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Quantification of Directional Benefit across Different Polar Response Patterns

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Abstract

The purpose of this study was to assess the relationship between the directivity of a directional microphone hearing aid and listener performance. Hearing aids were fit bilaterally to 19 subjects with sensorineural hearing loss, and five microphone conditions were assessed: omnidirectional, cardioid, hypercardioid, supercardioid, and "monofit," wherein the left hearing aid was set to omnidirectional and the right hearing aid to hypercardioid. Speech perception performance was assessed using the Hearing in Noise Test (HINT) and the Connected Speech Test (CST). Subjects also assessed eight domains of sound quality for three stimuli (speech in quiet, speech in noise, and music). A diffuse soundfield system composed of eight loudspeakers forming the corners of a cube was used to output the background noise for the speech perception tasks and the three stimuli used for sound quality judgments. Results indicated that there were no significant differences in the HINT or CST performance, or sound quality judgments, across the four directional microphone conditions when tested in a diffuse field. Of particular interest was the monofit condition: Performance on speech perception tests was the same whether one or two directional microphones were used.

Key Words: Diffuse field, directional microphones, directivity index, hearing aids, monofit, sound quality, speech perception

Abbreviations: BTE = behind-the-ear style hearing aid; CST = Connected Speech Test; DI = directivity index; HINT = Hearing in Noise Test; ITE = in-the-ear style hearing aid; KEMAR = Knowles Electronic Manikin for Acoustic Research; NAL-NL1 = National Acoustic Laboratories' nonlinear hearing aid fitting algorithm (version1) NST = Nonsense Syllable Test; SIR = Speech Intelligibility Rating test; SNR = signal-to-noise ratio

Sumario

El propósito de este estudio fue evaluar la relación entre la direccionalidad de un auxiliar auditivo con micrófono direccional y el desempeño del sujeto. Se adaptaron auxiliares auditivos bilateralmente a 19 sujetos con hipoacusia sensorineural, y se evaluaron cinco condiciones de micrófono: omnidireccional, cardioide, hipercardioide, supercardioide y de "adaptación única", donde en el auxiliar izquierdo se configuró como ominidireccional y en el derecho como hipercardioide. Se evaluó el desempeño para la percepción del lenguaje utilizando la Prueba de Audición en Ruido (HINT) y la Prueba de Lenguaje Conectado (CST). Los sujetos también evaluaron ocho dominios de calidad de sonido con respecto a tres tipos de estímulos (lenguaje en silencio, lenguaje en ruido y música). Se utilizó un sistema difuso en campo sonoro, compuesto de ocho altoparlantes formando las esquinas de un cubo, para emitir el ruido de fondo para las tareas de percepción del lenguaje, así como los tres estímulos utilizados para realizar los juicios de calidad de sonido. Los

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resultados indicaron que no existen diferencias significativas en los desempeños con HINT o con CST, o en los juicios de calidad de sonido, para las cuatro condiciones de micrófono direccional evaluadas en un campo sonoro difuso. La condición de "adaptación única" resultó de interés particular: el desempeño en las pruebas de percepción del lenguaje fue el mismo, independientemente de que se utilizaran uno o dos micrófonos direccionales.

Palabras Clave: Campo difuso, micrófonos direccionales, índice de direccionalidad, auxiliares auditivos, adaptación única, calidad de sonido, percepción del lenguaje

Abreviaturas: BTE = auxiliar auditivo de tipo retroauricular; CST = Prueba de Lenguaje Conectado; DI = Indice de direccionalidad; HINT = Prueba de Audición en Ruido; ITE = auxiliar auditivo de tipo intra-auricular; KEMAR = Maniquí Electrónico Knowles para Investigación Acústica; NAL-NL1 = Algoritmo no lineal para adaptación de auxiliares auditivos de los Laboratorios Nacionales de Acústica (Versión 1); NST = Prueba de sílabas sin sentido; SIR = Prueba de Puntuación de Inteligibilidad en el Lenguaje; SNR = tasa de relación señal/ruido

Directional microphone technology holds significant potential for enhancing speech intelligibility by improving the signal-to-noise ratio (SNR) in some listening situations (Ricketts and Dittberner, 2002). This SNR improvement, however, depends on both the source(s) of noise and the amount of reverberation in the environment (Hawkins and Yacullo, 1984; Ricketts, 2000a, 2000b; Novick et al, 2001). The benefit obtained with the use of a directional microphone generally decreases with the increase in reverberation. Hawkins and Yacullo (1984) noted a 3–4 dB decrease in SNR advantage with the use of directional microphones in more reverberant listening environments. This advantage is the same with short reverberation times (0.3 and 0.6 sec), but the advantage decreases at longer reverberation times (1.2 sec) (Hawkins and Yacullo, 1984). Other investigators have found similar results (e.g., Ricketts and Dhar, 1999; Novick et al, 2001).

Of concern in the previous literature is the issue of location and number of interfering noise sources. While earlier studies focused on 0/180 degrees placement of primary/competing signals (e.g., Hawkins and Yacullo, 1984; Valente et al, 1995; Nielsen and Ludvigsen, 1998), it is now well understood that the placement of a small number of speakers will have significant impact on the outcome, if those noise sources fall within the nulls of the particular polar response patterns (i.e., cardioid, hypercardioid, supercardioid). To circumvent this design bias, a "more diffuse" field was created by Pumford et al (2000) using four interference speakers and one primary signal speaker. Sentence recognition thresholds were measured with subjects wearing in-the-ear (ITE) and behind-the-ear (BTE) style directional microphone hearing aids. For the BTE hearing aid condition, the authors reported a difference of 5.77 dB SNR between the omnidirectional and directional modes. A difference of 3.27 dB was reported for the ITE hearing aid. As the investigators noted, however, the ITE omnidirectional condition provided better SNR performance than the BTE omnidirectional condition due to the placement of the microphone in the concha. Consequently, the actual performance with the two microphone modes was similar, although the benefit seemed to favor the BTE style.

Ricketts (2000c) has also studied the effects of the position of noise source(s). He noted that the impact of reverberation and noise source configuration on directional benefit can be explained adequately when the interaction between the spatial properties of the noise source(s) and the polar patterns of the hearing aids are considered. In a related study (Ricketts and Dhar, 1999) a "more diffuse" field using five speakers spaced around a center point at 90, 135, 180, 225, and 270 degrees relative to the subject was implemented. The Hearing in Noise Test (HINT) and the Nonsense Syllable Test (NST) were presented in two environments, an anechoic chamber and a "typical living room" listening environment. Three BTE hearing aids were studied in both the omnidirectional and the directional modes. In both the reverberant and anechoic listening conditions, a significant benefit was reported for directional amplification over omnidirectional amplification across the three hearing aids, for both the HINT and the NST. A 2–3 dB directional advantage was noted in the anechoic chamber over the reverberant environment. It was also reported that the directional advantage was 2–3 dB poorer than that reported earlier using a single noise source at 180 degrees azimuth to the listener, with a single noise source at 180 degrees azimuth.

It is clear that the placement of the interfering noise is directly related to the benefit measured. Each polar response pattern will have at least one (first-order cardioid) and as many as three (second-order hypercardioid) nulls, or angles at which the microphone has reduced sensitivity to any background interference (Dittberner et al, 2001). To circumvent describing the effectiveness in terms of the null placement, a measure of directivity, the directivity index (DI), is used. The measurement of directivity has been commonly applied in other disciplines for over 60 years. The generally accepted formula (from Beranek, 1954) is

$$DI(f) = 10 * Log_{10}\left[\frac{4\pi|p_{ax}|^2}{\int_0^{2\pi}\int_0^{\pi}|p(\phi,\theta)|^2\,|\sin\phi|\,d\phi\,d\theta}\right]$$

where,

$|P_{ax}|^2$ is the magnitude of the on-axis mean-square sound pressure microphone response to a plane-wave signal in free field.

$|P(\Phi, \theta)|^2$ is the magnitude of the off-axis mean-square sound pressure microphone response to a diffuse sound field.

In other words, the DI describes the on-axis response (P_{ax}) of a directional microphone system to sound in contrast to its off-axis response ($P[\Phi, \theta]$) . Although there is some evidence that higher DI values result in better hearing in background noise (Ricketts and Mueller, 1999), the direct relationship is unclear. Theoretical DI values vary across the cardioid (DI = 4.6), supercardioid (DI = 5.4), and hypercardioid (DI = 6.0) patterns. Those theoretical values are rarely achieved when the microphone is encased in a wearable hearing aid and mounted on the side of the head (Dittberner and Bentler, 2003). The purpose of this study was to assess speech perception performance in noise using hearing aids with different directivity indices. Only by eliminating the advantage of speaker(s) location is it possible to determine whether differences in DIs actually translate into differences in listener performance. In this study, it was also of interest whether the different patterns resulted in any qualitative differences for the listeners.

METHODS

Subjects

The subjects consisted of 19 adults (10 females, 9 males) aged 50–83 (mean of 67) with documented symmetrical sensorineural hearing losses. Ten of the subjects were new users of hearing aids, and nine of the subjects were considered experienced, having at least one year of previous hearing aid use.

Hearing Aid

The Unitron Sound F/X™ ITE with the Gennum Frontwave directional microphone was chosen for this study. This analog AGC-I hearing aid allows for the programming of two memories with different polar patterns in each. Available polar patterns included

Table 1. Directivity Index Values (DIs) for Each Polar Pattern (theoretical, free field, and on KEMAR)

		Free Field		Kemar	
	Theoretical	2D	3D	2D	3D
Omni	0	-0.59	-0.22	-0.35	0.21
Cardioid	4.6	4.60	4.59	2.87	3.46
Supercardioid	5.4	5.21	5.60	3.33	3.98
Hypercardioid	6.0	5.27	5.65	3.37	3.94

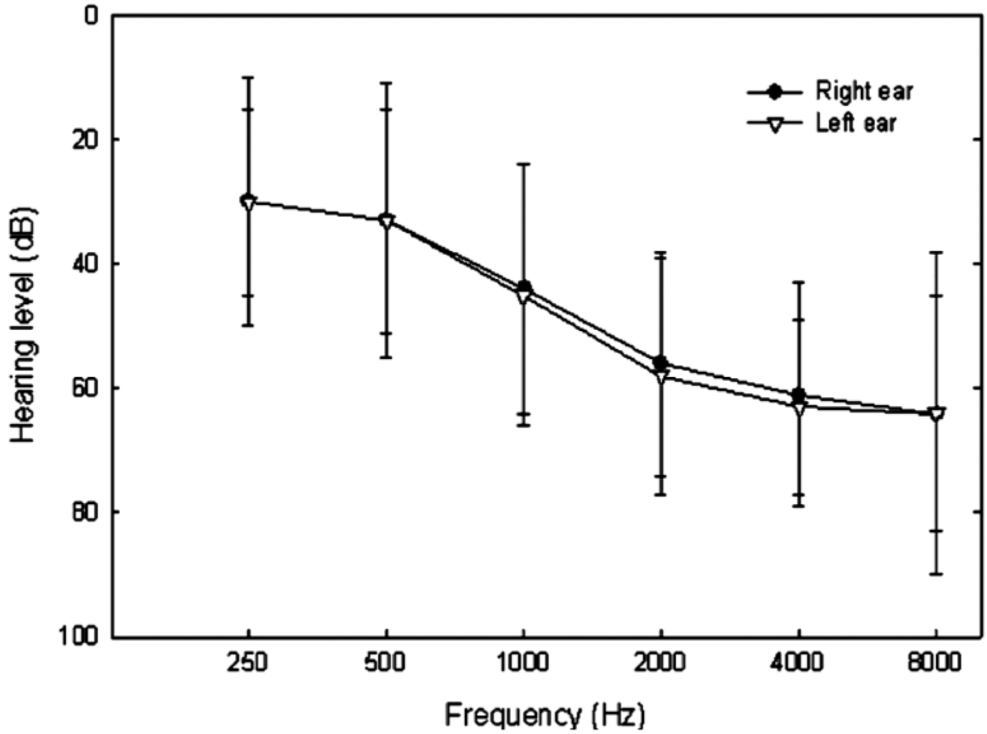


Figure 1. Mean audiometric results for the subjects in this investigation (shown with ranges at each frequency.

omnidirectional, cardioid, supercardioid, and hypercardioid. Table 1 provides the directivity index values, both theoretical and measured for the microphone conditions. The measured values were obtained in the anechoic chamber located in the sub-basement of the department building (specifications discussed below). Polar plots were obtained using a single noise source and a rotating turntable (for 10 degree incremental measures). The values represent an average across 500, 1000, 2000, and 4000 presentation stimuli. For

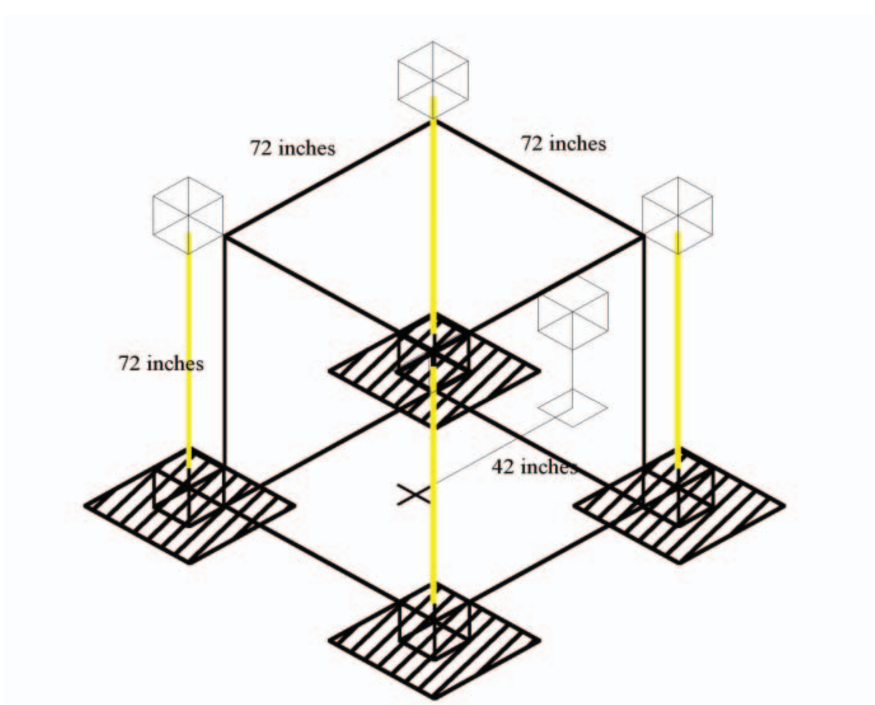


Figure 2. Schematic of the eight-speaker cube used in this investigation (after Veit and Sander, 1987).

complete methodology, refer to Ricketts and Dittberner (2002).

Procedures

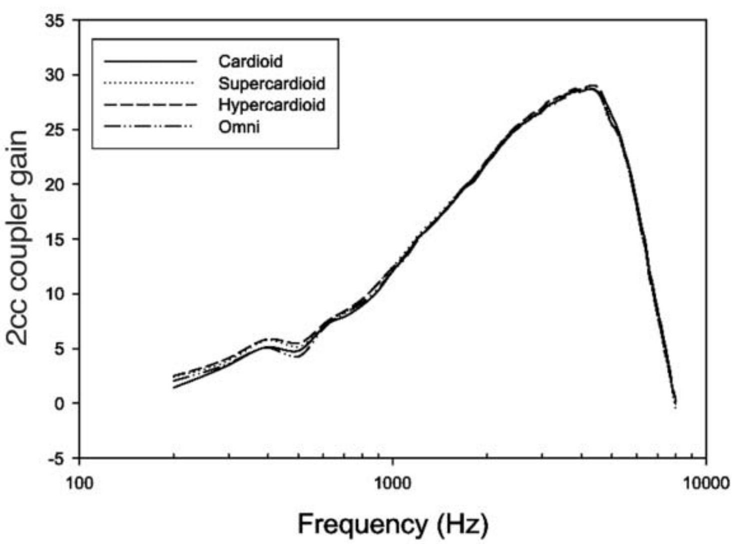
Audiometric evaluations were conducted for all subjects. Pure-tone thresholds were obtained for the frequencies of 250, 500, 1000, 2000, 4000, and 8000 Hz, using a GSI-61 audiometer (re: ANSI S3.6, 1996). Thresholds ranged from 10 dB HL to 90 dB HL from 250 to 8000 Hz (refer to Figure 1 for the average pure-tone thresholds). Following an explanation of the investigation and the signing of the subject consent forms, ear impressions were taken, and in-the-ear (ITE) style Unitron Sound F/X™ hearing aids were ordered. Each impression was clearly marked for accurate microphone port placement.

The Environment

All testing was conducted in an anechoic chamber comprised of a concrete room of 30 foot cube containing a steel-walled booth supported on steel beams attached to the floor by springs. The springs isolate the booth from vibration of the structure. The steel walls of the sound booth are filled with four inches of fiberglass insulation. The inside of the chamber is treated with fiberglass wedges measuring 3'10" in length. A wire mesh suspended level with the floor of the adjacent room provides support for movement around the interior. A three-foot-wide expanded metal catwalk extends into the chamber to support equipment. The interior of the anechoic chamber is a cube 20'9" (6.33 m) to a side, from wedge tip to adjacent wedge tip, yielding a free space area of approximately 8934 cubic feet (253 cubic meters). The anechoic chamber is designed to be a free acoustic field for frequencies down to 60 Hz. This limitation is imposed by the configuration of the fiberglass wedges used as acoustic baffles.

In theory, an artificial, spatially limited "diffuse" sound field can be created in an anechoic chamber with an infinite number of independent and equally intense sound sources. These sound sources would be distributed uniformly around the region of measurement in a spherical configuration. Veit and Sander (1987) found that an artificial diffuse sound field could be created using only eight loudspeakers, assuming an appropriate array was assembled. It follows that the different directivity patterns (and resultant DI values) could be assessed for our purposes without contamination due to reverberation or high noise floor.

For this study, a diffuse sound field



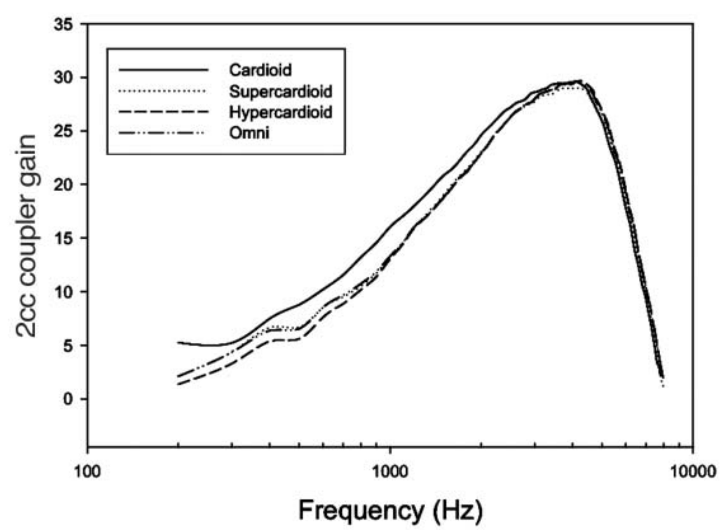


Figure 3. Coupler responses of the four microphone conditions: cardioid, supercardioid, hypercardioid, and omnidirectional, shown from a random sample of the right ear (left) and left ear (right) of ten subjects. The fifth microphone condition (monofit) was achieved by using an omnidirectional microphone on the left ear and a hypercardioid microphone on the right ear.

system composed of eight loudspeakers forming the corners of a cube, 72 inches to a side, around a center point (Figure 2) (Veit and Sander, 1987). The center point was measured at 42 inches from the primary loudspeaker, located at 0 degrees azimuth and elevation, between the two front loudspeaker pairs. The eight loudspeakers were angled, facing toward the subject. The noise signal was presented through the eight loudspeakers, while the main test signal was routed through the primary loudspeaker. Background noises were uncorrelated across loudspeakers.

Test Conditions

Five microphone conditions were examined: omnidirectional, cardioid, hypercardioid, supercardioid, and monofit, wherein the left hearing aid was set to omnidirectional and the right hearing aid to hypercardioid. Corresponding theoretical DI and measured DI values for each microphone configuration can be found in Table 1. Coupler responses for the different microphone conditions were obtained with the sound source at 0 degrees azimuth relative to the aid position in the sound chamber. The averages across ten randomly selected subjects are shown in Figures 3a and b. The figures confirm that the programming of the different polar patterns did not significantly impact the gain/frequency responses available to the subjects during the data collection phase.

The frequency response of the hearing aids for each subject was programmed to match National Acoustics Laboratory nonlinear targets (NAL-NL1) (Dillon, 1999) within 5 dB rms (root mean square) for a 65 dB SPL input (500, 1000, 2000, and 3000 Hz) and for 50 and 80 dB SPL inputs (2000 Hz). No adjustments to frequency response were made following the hearing aid fitting. Using a double-blinded design, neither the subjects nor the tester knew which microphone configuration was utilized during each of the five testing conditions.

The Hearing in Noise Test (HINT) (Nilsson et al, 1994) was used to measure speech perception in noise. The subjects were instructed to repeat 20 sentences spoken by a male talker in the presence of speech-shaped noise presented at a fixed level (65 dBA SPL). The level of the sentence was varied depending on the correctness of the response. Calculation of the signal-to-noise ratio (SNR) necessary for 50% performance was done by averaging the presentation level of sentences 5 through 20 and relating that value to the 65 dBA noise level.

The Connected Speech Test (CST) (Cox et al, 1987) was also used as a measure of speech intelligibility in noise. Multitalker babble was presented through the eight cube speakers at a +2 signal-to-noise ratio related to the female talker (presented at 61 dBA).

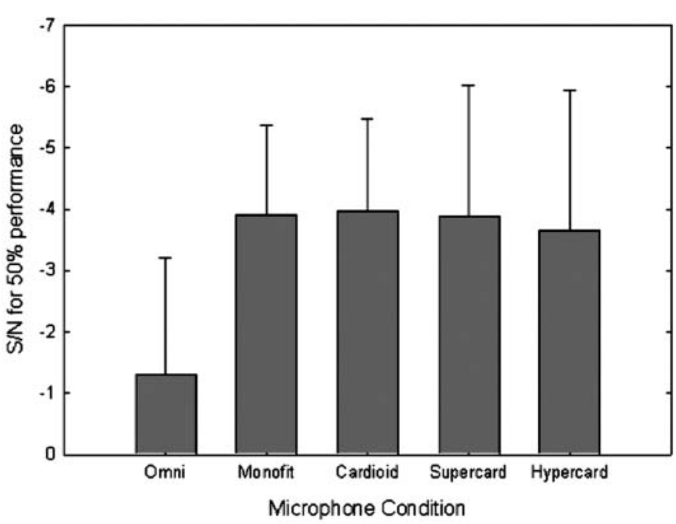


Figure 4. Mean scores (with standard deviations) across subjects and microphone conditions for the Hearing In Noise Test.

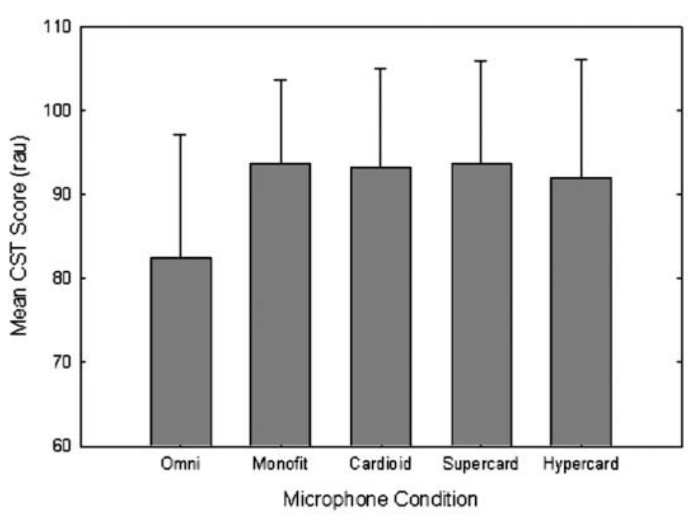


Figure 5. Mean scores (with standard deviations) across subjects and microphone conditions for the Connected Speech Test.

Table 2. Mean Sound Quality Ratings of Speech in Quiet across 19 Subjects

	Omni	Monofit	Cardioid	Supercardioid	Hypercardioid
Fullness	8.87(1.0)*	8.68(1.1)	8.47(1.0)	8.63(1.1)	8.76(1.0)
Nearness	9.03(1.0)	8.92(1.0)	8.79(0.9)	8.74(1.1)	8.97(1.0)
Brightness	8.71(1.1)	8.53(1.1)	8.47(1.2)	8.61(1.1)	8.42(1.3)
Fidelity	9.29(0.7)	9.11(0.9)	9.03(0.9)	9.18(0.9)	9.11(1.0)
Spaciousness	9.11(0.9)	8.32(2.4)	8.18(2.1)	8.34(2.2)	8.47(1.9)
Loudness	7.74(1.7)	8.16(1.5)	7.63(1.7)	7.84(1.6)	8.00(1.5)
Softness	6.32(2.2)	6.37(1.9)	5.97(2.2)	5.66(2.4)	5.71(2.0)
Clarity	9.11(0.8)	8.92(1.0)	8.92(1.1)	9.00(0.9)	9.18(0.5)

* Standard deviations in parentheses.

Table 3. Mean Sound Quality Ratings of Speech in Noise across 19 Subjects

	Omni	Monofit	Cardioid	Supercardioid	Hypercardioid
Fullness	8.13(1.0)*	7.79(1.5)	7.74(1.5)	8.16(1.5)	8.00(1.4)
Nearness	8.47(1.2)	8.00(1.4)	8.00(1.5)	8.32(1.6)	8.26(1.1)
Brightness	7.87(1.5)	8.16(1.73)	7.61(1.6)	7.68(1.7)	7.90(1.2)
Fidelity	8.18(1.5)	8.68(1.4)	8.79(1.1)	8.66(1.5)	8.58(1.1)
Spaciousness	8.03(1.5)	7.18(2.5)	7.16(2.3)	8.00(1.4)	7.79(2.0)
Loudness	6.76(1.9)	6.63(1.7)	6.58(1.7)	6.74(1.7)	6.66(1.5)
Softness	6.42(2.0)	6.34(1.5)	6.34(1.8)	6.24(2.1)	6.26(1.6)
Clarity	8.53(1.1)	8.11(1.4)	8.37(1.1)	7.79(2.3)	8.34(1.4)

*Standard deviations in parentheses.

Table 4. Mean Sound Quality Ratings in Music across 18 Subjects

	Omni	Monofit	Cardioid	Supercardioid	Hypercardioid
Fullness	8.33(1.7)*	8.36(1.0)	8.44(1.1)	8.50(1.3)	8.11(1.4)
Nearness	8.69(1.3)	8.36(2.1)	8.83(1.0)	8.75(1.2)	8.64(1.3)
Brightness	8.33(1.5)	8.25(1.4)	8.14(1.1)	7.64(1.1)	8.25(1.1)
Fidelity	8.17(1.9)	8.28(1.4)	8.42(1.6)	8.58(1.7)	8.72(1.4)
Spaciousness	8.06(2.6)	7.94(2.2)	8.58(1.8)	8.69(1.2)	7.89(2.4)
Loudness	7.39(2.4)	7.31(1.9)	7.94(1.7)	7.19(2.2)	7.08(1.8)
Softness	5.89(2.3)	6.75(2.0)	5.28(2.5)	5.67(2.7)	5.81(2.0)
Clarity	7.94(2.0)	8.17(2.0)	8.14(1.9)	7.94(1.9)	8.72(1.0)

*Standard deviations in parentheses.

Four randomized passage pairs were included in each condition. The subject was instructed to repeat each sentence, or any recognizable portion thereof. Scores were calculated as percent correct for key words. The percentages were then converted to rationalized arcsine units (Studebaker, 1985), in order to normalize the variance.

Subjects assessed eight aspects of sound quality for three stimuli (speech in quiet, speech in noise, and music). Sound quality aspects rated included fullness, nearness, brightness, fidelity, spaciousness, loudness, softness, and clarity (Gabrielsson and Sjogren, 1979). The music stimulus was presented in eight one-minute segments at 75 dBA. Segments with a wide dynamic range were selected from Mozart symphonies. Each subject was instructed to listen for the entire segment before making each rating on a scale of zero to ten, in half point increments. Standard-length segments were used in the music condition in order to provide some standardization to the stimulus. Speech was presented at a level of 64 dBA in noise (+8 signal-to-noise ratio) and quiet conditions. The speech stimulus used was taken from the Speech Intelligibility Rating (SIR) test (Cox and McDaniel, 1989) presented by a male speaker. The background noise for the speech in noise condition consisted of the same multispeaker babble utilized in the CST testing. For the speech in noise and speech in quiet conditions, subjects were instructed to move through the ratings at their own pace.

RESULTS

Descriptive Statistics

Group Analyses

Mean scores and standard deviations for each of the five microphone conditions were calculated for the HINT and the CST and are shown in Figures 4 and 5.

Subjects also rated eight aspects of sound quality for three stimuli for each condition. Loudness discomfort precluded completion of testing in music for subject 03. Mean scores and standard deviations are shown in Tables 2, 3, 4.

To evaluate the probability of the observed differences on the HINT across microphone conditions, a repeated measures analysis of variance (ANOVA) was conducted. This evaluation showed that at least one condition was significantly different from at least one other condition ($F_{4,72} = 11.809$; $p < .001$). Because of the significant main effect of microphone condition, post hoc pairwise comparisons were made, using Bonferroni correction for multiple tests. This analysis revealed that the omnidirectional condition was significantly worse than all other conditions ($p < .002$). No other pairwise comparisons approached statistical significance at the $p = .05$ level.

A repeated measures ANOVA was also conducted on CST data. This evaluation showed that at least one condition was significantly different from at least one other condition ($F_{4,72} = 12.283$; $p < .001$). Because of the significant main effect of microphone condition, post hoc pairwise comparisons were made, using Bonferroni correction for multiple tests. This analysis also revealed that the omnidirectional condition was significantly worse than all other conditions ($p < .002$). No other pairwise comparisons approached statistical significance at the $p = .05$ level.

Means and standard deviations for each aspect of sound quality in speech in quiet, speech in noise, and music are displayed in Tables 2, 3, and 4, respectively. Repeated measures ANOVA tests were conducted for each of the eight sound quality characteristics in speech in quiet, speech in noise, and music. No significant differences were found ($p > .05$).

Repeated-measures ANOVA procedures presume that there is no interaction between the subject and any level of the treatment variable. That is, such analyses presume that if one subject is more likely to do well with one treatment, then the rest of the subjects are also more likely to do well with that treatment. This assumption is known as additivity because the grand mean score for a given subject is assumed to sum with the grand mean score for a microphone condition to produce the most likely score on the test for that combination of subject and microphone condition. When the subject and microphone effects do not sum in this way, the typical ANOVA model no longer represents the underlying structure of the data, and analysis of individual subject data is desirable.

One method of evaluating additivity is with the use of Tukey's Test of Nonadditivity

Table 5. Numbers of Subjects in Each Best-Worst Condition Pair for the CST

		Best Condition			
		Monofit	Cardioid	Supercardioid	Hypercardioid
Worst Condition	Monofit	X	0	0	1
	Cardioid	0	X	2	1
	Supercardioid	1	2	X	1
	Hypercardioid	1	0	2	X

(Kirk, 1995). This test evaluates the probability that microphone conditions have the same effect for all subjects. Kirk suggested that a criterion significance level of $p < 0.10$ should be used in interpreting this test. This is because it is regarded as preferable to detect cases of nonadditivity than to presume nonadditivity when the additive model would suffice. Additivity for both the HINT and the CST was examined in this way. The test of nonadditivity was not significant for the HINT ($F_{1,71} = 1.4278$; $p = .2361$) but was significant for the CST ($F_{1,71} = 3.8333$; $p = .0542$). We regarded this difference to be associated with the different reliabilities of the tests. The internal consistency reliability (Cronbach's alpha) of the HINT data in this study was .7, while the alpha statistic for the CST was .9. It is likely that nonsignificant results of the test of nonadditivity is due to the relatively large amount of measurement error in HINT scores, which would greatly reduce the power of any test of nonadditivity. Because of this, individual analyses were conducted with only the CST.

Individual Analyses

Using data provided by Cox et al (1988), the 90% critical difference for the CST was estimated to be 8.58 rau. Excluding the omnidirectional condition, the differences between the best and worst directional conditions were evaluated. The number of individual subjects for whom the best condition-worst condition difference exceeded the critical difference is shown in Table 5. Eight subjects showed no significant difference between best-worst pairs. To determine if there was a systematic relationship between best and worst pairs, Fisher's Exact Test was used. This test evaluates the probability that the observed data would be generated if no relationship existed between the best and worst conditions. A significant result on Fisher's Exact Test would suggest that some subjects could be expected to have a given best/worse pair more frequently than others. No significant relationship was found (Fisher's exact $p > .05$), which is consistent with the finding of no differences among directional microphone conditions in the group-level analysis. It is of interest to note that, when subjects were asked to choose a preferred bilateral directional condition, five subjects chose cardioid, five subjects chose hypercardioid, and nine subjects chose supercardioid patterns.

DISCUSSION

Results of the present investigation indicate that subject performance in the omnidirectional condition was significantly worse than all other conditions. This finding held for both the HINT and CST. That is, any amount of directionality was shown to improve performance over the omnidirectional comparison. Results of subject preference in speech in quiet, speech in noise, and music background showed no significant differences across the microphone conditions.

These results are consistent with previous investigations of directional versus omnidirectional microphone effectiveness, in which an advantage was reported for directional microphones. In an early investigation, Hawkins and Yacullo (1984) noted a 3–4 dB increase in SNR advantage with the use of directional microphones in more reverberant listening environments. The magnitude of that SNR advantage is slightly higher than the 2.5 dB measured in the present study, possibly related to the use of a diffuse field in the present study. The Pumford et al (2000) study noted a 3.27 dB advantage over omnidirectional for an ITE hearing aid in a four-speaker "more diffuse" field. Again, the slight difference between those results and the current study may be due to more difficulty in listening in the eight-speaker diffuse field arrangement.

No significant differences were found among the directional conditions even though the manufacturer-provided (theoretical) Directivity Indices (DI) ranged from 4.6 to 6. It is apparent from Table 1 that the free-field and KEMAR DI values were actually closer in value to each other than the theoretical values provided. Although the polar patterns and theoretical derivations of directivity suggest that differences in performance and benefit may exist, the empirically derived values suggest otherwise (Dittberner and Bentler, 2003). At the same time it can be argued that, for a given environment with a fixed noise source, a particular polar pattern (because of its null placement and the absence of other noise and reverberation) may provide more advantage to the listener than another. Such an example makes the case for the use of multiple-memory programming of different patterns, or an adaptive pattern. Continued research on the efficacy of either alternative option in real world listening environments is necessary.

The results of the monofit condition warrant further consideration. Rather than falling somewhere between the bilaterally fit directional conditions and the omnidirectional condition, the monofit results aligned well with the bilateral directional conditions. This finding is consistent with comments made by Zurek (1993) regarding binaural listening. Zurek noted that humans may use information centrally on a band-by-band (or, as in this case, ear-by-ear) basis, suggesting that the speech-to-interference ratio in binaural listening is never worse than the better of the two ears (Zurek, 1993). Therefore, the improved signal-to-noise ratio granted by the right hearing aid utilizing the hypercardioid polar pattern would provide sufficient improvement in performance.

A related study by Karsten and Turner (2000) might also be used to explain the monofit results. Speech recognition was examined for subjects with bilateral asymmetrical sensorineural hearing losses. For each subject, a centered listening position was determined, for which sound level was perceived to be equal in each ear. Presentation level was maintained in the poorer ear and varied in 5 dB steps in the better ear, from 20 dB below centered position to 10 dB above centered position. Monaural speech recognition scores were also found for each ear. The monaural better-ear condition was compared to the best condition for each subject. With the exception of one individual, results indicated that the addition of the poorer ear (best condition) resulted in no significant difference from the better ear alone. These results indicate that information from the poorer ear neither improves on nor hinders the speech recognition ability of the better ear (Karsten and Turner, 2000). While background noise was not utilized in their study, the results may be considered in terms of signal-to-noise ratio at each ear. In the monofit condition investigated in the current study, the poorer SNR in the left ear did not appear to be detrimental to the speech perception ability of the right ear with the better SNR.

In conclusion, our results indicate that differences in theoretical directivity index (DI) values of directional microphone systems do not necessarily impact speech perception or sound quality for the listeners in a diffuse field environment. Further, the use of bilateral hearing aids with only one utilizing a directional microphone resulted in similar performance and sound quality judgments to bilateral hearing aids with directional microphones in each.

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