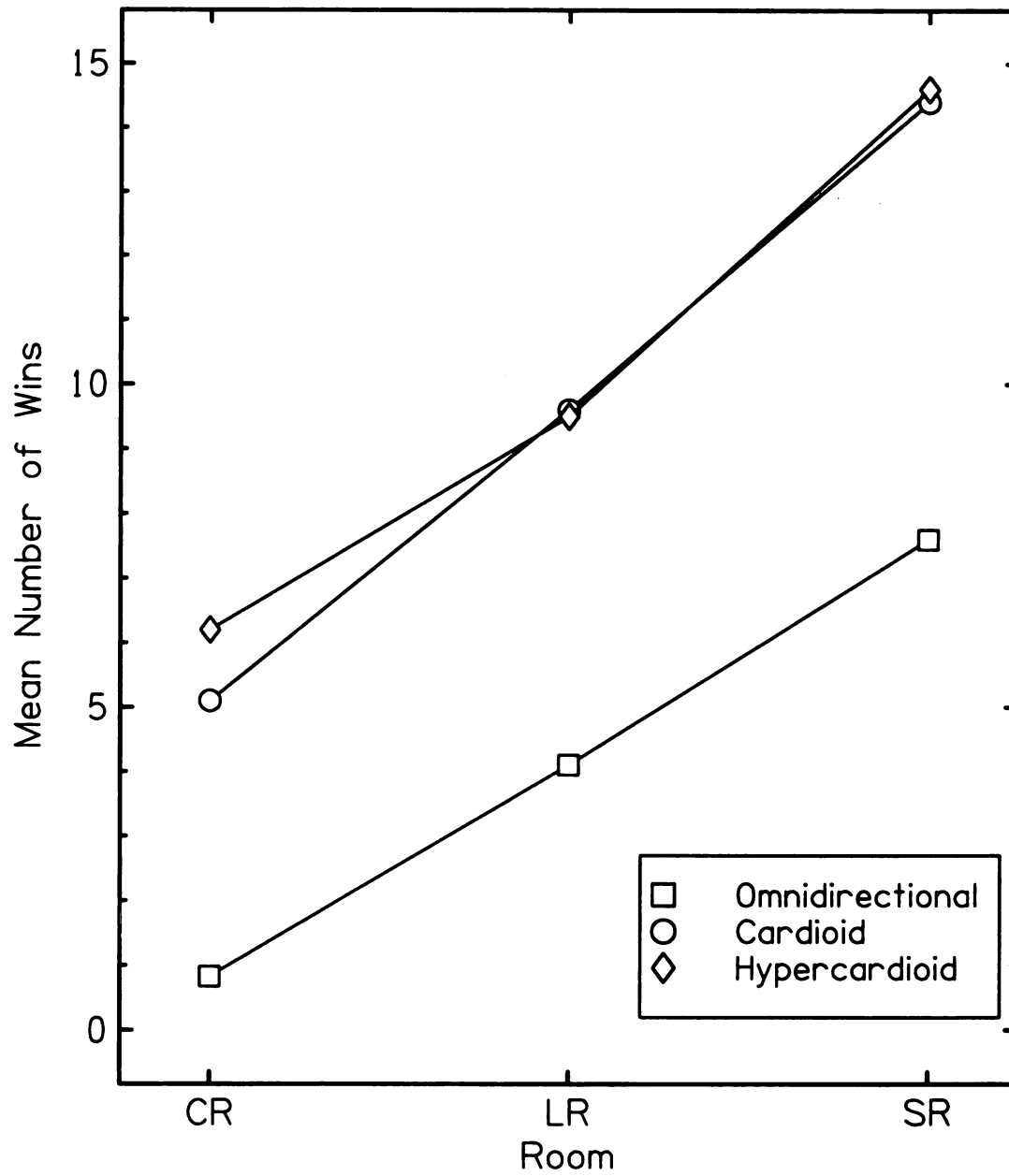


Figure 3.4. Mean preferences in the AB procedure across rooms and groups.

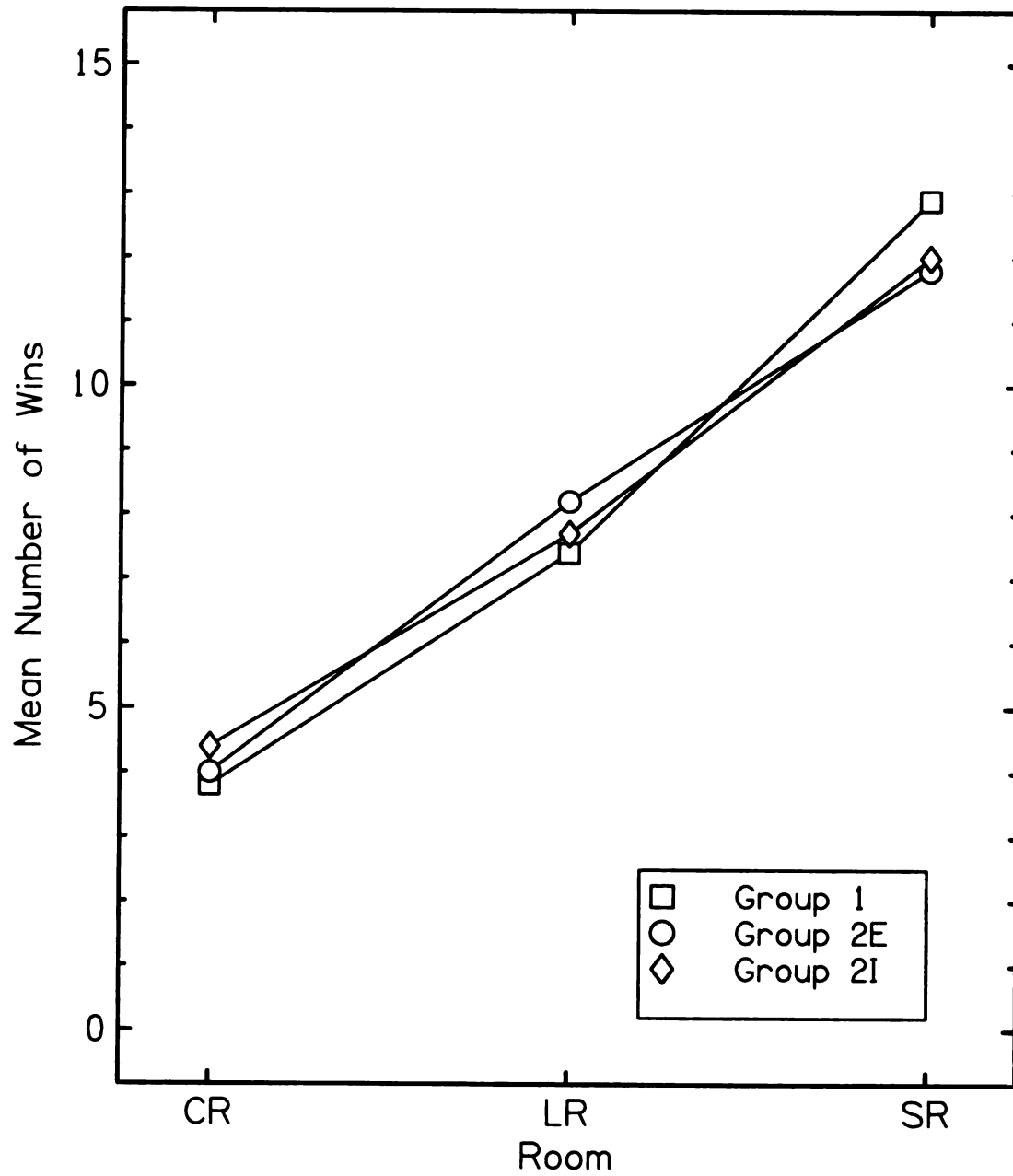


Figure 3.5. Mean preferences in the AB procedure across microphones, rooms, and groups.

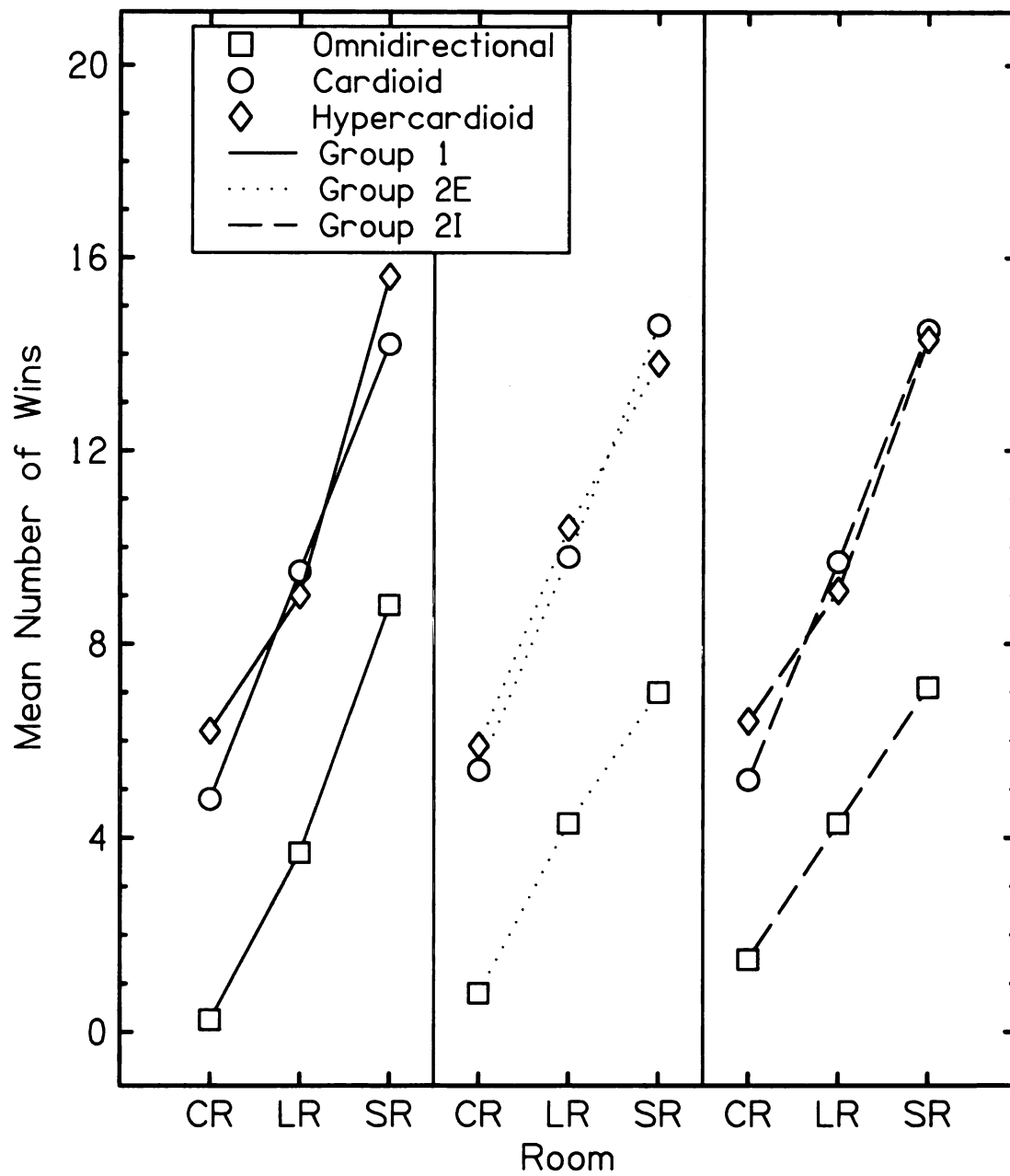


Figure 3.6. Mean preferences and Bonferroni-corrected 95-percent confidence intervals (CI_{95}), indicated by error bars, across microphones based on AB (left panel) and ABN Preference (right panel) data.

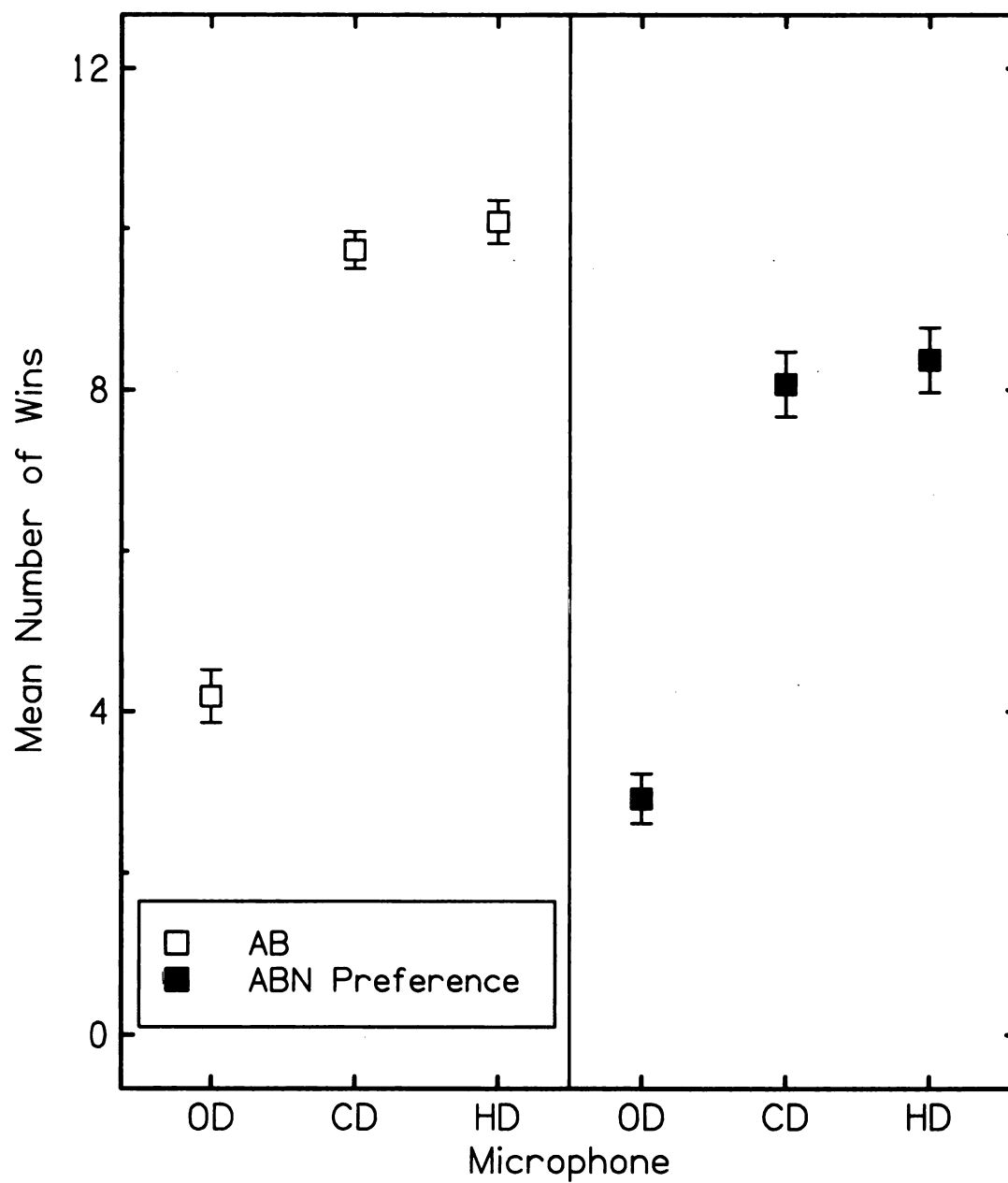


Figure 3.7. Mean preferences and Bonferroni-corrected 95-percent confidence interval (CI_{95}), indicated by error bars, across rooms based on AB (left panel) and ABN Preference (right panel) data.

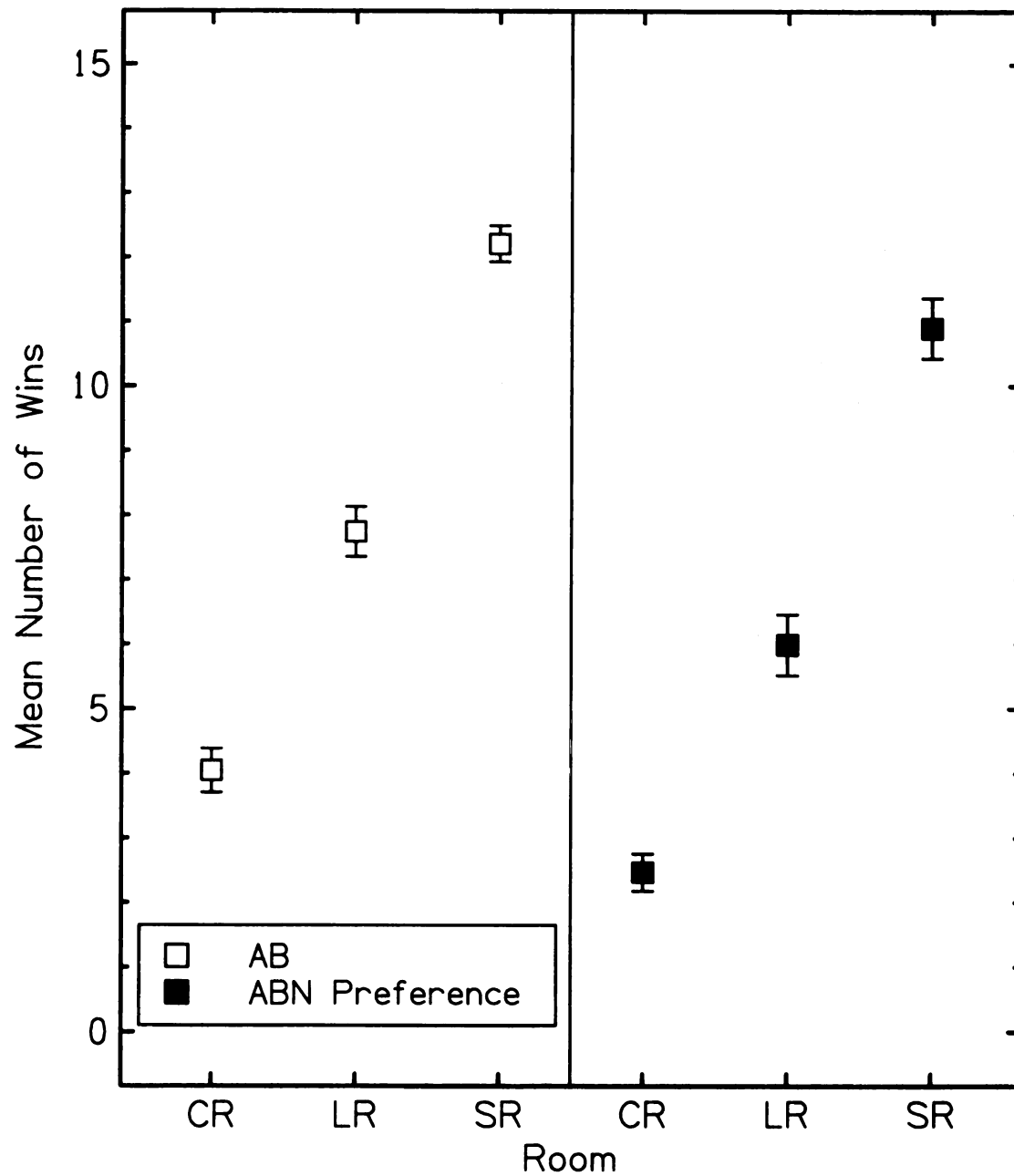


Figure 3.8. Mean preferences across microphones and rooms based on AB (left panel) and ABN Preference (right panel) data.

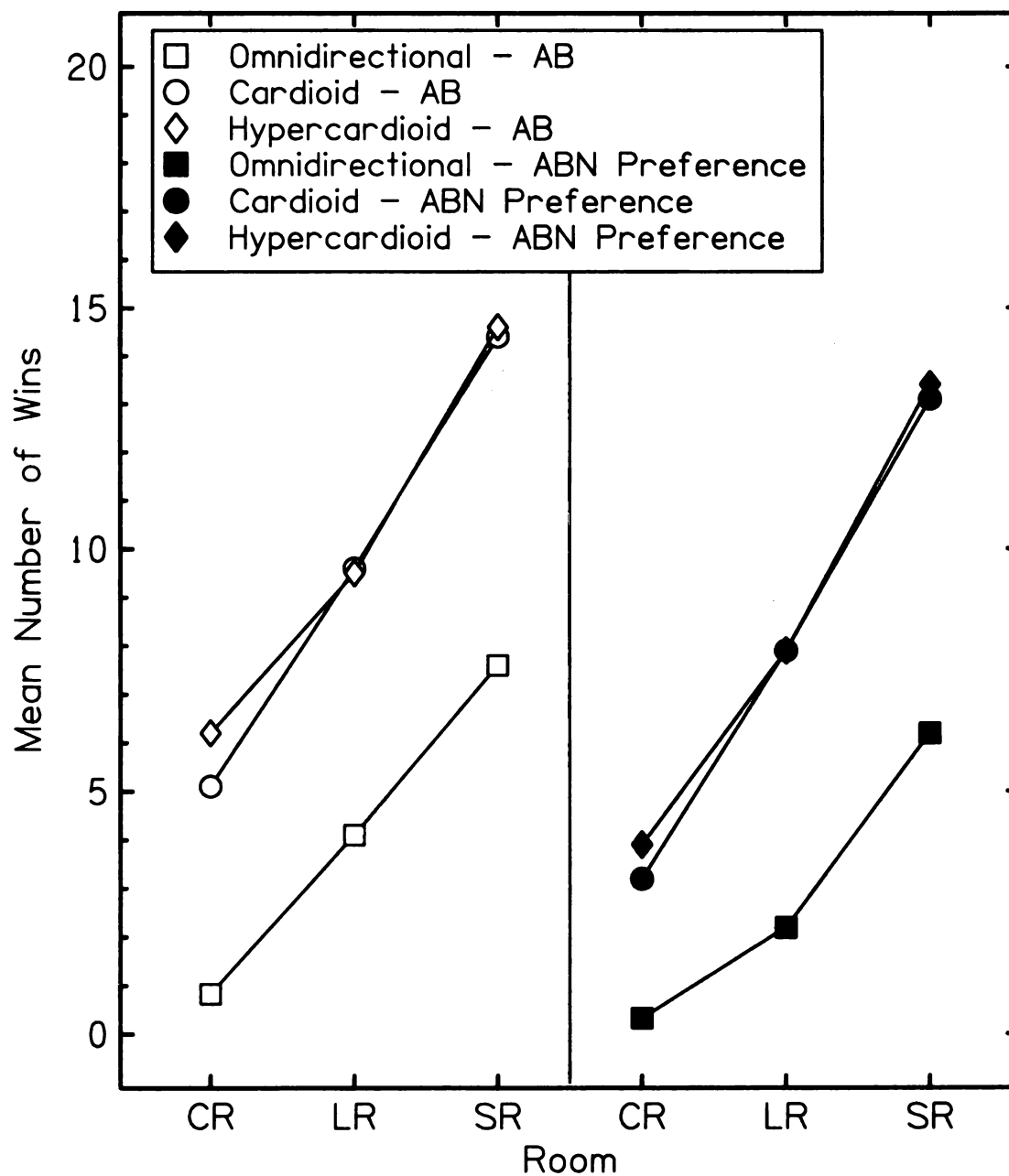


Figure 3.9. Mean preferences across rooms and groups based on AB (left panel) and ABN Preference (right panel) data.

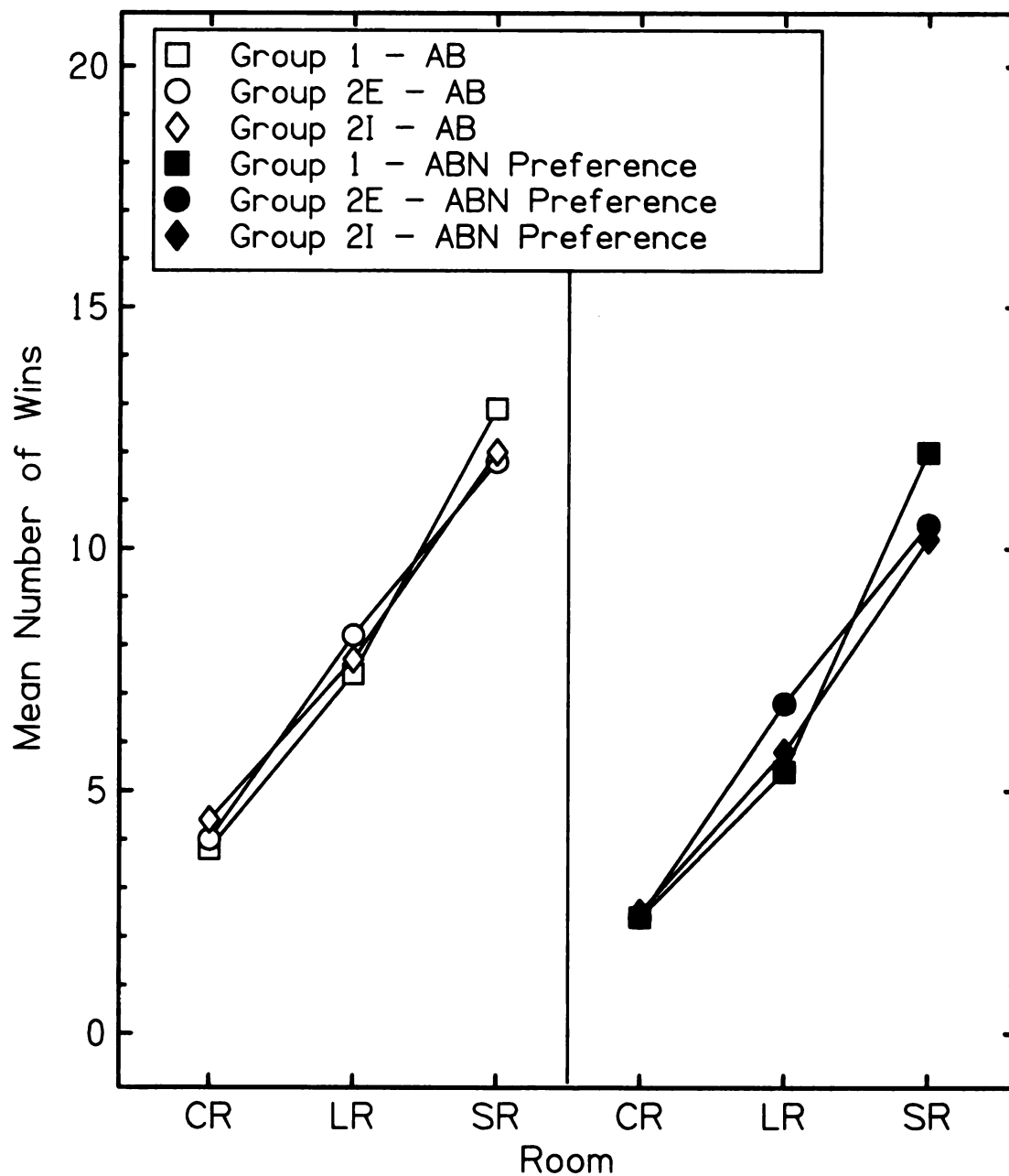


Figure 3.10. Mean preferences across microphones and groups based on ABN Preference data.

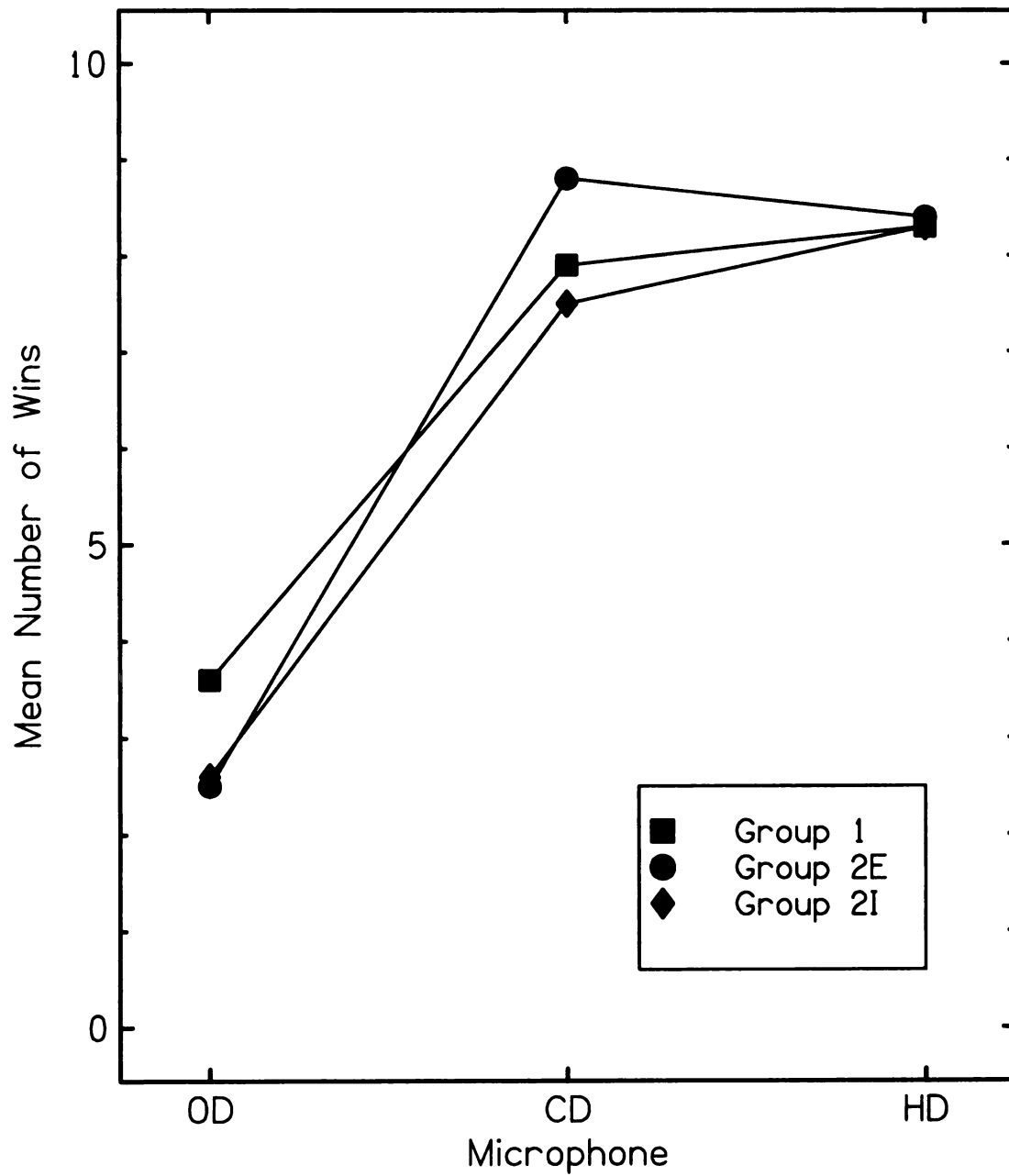


Figure 3.11. Mean ties and Bonferroni-corrected 95-percent confidence intervals (CI₉₅), indicated by error bars, across microphones based on ABN No-Preference data.

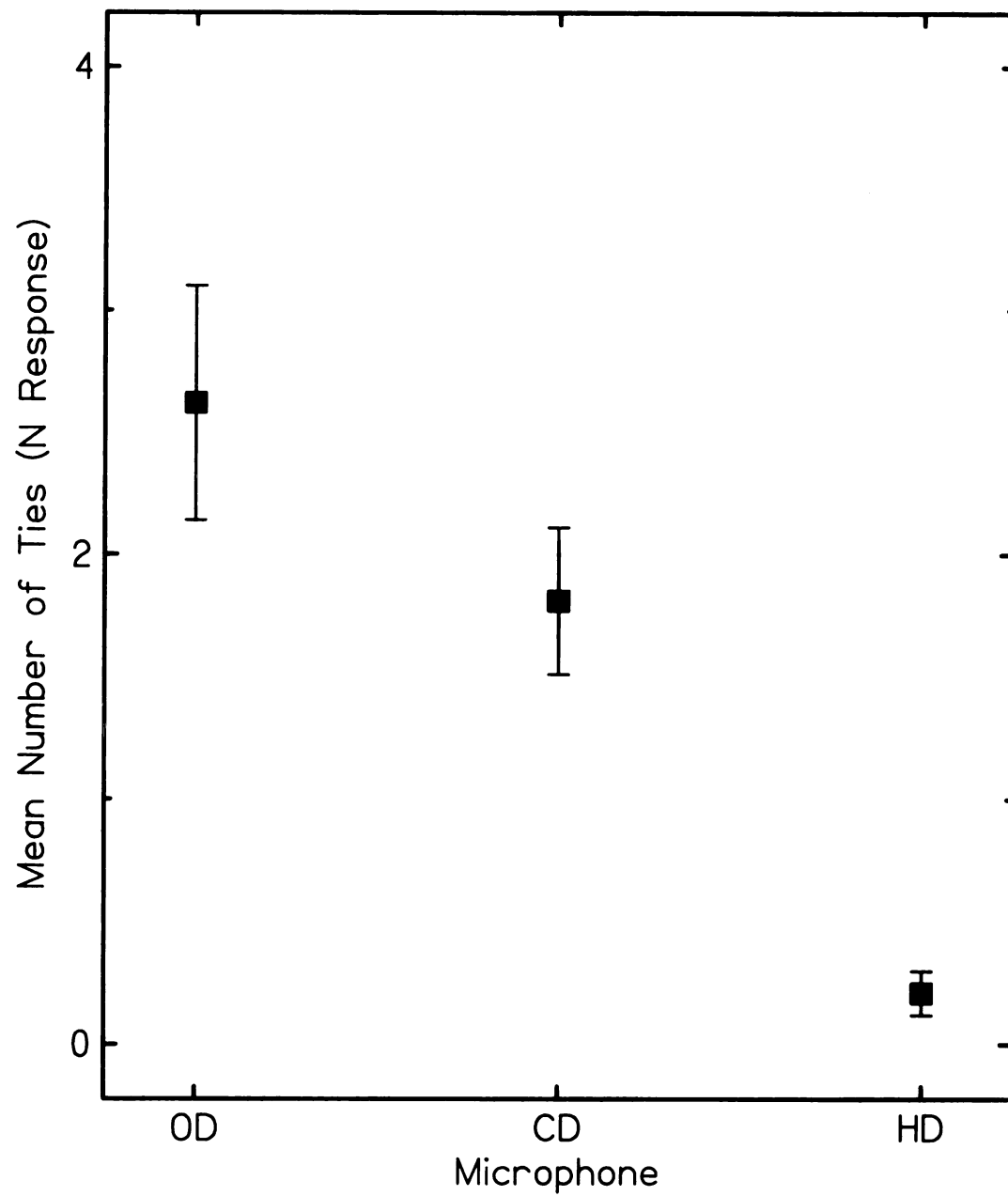


Figure 3.12. Mean ties and Bonferroni-corrected 95-percent confidence intervals (CI₉₅), indicated by error bars, across rooms based on ABN No-Preference data.

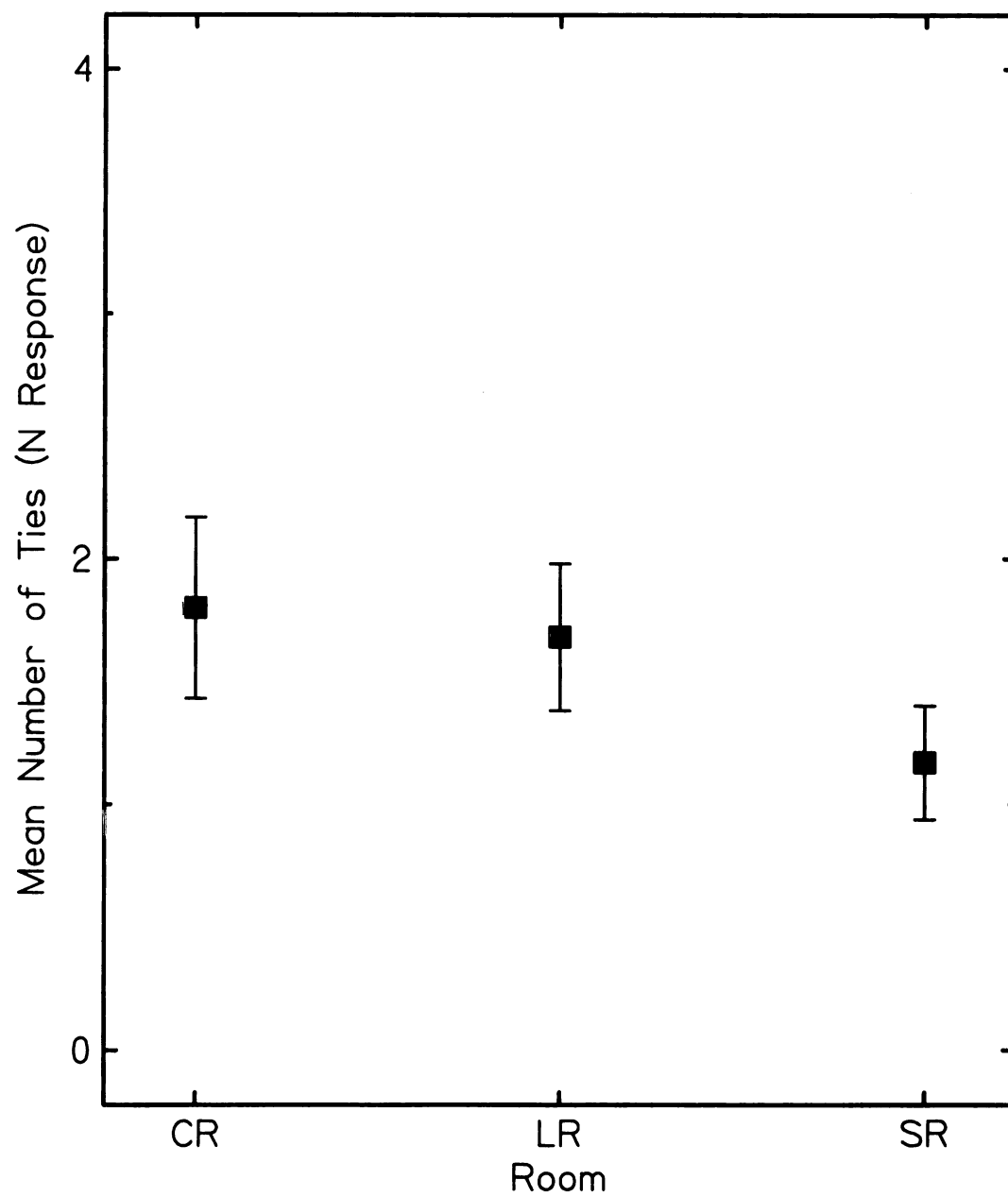


Figure A.1. Schematic illustration of an omnidirectional microphone. (Adapted from Knowles Electronics, as reported in Valente, 2000).

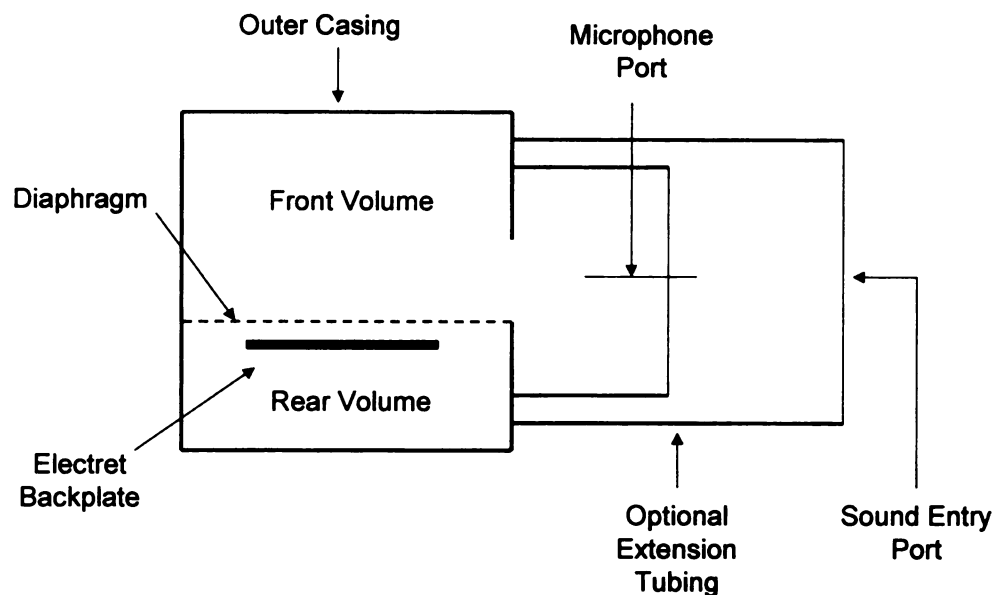


Figure A.2. Schematic illustration of a single-microphone directional device. (Adapted from Knowles Electronics, as reported in Valente, 2000).

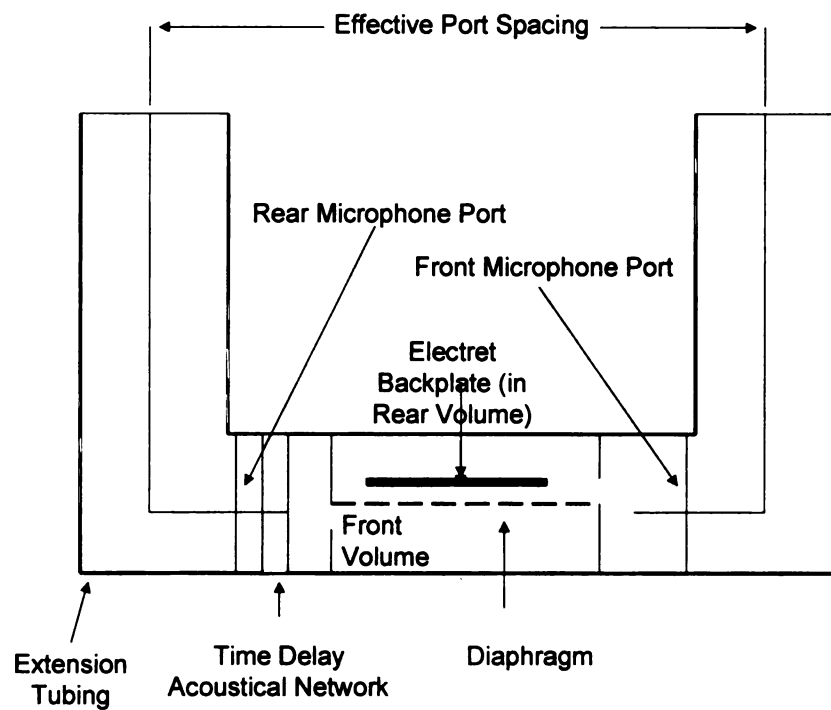


Figure A.3. Schematic illustration of a dual-microphone directional device.
(Adapted from Agnew and Block, 1997).

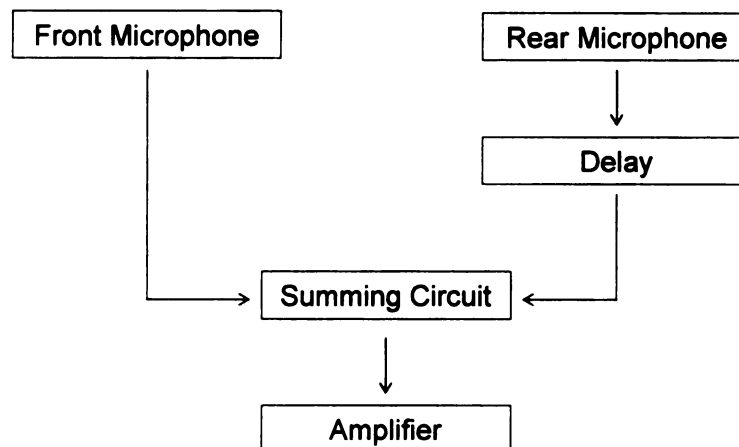


Figure A.4. Differences in low-frequency gain for omnidirectional and directional microphones. Adapted from Wolf et al. (1999).

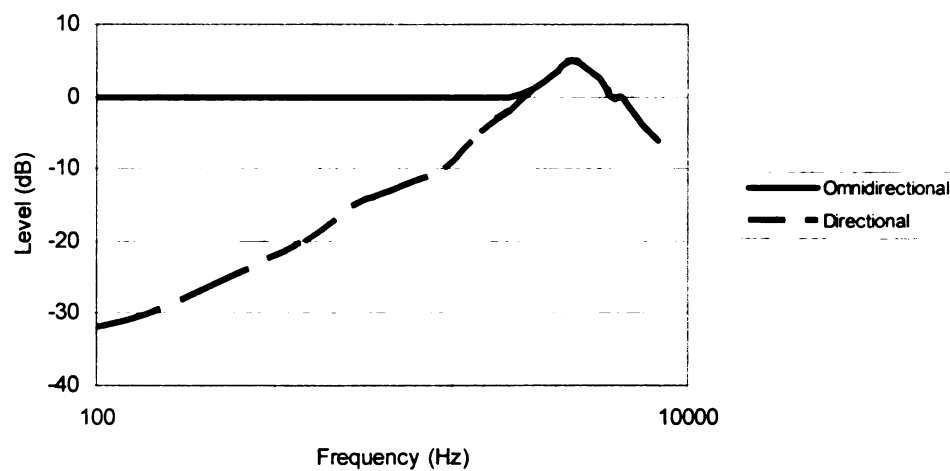


Figure B.1. Graphical representation of a polar plot.

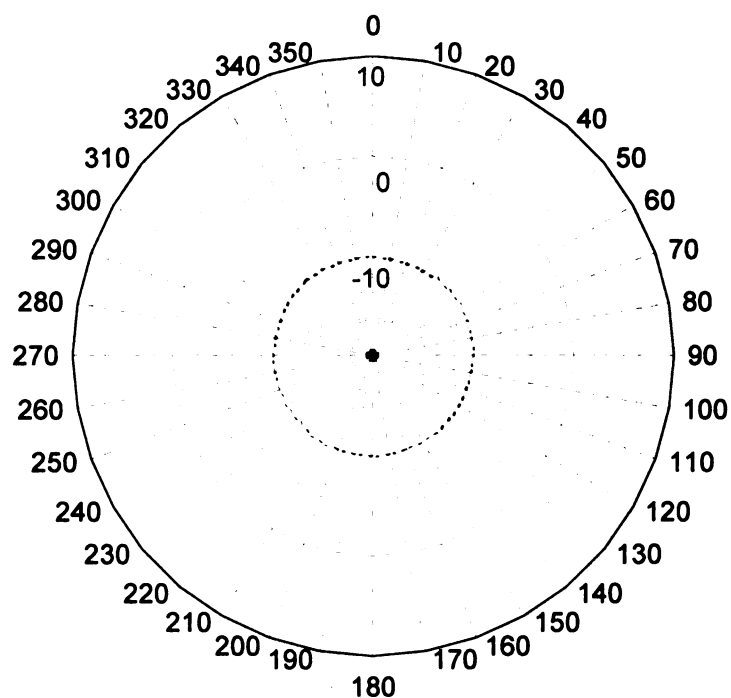


Figure B.2. Polar plot depicting the response of an omnidirectional microphone in free field.

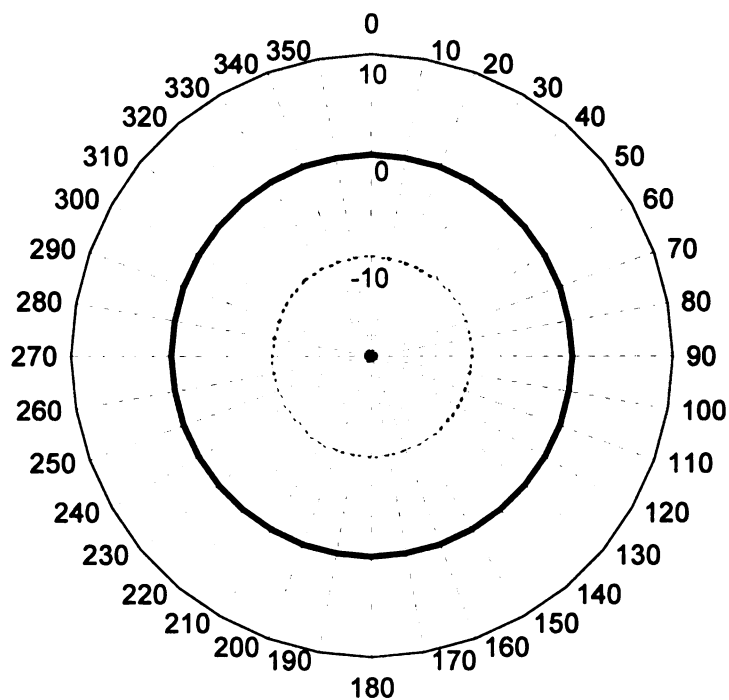


Figure B.3. Polar plot depicting the response of a cardioid microphone in free field. Adapted from Valente (2000).

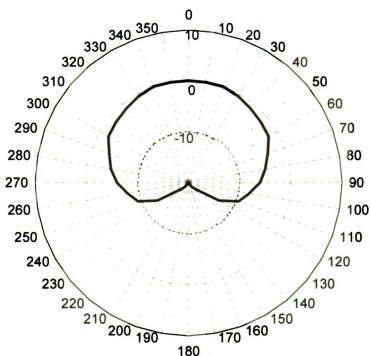


Figure B.4. Polar plot depicting the response of a hypercardioid microphone in free field. Adapted from Valente (2000).

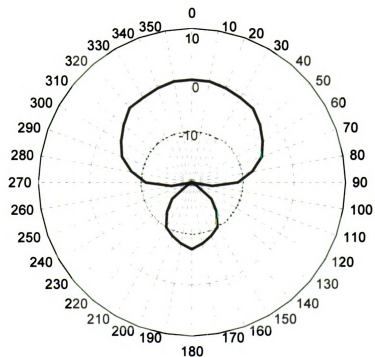


Figure B.5. Polar plot depicting the response of a supercardioid microphone in free field. Adapted from Preves (1997).

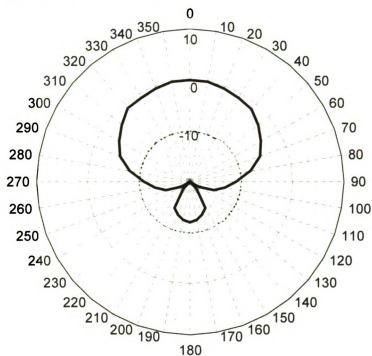
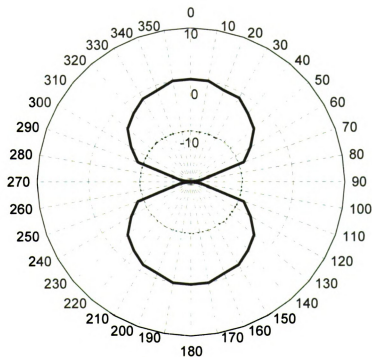


Figure B.6. Polar plot depicting the response of a bidirectional microphone in free field. Adapted from Valente (2000).



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