Hearing-in-Noise: Comparison of Listeners with Normal and (Aided) Impaired Hearing

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Abstract

In this study, the performance of 48 listeners with normal hearing was compared to the performance of 46 listeners with documented hearing loss. Various conditions of directional and omnidirectional hearing aid use were studied. The results indicated that when the noise around a listener was stationary, a first- or second-order directional microphone allowed a group of hearing-impaired listeners with mild-to-moderate, bilateral, sensorineural hearing loss to perform similarly to normal hearing listeners on a speech-in-noise task (i.e., they required the same signal-to-noise ratio to achieve 50% understanding). When the noise source was moving around the listener, only the second-order (three-microphone) system set to an adaptive directional response (where the polar pattern changes due to the change in noise location) allowed a group of hearing-impaired individuals with mild-to-moderate sensorineural hearing loss to perform similarly to young, normal-hearing individuals.

Key Words: Directional microphones, hearing aids, HINT test

Abbreviations: HINT = Hearing-in-Noise Test; SNR = signal-to-noise ratio

Sumario

En este estudio, el desempeño de 48 sujetos con audición normal se comparó con el desempeño de 46 sujetos con una pérdida auditiva documentada. Se estudiaron varias condiciones relacionadas con el uso de auxiliares auditivos direccionales y omnidireccionales. Los resultados indicaron que cuando el ruido alrededor de un sujeto era estacionario, el uso de micrófonos direccionales de primero o segundo orden le permitió a un grupo de personas con hipoacusia sensorineural, bilateral y de grado leve a moderado, desempeñarse similarmente a un grupo de sujetos normo-oyentes, en una tarea de lenguaje en ruido (p.e., necesitaron la misma tasa de relación señal/ruido para lograr un entendimiento del 50%). Cuando la fuente de ruido se movió alrededor del sujeto, sólo el sistema de segundo orden (tres micrófonos), configurado para una respuesta direccional adaptativa (donde el patrón polar cambia debido al cambio en la localización del ruido) le permitió a un grupo de individuos

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hipoacúsicos, con una pérdida auditiva sensorineural leve a moderada, desempeñarse como individuos normo-oyentes jóvenes.

Palabras Clave: Micrófonos direccionales, auxiliares auditivos, prueba de HINT

Abreviaturas: HINT = prueba de audición en ruido; SNR = tasa de relación señal/ruido

Early studies comparing performance of listeners with normal hearing to listeners with hearing loss have indicated that persons with hearing loss require a better signal-to-noise ratio (SNR) than those with normal hearing (e.g., Davis, 1947; Plomp, 1978). Although reduced audibility is the most obvious explanation for the reduced speech recognition and discrimination ability, problems in the realms of frequency selectivity and temporal resolution have been implicated as well (e.g., Florentine et al, 1980; Gelfand, 1982; Healy and Bacon, 2002). Even as the audibility deficit is resolved with the use of hearing aid amplification, the listener can expect reduced performance due to the masking effects of noise (Tillman et al, 1970; Boothroyd, 1993). More specifically, Tillman et al (1970) noted a 30 dB disparity between signal-to-noise ratios necessary for 40% intelligibility of monosyllabic words embedded in competing sentence "noise" for their subjects with normal and impaired hearing. Following several studies in this area, Plomp (1978) concluded that no hearing aid could improve SNR to that of the normal-hearing listener.

Nabelek and Mason (1981) and Nabelek (1982) examined differences across listeners with normal and impaired hearing and determined that the impact of noise and reverberation is increasingly more detrimental for listeners as hearing levels worsen, especially for those with asymmetry in hearing levels. Without normal hair cell population, a number of investigators have contended that the ability to detect changes in frequency or onset/offset of timing cues, and the ability to integrate intensity over time, are typically poorer in the subjects with hearing loss (Skinner, 1988).

Recently, Killion (1997) has provided data to suggest that listeners with minimal hearing loss (30 dB HL) can expect a 4 dB deficit in SNR performance, with another 1 dB added for each 10 dB increase in hearing loss. His findings were based on a compilation of studies assessing SNR for 50% performance using the Speech-in-Noise (SIN) test. He notes that these estimates may be conservative for higher level inputs where distortion effects have an impact.

Various attempts have been made, in the realm of signal processing schemes, to enhance the speech signal for the hearing-impaired/hearing aid user. Amplitude compression with a variety of time constants, multichannel signal processing, and schemes such as consonant-vowel-consonant (CVC) enhancement (Hickson and Byrne, 1997) and speech-rate slowing (Nejime and Moore, 1998) have been evaluated in an effort to find some strategy that can successfully restore hearing ability. Additionally, analog and digital noise reduction schemes have provided "easier listening" but have not shown the anticipated improvement in the performance of the hearing aid wearer (e.g., Bentler et al, 1993; Walden et al, 2000; Alcantara et al, 2003).

The resurgence of the directional microphone hearing aid seems to hold the most potential for enhancing speech intelligibility by improving the SNR in at least some listening situations. The magnitude of that improvement, however, depends on the source(s) and distance of the noise as well as the amount of reverberation in the environment (e.g., Nielsen and Ludvigsen, 1978; Hawkins and Yacullo, 1984; Ricketts and Dhar, 1999; Pumford et al, 2000; Ricketts, 2000; Novick et al, 2001). Most of the studies, to date, have evaluated the fixed one- or two-microphone designs; that is, the polar pattern achieved by the microphone characteristics (particularly, the spacing and delay

element, whether acoustic or electrical) is held constant. More recently, an adaptive directional design has been introduced into the wearable hearing aid. In this design, the characteristics of the polar pattern are under control of the designed algorithm and continually adjusted according to the properties of the environmental sounds. As such, only those hearing aids using two or more microphones can implement this adaptive option. The evolving polar pattern depends on the summed outputs of the separate microphone signals. The noise source is suppressed by the resultant low sensitivity of the microphone in one or more directions (Soede et al, 1993). Several studies have investigated the advantages of a first-order (two microphones) adaptive microphone design (Ricketts and Henry, 2002; Bentler et al, in press a). Although the results were promising for single or slow moving noise sources, the effectiveness in realistic backgrounds has been challenged. With the introduction of second-order (three-microphone design) directional hearing aids, with higher directivity capability, one might expect even better performance by the hearing-impaired/hearing aid user.

The purpose of this research was to answer the following questions:

1. Can older people with sensorineural hearing loss, wearing directional microphone hearing aids, understand speech-in-noise as well as young college students with normal hearing?

2. Does the difference between the hearing-impaired and normal-hearing groups depend on whether a two- or three-microphone directional design is employed?

3. Does the difference between the hearing-impaired and normal-hearing group depend on whether the background noise is stationary or moving?

METHODS

Subjects

Forty-eight undergraduate and graduate college students with normal hearing (thresholds better than 15 dB HL) and an average age of 21.9 years (18 to 29 year range) participated in this investigation. Half of these students were from the University of Iowa, and half of the students were from the University of Pittsburgh. None of the subjects

had experience listening to the Hearing-in-Noise Test (HINT) (Nilsson et al, 1994). The data from these subjects created the normative values for the HINT under the various noise conditions used in this investigation. Forty-six subjects with mild-to-moderate sensorineural hearing impairment and an average age of 62 years (27 to 85 year range) also participated in this investigation. The mean left and right audiogram with +/-1 standard deviation error bars is displayed in Figure 1. Twenty subjects were new users of hearing aids, and 26 of the subjects were considered experienced, having at least one year of previous hearing aid use. These subjects were participating in a larger clinical trial investigation being conducted, with approximately half coming from each of the two sites. These subjects were evaluated with the HINT under various hearing aid signal processing schemes and the same noise conditions as the normal-hearing subjects.

Based on a .05 level of significance and a desired power of .8 with a medium effect size (.6), a power analysis indicated that 45 hearing-impaired and 45 normal-hearing subjects would be needed for the analysis.

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). Pure-tone signals were presented through ER-3A insert earphones. All subjects with normal hearing had audiometric thresholds better than 15 dB at all frequencies. For the subjects with hearing loss, thresholds ranged from 20 dB HL to 75 dB HL from 500 to 3000 Hz with bilateral symmetry within 15–20 dB for any given frequency (refer to Figure 1 for the average pure-tone thresholds). No subject had an air-bone gap greater than 10 dB. For the subjects with hearing loss, earmold impressions were taken bilaterally, and acrylic earmolds with pressure vents were ordered.

Hearing Aid

The Siemens Triano™ behind-the-ear hearing aid was used in this investigation. The Triano-3 (second order, three microphones) was compared to the Triano-S (first order, two microphones) design. The polar
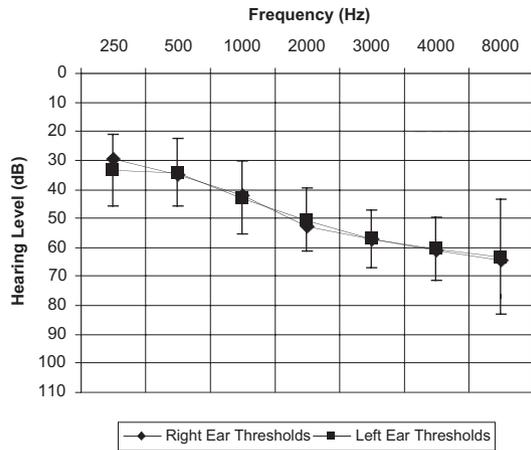
Figure 1. Average pure-tone threshold results for the right and left ears of 46 hearing-impaired subjects. Bars represent 1 standard deviation.

patterns that can be achieved with the second-order design are considerably more complex and the resultant directivity index (DI) theoretically higher. The directional microphone for both models can be programmed to fixed or adaptive function. In the fixed mode, the polar pattern is hypercardioid in shape; in the adaptive mode, the polar pattern is constantly changing to adjust the null(s) to the angle of the highest level of interference. The manufacturer-stated DI for the Triano-3 model ranges from 6.5 to 7.0; the manufacturer-stated DI for the Triano-S is 4.3 dB. To verify those values, a random sample of the hearing aids was assessed pre-and post-testing. The free-field DI values for the Triano-3 model ranged from 6.5 up to 7.8 dB DI-a (flat average across .5–5 kHz). The KEMAR DI values for the Triano-3 model ranged from 4.5 up to 6.0 dB DI-a (flat average across .5–5 kHz). The DI measured for the Triano-S model was comparable to the manufacturer-stated DI (4.3 dB). The methodology used to compute the DIs is discussed in Dittberner and Bentler (2002).

The hearing aid utilizes input and output compressors. The AGC-O serves as an output limiter, with an attack time (TA) of <.5 msec and a release time (TR) of 100 msec. The individual 16 channels employ AGC-I compression (TA of 5 msec, and TR of 90 msec for short duration signals and TA of 900 msec and TR of 1.5 sec for longer duration signals). Compression kneepoints varied as a func-

tion of hearing loss and dynamic range, but generally fell in the range of 40–50 dB SPL.

The subjects with hearing loss were fit with the hearing aids using the manufacturer's preferred fitting algorithm using the CONNEXX software. The manufacturer-implemented NAL-NL-1 fitting strategy (Dillon, 1999) was employed with the frequency specific LDLs entered for output limitation, binaural summation set to 0 dB, and pressure (1 mm) vent setting for the earmold. The low frequencies were equalized by the manufacturer's default algorithm. Automatic feedback suppression was maximized. Automatic noise reduction ("Speech Comfort") was turned off. Real Ear Aided Response (REAR) measures were obtained to ensure audibility, but no attempt to alter the response for closer proximity to target values was made.

Speech perception ability was assessed using the Hearing-in-Noise Test (HINT) (Nilsson et al, 1994), modified for this investigation. The HINT is an adaptive, psychometric procedure that requires the participation of a subject to repeat back recorded sentences of a male talker in the presence of speech-shaped noise. The intensity of the sentence is adaptively adjusted whereas the noise level remains fixed. A sentence must be accurately repeated in order for it to be considered correct. However, small substitutions in verb tense and the articles "a" and "the" are allowed (Nilsson et al, 1994).

Tannoy® i5 AW point source speakers were used for the HINT sentence presentation as well as for the noise presentation. Separate Samson® Servo 120 power amplifiers with separate channel attenuators were used to drive the signal to the primary talker speaker and to the six competing noise speakers. ART® 355 31-band two-channel graphic equalizers were used for all necessary signal shaping. A Marantz® PMD 331 compact disc player was used for presentation of the sentences. Three two-channel Teac P1250 compact disc players were used to present the background noise for both the stationary and moving noise conditions. The frequency response of the speaker presenting the test signal was matched to the speakers presenting the background noise. For the fixed noise condition, the six separate speakers outputted the same uncorrelated noise from the HINT CD. For the moving noise condition, only one speaker at a time presented two seconds of noise, and the speaker presentation

was randomized with no silent intervals. Time-averaged Leq was held constant at 70 dBA. The same analysis equipment was used at both sites to verify that each speaker, power amplifier channel, and graphic equalizer was contributing equally. The three custom-derived CDs containing the HINT noise were individually, sample by sample, created to represent six channels of independent and uncorrelated noise per track (total of six tracks). The timing of the noise onset was not matched to the target sentences in any manner.

An identical sound field arrangement was used at each site. The subject was placed in the center of the 84 x 88 inch field at 0° azimuth to the single primary signal speaker located at eye level in one corner of the booth, and the six speakers with background noise were placed at the top and bottoms of the other three corners of the booth, angled to the center position.

Four microphone conditions were examined in the stationary noise (2 mic omni, 2 mic directional, 3 mic omni, 3 mic directional) and six conditions in the moving noise (2 mic omni, 2 mic directional, 2 mic adaptive directional, 3 mic omni, 3 mic directional, 3 mic adaptive directional).

Each subject was first instructed in his or her rights as a test subject and the investigators' obligations to the subject and current study. Two lists of 10 sentences were randomly chosen from 24 lists on the CD. The order of list presentation (re: test conditions) also was randomized across subjects. As per the test design, standardized instructions were read to each subject. After confirmation that the instructions were understood, the first block of 20 sentences was presented at a reduced SNR (re: fixed noise level of 70 dBA). The sentence level was increased in 4 dB increments until it was repeated correctly. This defined the starting presentation level of the rest of the sentences. The next three sentences were presented either 4 dB up or 4 dB down from the previous sentence's level depending on whether the sentence was repeated correctly (increase level if incorrect and vice versa). When the fifth sentence was presented, level changes occurred in increments of 2 dB. Of the 20 sentences presented for each of the 16 test conditions, the first four sentences were not considered in the SNR computations.

RESULTS

The average HINT signal-to-noise ratio scores for the normal-hearing subjects and hearing-impaired subjects in various signal processing schemes (two-microphone, three- microphone, omnidirectional, and/or fixed directional) in stationary noise are presented in Figure 2. The average HINT signal-to-noise ratio scores for the normal-hearing subjects and hearing-impaired subjects in various signal processing schemes (two-microphone, three-microphone, omnidirectional, fixed directional, and/or adaptive directional) in moving noise are presented in Figure 3. Independent-samples t-tests were used to compare the normal-hearing subject results to each hearing aid condition of the hearing-impaired subjects, and the results are shown in Table 1.

When the noise condition was stationary, the young normal-hearing subjects performed better (required a less advantageous signal-to-noise ratio) than older individuals with hearing loss listening through hearing aids in both of the omnidirectional hearing aid microphone conditions (i.e., two- and three-microphone designs). Individuals with hearing loss listening through bilateral hearing aids with fixed directional microphones (two-or three-microphone design) performed similarly to young, normal-hearing
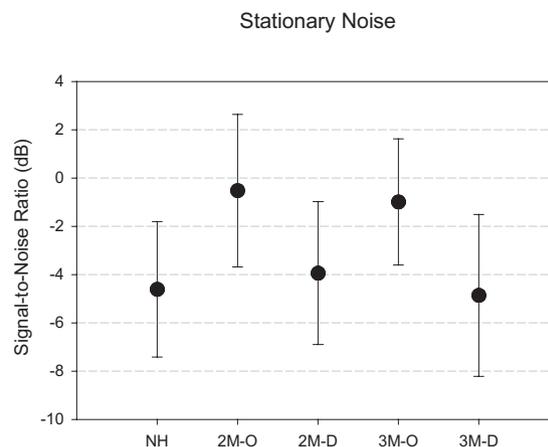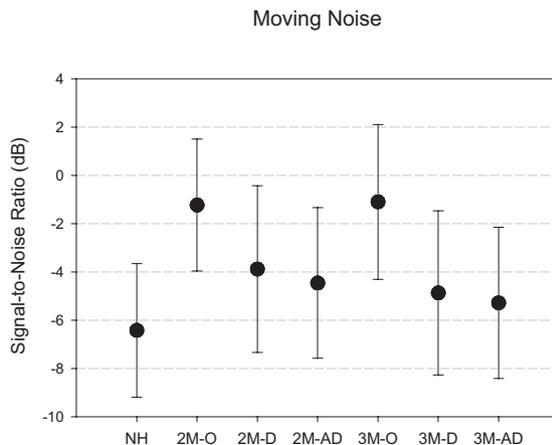
Stationary Noise

Figure 2. Means and +/-1 standard deviation bars of HINT results with stationary noise for five listening conditions (NH = normal-hearing subjects; 2M-O = two-microphone hearing aid set in the omnidirectional response; 2M-D = two-microphone hearing aid set in the fixed directional response; 3M-O = three-microphone hearing aid set in the omnidirectional response; 3M-D = three-microphone hearing aid set in the fixed directional response).

individuals (no significant difference between results).

When the noise was moving around them, the young normal-hearing subjects performed better than the hearing-impaired group in all of the two-microphone hearing aid conditions (omnidirectional, fixed directional, and adaptive directional) and in the omnidirectional and fixed directional three-microphone conditions. Only when the hearing-impaired group listened through the three-microphone adaptive directional system did they perform similarly to young, normal-hearing subjects (no significant difference between results).

Table 2 provides the percent of hearing-impaired individuals listening through a given hearing aid technology whose performance was within +/-2 standard deviations of the performance of young, normal-hearing individuals performing the same task. It is apparent that in both the stationary and moving noise conditions, the percent of hearing-impaired subjects performing similarly to the normal-hearing subjects is lowest for the omnidirectional mode (58% and 57% for the 2 mic and 3 mic) and highest for the adaptive directional mode (91% and 94% for the 2 mic and 3 mic).

Moving Noise

Figure 3. Means and +/-1 standard deviation bars of HINT results with moving noise for seven listening conditions (NH = normal-hearing subjects; 2M-O = two-microphone hearing aid set in the omnidirectional response; 2M-D = two-microphone hearing aid set in the fixed directional response; 2M-AD = two-microphone hearing aid set in the adaptive directional response; 3M-O = three-microphone hearing aid set in the omnidirectional response; 3MD = three-microphone hearing aid set in the fixed directional response; 3M-AD = three-microphone hearing aid set in the adaptive directional response).

Table 1. Results of Independent Samples t-tests for Normal-Hearing Subjects Compared with Hearing-Impaired Subjects in Stationary Noise and in Moving Noise

Stationary Noise				
Condition	F	t	df	Significance (2-tailed)
2 mic, omnidirectional vs. normal hearing	1.117	6.45	89.865	0.000
2 mic, directional vs. normal hearing	**1.082**	**0.937**	**91.247**	**0.351**
3 mic, omnidirectional vs. normal hearing	0.032	6.272	91.896	0.000
3 mic, directional vs. normal hearing	**2.989**	**-0.562**	**87.98**	**0.575**

Moving Noise				
2 mic, omnidirectional vs. normal hearing	0.251	9.069	91.936	<0.001
2 mic, directional vs. normal hearing	0.326	3.996	88.263	<0.001
2 mic, adaptive directional vs. normal hearing	0.464	3.302	90.955	0.001
3 mic, omnidirectional vs. normal hearing	0.437	8.548	90.32	<0.001
3 mic, directional vs. normal hearing	0.403	2.525	88.737	0.013
3 mic, adaptive directional vs. normal hearing	**0.034**	**1.981**	**90.854**	**0.051**

Note: Bold type indicates conditions that were not significantly different (e.g., where hearing-impaired individuals using a particular technology performed similarly to normal-hearing individuals). Significance was set at p < .05. Significant results always indicate that the normal-hearing subjects performed better than the hearing-impaired subjects.

DISCUSSION

The results indicate that when the noise around the subjects was stationary, a first- or second-order directional microphone allowed a group of older hearing-impaired listeners with mild-to-moderate, bilateral, sensorineural hearing loss to perform similarly to young, normal-hearing listeners on a speech-in-noise task (i.e., they require the same signal-to-noise ratio to achieve 50% understanding). When the noise source was moving around the listener, only the second-order (three-microphone) system set to an adaptive directional response (where the polar pattern changes due to the change in noise location) allowed the hearing-impaired

Table 2. Percent of Hearing-Impaired Subjects Using One of Six Hearing Aid Signal Processing Schemes in One of Two Background Noise Types (Stationary or Moving) Who Performed within the Range (+/−2 Standard Deviations) of Normal Listeners in the Same Listening Situations

	Percent within +/−2 Standard Deviations of Normal Results*	
Condition	Stationary Noise	Moving Noise
2 mic, omnidirectional	70%	58%
2 mic, directional	96%	87%
2 mic, adaptive directional	not tested	91%
3 mic, omnidirectional	76%	57%
3 mic, directional	94%	89%
3 mic, adaptive directional	not tested	94%

*The percent represents individuals who fell within the range or were better than the best score of the range.

individuals to perform similarly to the young, normal-hearing individuals. In fact, 96% and 94% of the hearing-impaired subjects performed within normal limits when using the two-microphone, fixed-directional system or the three-microphone, fixed-directional system, respectively, in the stationary noise.

In the omnidirectional setting, 70% and 76% of the hearing-impaired subjects performed similarly to normal listeners in the stationary noise condition with either a two- or three-microphone system, respectively. In the moving noise condition, only 58% and 57% of hearing-impaired listeners in this study performed similarly to normal listeners with the omnidirectional mode of the two-microphone or three-microphone system, respectively.

Results suggest that both the two-microphone and the three-microphone directional conditions resulted in considerable improvement in performance relative to the omnidirectional microphone condition. The added improvement in performance gained from the adaptive mode in the moving noise was small, although significant, for the three-microphone condition. That is, only when the adaptive mode was coupled with the three-microphone system and the noise source was moving around the person were the results statistically indistinguishable. Ninety-four percent of the individuals with hearing loss performed within the normal range as defined by the normal subjects in this study when using the three-microphone, adaptive directional system in a moving noise condition.

A number of authors have noted that in the presence of multiple noise sources, an adaptive directional two-microphone system may not be advantageous (e.g., Greenberg and Zurek, 1992; Kompis and Dillier, 2001; Peterson et al, 1990). In this study, only one noise source was present at a time, as the noise was randomly moved between the speakers. In addition, the criterion by which we judged the systems was comparison to the performance of normal listeners. Normal performance can be assumed to be the ultimate goal of any hearing aid technology and of any listener with impaired hearing. Although either directional microphone design (two microphones, three microphones) resulted in performance similar to that of normal-hearing subjects in stationary noise, only performance with the adaptive directional three-microphone system was similar to the performance of the normal-hearing subjects in the moving noise condition.

The data may appear to be in disagreement with data from Ricketts and Henry (2002), who found a significant benefit from an adaptive directional two-microphone system when hearing-impaired subjects were listening in moving noise. Ricketts and Henry (2002) used a noise that moved counterclockwise across five speakers equally spaced around the listener. The noise remained stationary at each speaker for one HINT sentence with the remaining loudspeakers silent during that interval. The moving noise condition used in the present investigation was considerably more challenging. In addition, our criterion (performance within normal limits dictated by a group of normal listeners) is different from comparing hearing aid conditions to each other and may be considered to be even stricter. The fact that their data revealed significant improvement

with the adaptive two-microphone design was related to design differences.

When the noise was stationary, the directional setting in either the two- or three-microphone system was sufficient to produce normal performance in the hearing-impaired group. Several investigators have indicated that a two-microphone, adaptive directional system may provide greater reduction of background noise than a two-microphone, fixed-directional system when (1) a single interfering noise source is present and (2) the single noise source occurs outside the polar pattern nulls of the fixed directional system (Peterson et al, 1988; Soede, 1990; Soede, Berkhout et al, 1993; Soede, Bilsen, Berkhout, 1993; Soede, Bilsen, Berkhout et al, 1993; Kates and Weiss, 1996). We did not evaluate the adaptive directional setting in either the two- or three-microphone system in stationary noise in this investigation because one would assume that the true test of an adaptive system would be in an environment with moving noise where the system would, indeed, need to adapt to the location of the noise.

It is interesting to note that the subjects with hearing loss (and hearing aids) showed similar performance in the stationary and fixed noise conditions, while the subjects with normal hearing showed improved performance in the moving noise condition. While it is unclear why that occurred, it is possible that the change in placement of the noise source provided improved signal-to-noise ratio in one ear during a portion of the testing, and that improvement was more beneficial to the normal listeners. Zurek has 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). Such a finding was reported by Bentler et al (in press b), who found that subjects perform as well using two hearing aids, only one of which has a directional microphone, as they do with two hearing aids, each with directional microphones.

It was our intention to evaluate first- and second-order microphones in both fixed and adaptive directional settings in a listening environment typically used in investigations and clinical evaluations (i.e., stationary noise) and a more realistic listening environment (i.e., moving noise) that could be created in a test booth. In addition, given the availability of higher-order microphones with adaptive processing capability, we decided to make performance by young, normal listeners the criterion by which the hearing aid conditions would be judged. Using the traditional listening environment created in many clinical situations (i.e., stationary noise), a fixed-directional first-order or second-order microphone produced similar results. While one must consider that the noise environment provided in this investigation was without the effects of reverberation, the use of moving noise provided a more realistic environment for assessing the adaptive microphone design. With this design, only while using the adaptive directional three-microphone system were the subjects with mild-to-moderate hearing impairment able to perform within normal limits.

CONCLUSION

In this investigation, the performance of 46 subjects with mild-to-moderate degrees of hearing loss was compared to that of a group of young listeners with documented normal hearing. It was found that when the noise around a listener was stationary, a first- or second-order directional microphone hearing aid resulted in speech perception performance similar to normal hearing listeners. When the noise source was moving around the listener, only the second-order (three-microphone) system set to an adaptive directional response (where the polar pattern is changing due to the change in noise location) allowed the group of hearing-impaired individuals to perform similarly to young, normal-hearing individuals. In both the stationary and the moving noise conditions, no additional reverberation beyond that inherent in a sound-treated booth was added. This is the first published report wherein performance with directional microphone technology has been compared to performance of listeners with normal hearing. The results are exciting for manufacturers, audiologists, and consumers alike and should encourage future researchers to consider such a comparison in future studies of newly developed technologies.

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