Real-world performance of an ITE directional microphone

By Mead Killion, Robert Schulein, Laurel Christensen, David Fabry, Larry Revit, Patty Niquette, and King Chung

Things change. Two recent changes fueled our desire to find out just how much modern directional microphones reduce background noise—and increase speech intelligibility—in real-world situations. The first change was the improved directivity now available in directional-microphone hearing aids compared to a decade ago. The second was the improved consumer satisfaction ratings reported recently for a BTE hearing aid with directional microphones.[1]

Several laboratory and clinical test booth measures of the improved signal-to-noise ratio (SNR) provided by directional-microphone hearing aids have been reported and are discussed below. We wanted to learn how much the recently introduced D-MIC™ directional microphones improved not only laboratory measures, but intelligibility in the real world—in restaurants, parties, and noisy outdoor settings. In this paper we describe objective results, obtained from novel on-site recordings, of the real-world benefit in SNR that someone with a hearing loss can expect from a directional microphone.

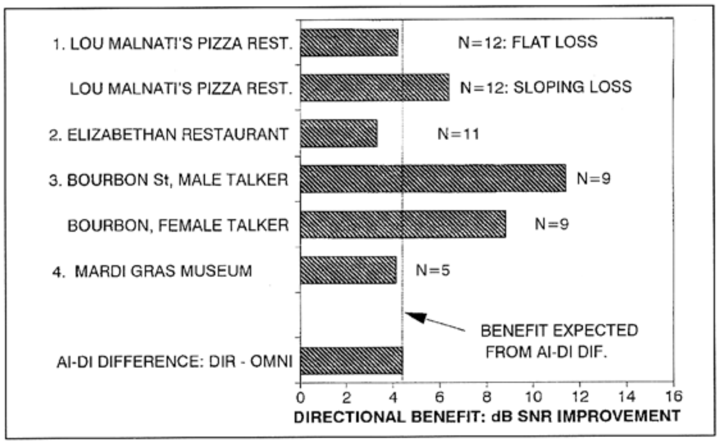

Figure 1. *Effective noise reduction produced by D-MIC in four real-world situations: results from hearing-impaired listeners.*

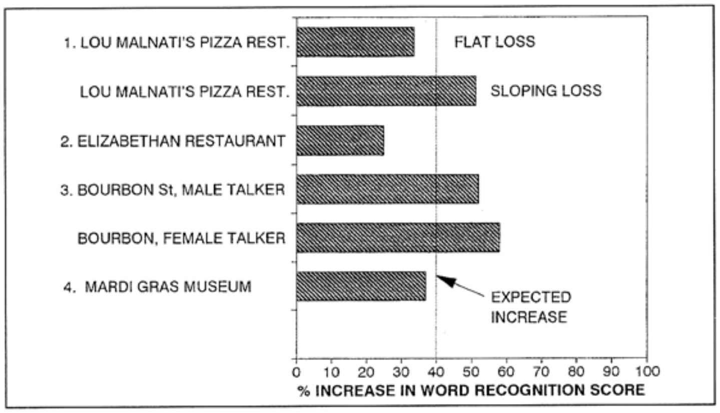

Figure 2. *Increased intelligibility from D-MIC in four real-world situations: same listeners as for Figure 1.*

We expected that a well-designed ITE directional microphone would produce improvements in intelligibility of 20 to 60 percentage points on a speech-in-noise test in real-world noisy surroundings, corresponding to a reduction in background noise of 3 dB to 5 dB indoors and 4 dB to 8 dB outdoors, depending on acoustic conditions and hearing loss. Specifically, we expected the real-world improvements to be similar to those predicted by laboratory measurements of the Directivity Index of these microphones described in the DI sidebar.[2]

For fear the reader may drop out before the end of the article, we have placed the summary figures, 1 and 2, at the beginning. The SNR improvements shown in those figures correspond to essentially normal levels of performance in noise for our average hearing-impaired listener tested with directional-microphone recordings.

The CD accompanying this article contains recorded A-B-A comparisons between directional and non-directional microphone performance, as well as on-site recordings of several blocks of sentences used to obtain the data reported here. The latter may be used clinically to measure SNR benefit.

WHAT HAPPENED TO DIRECTIONAL HEARING AIDS?

Figure 3 shows data reported by Beck in 1982.14 These show the directivity index measured on 11 directional and 6 omni BTE hearing aids. As observed in that report, the DI of several directional-microphone hearing aids was worse than that of two of the omni-microphone hearing aids (whose microphone location was probably over the ear and somewhat in front of the pinna).

The data in Figure 3 provide a partial explanation for the near demise of directional-microphone hearing aids after the 1980s. Even though some directional-microphone hearing aids provided significant and demonstrable benefit[15, 16] and some a much greater Directivity Index[3, 4] than that of the 1980s microphones shown in Figure 3, the average BTE performance reported by Beck was not as good as the 1.6-dB DI improvement we recently measured on KEMAR for a hand cupped behind the ear.

Also shown in Figure 3 are the reported DIs for the

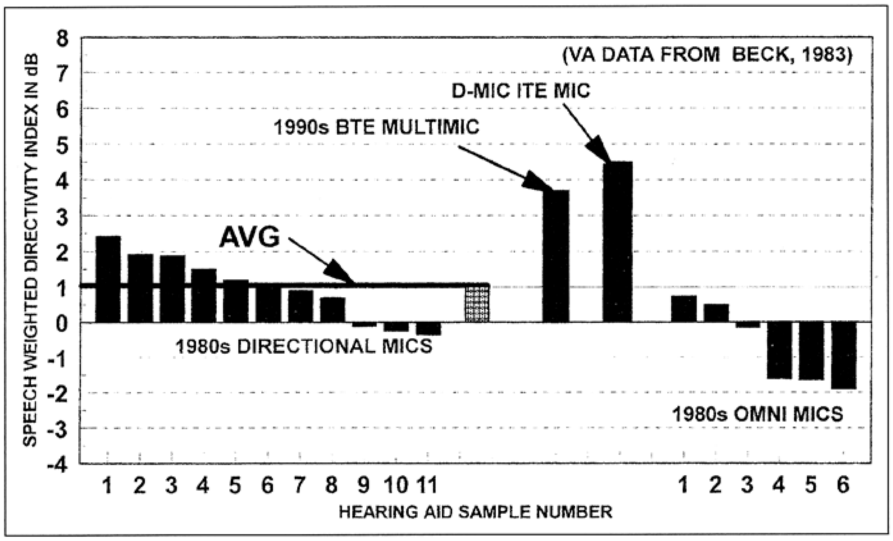

Figure 3. *Performance of 1980s directional-microphone hearing aids compared to modern ones.*

AudioZoom™ dual-microphone directional BTE hearing aid (which obtained the high consumer ratings mentioned above), and for a new D-MIC™ microphone designed for ITE applications.[17] Both microphones show markedly improved DIs over those reported by Beck, but not over the values reported by Preves in 1976 for experimental ITE directional microphones[4], or for the BTE directional microphones used in the 1980 Knowles 33-1/3 rpm soundsheet demonstration recordings[18], recordings that are replicated on the accompanying CD.

THE AIDI

The first author and Wim Soede recently used an Articulation Index-weighted DI (AI-DI) in an attempt to weight frequency-dependent directional performance according to its importance for speech recognition. For example, Figure 4 shows the measured DI by frequency for the directional and omni microphones in the D-MIC design, calculated from anechoic chamber measurements on ITE microphones placed on KEMAR. The AI-DI for the omni microphone is approximately 0.3 dB (average of anechoic and diffuse-field chamber measurements[2]); the AI-DI of the directional microphone is 4.7 dB. The expected *improvement* in the effective SNR for speech is thus 4.4 dB.

Our hypothesis was that results measured in restaurants, indoor parties, etc. would show an SNR improvement approximately equal to the AI-DI improvement (4.4 dB) for the directional microphone. We expected greater improvement at outdoor parties, where there would be fewer reflections to reintroduce rejected rear noises at the front. We have found that each dB of SNR improvement increases the words-in-sentences score of the typical hearing-impaired person by about 9% as measured with the SIN test[19], so we expected that a 4.4-dB SNR improvement would produce an average improvement in intelligibility of 40 percentage points.

ON-SITE RECORDINGS

Etymotic Research's new D-MIC cartridges, which contain both directional and omnidirectional microphones, were chosen for these experiments. Some of us have a commercial interest in this microphone, but there was a good scientific reason for the choice: The D-MIC directional microphone output can be internally equalized to produce the same frequency response (flat) as the omni microphone. Thus, any changes in intelligibility found in these experiments could be attributed solely to directivity, not to a low-frequency roll-off.

We equipped several pairs of ITE hearing aids with D-MIC cartridges and subminiature Microtronic four-pin connectors. One pin was connected to the omni microphone output, one to the directional microphone-flat output. Cables were assembled to permit each of the two stereo microphone outputs—directional and omni—to be connected to a hand-held digital analog tape (DAT) recorder.

The person acting as "recording dummy" wore two custom ITE hearing aids, with the cables described above connected between the aids and two DAT recorders carried in a small belt pack. The outputs of the omni and directional microphones were recorded simultaneously, permitting later comparison of the two microphone outputs under identical conditions. Both omni and directional recordings sounded quite natural.

THE LOCATIONS

We made real-world recordings at four locations: (For more on the technical details of the recordings, see Appendix A.)

(1) Lou Malnati's Pizza Restaurant in Elk Grove Village, IL: Relatively noisy (70 dBA-80 dBA); Dummy = RBS, Talker = GIG

(2) Elizabethan Restaurant in Rochester, MN: Quiet, high ceilings (60 dBA-65 dBA); Dummy = RBS, Talker = MCK

(3) Corner of Bourbon and St. Louis Streets in New Orleans: *Amplified* music from each corner's establishment (90 dBA-95 dBA); Dummy = MCK, LAC; Talker = LAC, MCK

(4) Mardi Gras museum in New Orleans (cocktail party) Student party with dancing (80 dBA-85 dBA); Dummy = LAC, Talker = RL

In addition, we made two attempts to simulate real-world conditions:

(5) Mayo Clinic Test Booth in Rochester, MN: Signal from loudspeaker in front, noise from four loudspeakers at ±45° and ±135°; front ±45° speakers reduced 5 dB re rear

(6) ER Classroom, Elk Grove Village, IL: Christmas Party simulation, 20 live ER people; Dummy = KEMAR, Talker = GIG; babble and talker recorded separately in the same location (80 dB-85 dB)

Making the real-world recordings turned out to be fun. There weren't enough people near our table in the Elizabethan restaurant the day we set up to record, so we treated everyone we could find in the Mayo Audiology Department to a free lunch in exchange for their sitting nearby and carrying on lively conversations. On Bourbon Street, one woman, leaning over to see what one talker was reading, saw the title and, in a tone of disbelief, loudly proclaimed, "They're doing a *sin test* on Bourbon Street!"

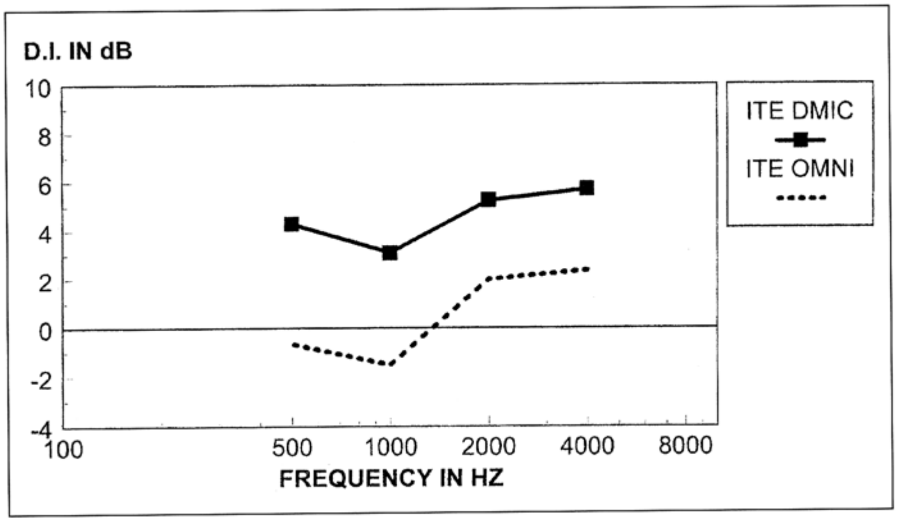

Figure 4. *Directivity Index comparison between directional and omnidirectional ITE microphones used in the present experiments.*

A brief history of directional mics

Before the importance of head and ear effects became widely appreciated, some directional-microphone hearing aids were designed to produce a 15-dB to 25-dB rejection of sounds from the rear when suspended by themselves in an anechoic chamber. Unfortunately, when worn on the head, those designs often provided much less directivity.

Improved designs resulted when head diffraction and reflection, provided by KEMAR measurements[3, 4], were taken into account. Improvements in noise rejection of 7 dB to 8 dB over omni-microphone performance have been reported for BTE hearing aids using such microphones, when they were evaluated in clinic test booths with the target loudspeaker in front and the competing noise loudspeaker in the rear.[5,6] Chasin reported similar findings for an ITE directional aid.[7]

Even if all the noise coming from behind is rejected, however, there is an appreciable problem in the real world. Noise from the rear will pass by the listener, bounce off the front and side walls, and arrive only a tiny bit later from the front. Indeed, even when the speaker is in front of you, if the person is more than a few feet away, the major part of the energy at your eardrum comes from room reflections.[8] Similarly, a good deal of the sound energy from someone speaking a few feet behind you will arrive at your eardrum from the front (and the sides) at a level that is often only 5 dB to 8 dB below the direct sound from the rear.

Studebaker et al. documented this problem with measurements in an anechoic chamber, test booth, living room, and classroom.[9] Their data showed that directional-microphone response minima which appeared at some angles under anechoic or test-booth conditions virtually disappeared in a living room or classroom. Similarly, Madison and Hawkins reported 12-subject data showing a 10.7-dB SNR improvement with a directional BTE under anechoic conditions, but only a 3.4-dB SNR improvement in a reverberant room.[10]

Recognizing this problem, engineers in the broadcast and recording industry adopted the Directivity Index (DI) for microphones. The DI is the advantage in microphone sensitivity, measured in dB, for sounds arriving from the front over sounds arriving from—loosely speaking—everywhere else.[11] The maximum possible DI for the type of directional microphones now being used in hearing aids is 6.0 dB.[12] In other words, when room reflections dominate, the background noise reflected into the microphone from the front and sides limits the maximum noise rejection to 6 dB. The reader interested in more details is referred to Preves for an excellent review of problems in applying directional microphones to hearing aids.[13]

SUBJECT TESTING

Both normal and hearing-impaired subjects were used for determining the objective SNR improvement, if any, with the ITE directional microphones as compared to the omni microphones. In each test block, there are five sentences with five key words per sentence for each of the four different SNRs. At each of the four SNRs, therefore, there is the equivalent of a 25-word test. Partial scoring (0.5) for words sounding like the target word was used; otherwise scoring was standard.

The percent scores were plotted against the SNRs; from this curve the SNR corresponding to 50% correct response was estimated visually. For example, 25% correct at SNR = 0 dB and 75% correct at SNR = 5 dB would yield an SNR for 50% correct of 2.5 dB. The typical normal-subject slope on the SIN test is 11%/dB, so the example above is also reasonable: 50%/5dB = 10%/dB.

Normal-hearing subjects were tested at a presentation of 70 dB HL. Hearing-impaired subjects were tested at the level they judged to be "Loud but OK" (the loudness level just below "Uncomfortably Loud") using the IHAFF/Hawkins/Pascoe loudness scaling. As discussed elsewhere, available data indicate that hearing-impaired subjects will typically obtain near-maximum at this level without additional frequency-response shaping.[20]

The presentation order was generally counterbalanced across subjects, and the omni/directional choice was always counterbalanced: If subject #1 heard the omni recording of sentence Block #1A recorded at Lou Malnati's Pizza restaurant, Subject #2 heard the directional recording of that same block. Since both recordings of that block were made at exactly the same time, any difference in average scores should represent the ability of the directional microphones to reject background noise.

Evidence of a learning effect is illustrated in Figure 5. When subjects were tested on an omni-microphone recording with sentences they had previously heard more clearly on a directional microphone recording, their scores were much higher than when they were tested with fresh sentences. To avoid contamination of the results by a learning effect for lists used a

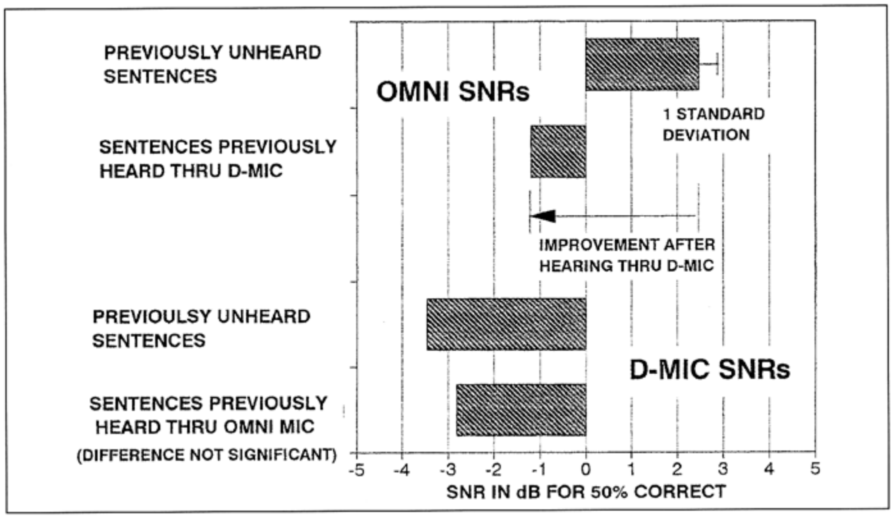

Figure 5. *Test-retest learning effects when large differences in intelligibility occur between test conditions.*

second time, we compiled only first-time scores in the data reported here. The resulting standard error of the mean was higher than we planned, but still adequate: With 12 subjects in each group the standard error of the across-subject mean SNR was about 0.7 dB. Thus, we can be 95% confident that the average improvement for the sloping-loss subjects tested on the Lou Malnati's recordings exceeded 5 dB, and might have been as high as 8 dB.

We found a much higher standard deviation in scores using our real-world recorded blocks of sentences. We attribute this to several factors: (1) Increased variability in talker level, (2) increased variability in background noise levels, and (3) increased variability in *direction* of the dominant interfering noise, which could vary from moment to moment. The result was that the test blocks were much less homogeneous than those in the SIN test, which were made in a recording studio. In other words, our test blocks represented the vagaries of the real world.

We used the same set of five sentences for both microphones to determine the change in intelligibility between microphones. The set of sentences in each block producing word scores of 15% to 30% with the omni microphone would typically result in scores 20 to 60 percentage points higher with the directional microphone. Those differences were averaged across subjects and blocks to produce the word-score percentage benefit.

BENEFITS

Figure 1 summarizes the improvement in SNR from the D-MIC ITE microphone at the various locations. The number of test subjects used in each case is noted on the figure as N = . Unless noted, all subjects had mild to moderate hearing impairment. Indoor locations 1, 2, and 4 showed effective noise reductions consistent with the AI-DI expectations of a 4.4-dB improvement for the directional microphone.

The one outdoor location produced a nearly 9-dB improvement. This is not surprising, since those recordings were made in the middle of the (blocked-off) street, with the two loudest bands at about ±120° (i.e., heard over the shoulders of the recording "dummy"). The bands playing on the other corners, at about ±30°, were farther away and not as loud. Because the person acting as recording dummy stood near the street corner past the corners of the buildings, there were no significant nearby reflections from the loudest sources of music back to the recording location. Thus, the two loudest sources at ±120° were probably attenuated by 10 dB to 15 dB or so, as they would be in an anechoic environment. The dense crowd of loud-talking people walking all around provided a fair amount of "diffuse" noise. There was no wind that night, so wind noise—the bane of directional-microphone applications—was not a problem.

Figure 2 shows the same basic information as Figure 1, but in terms of improvement in intelligibility. Different subjects required different SNRs to function, but it was usually possible to select an SNR for which the omni score fell between 20% and 40%. The differences between those omni scores and the directional scores obtained at the same SNR were averaged to obtain the data in Figure 2. The reader will appreciate that these increases—of 20% to 60% in intelligibility—far exceed any improvement reported for even the most modern hearing aid circuits.[21]

More importantly, our 12 normal-hearing subjects required an average of 0.7 dB SNR to obtain 50% correct scores on the omni-microphone recordings made at Location 1 (Lou Malnati's). Our 12 flat-loss and sloping-loss subjects required 5.3 dB and 8.2 dB, respectively, consistent with the SNR deficits reported elsewhere.[20] On the directional-microphone recordings, however, they required only 1.0 dB and 1.8 dB, respectively. The use of directional microphones brought their performance in noise within normal limits in those real-world restaurant conditions. Directional microphones alleviate the SNR deficit directly, by increasing the SNR.

We have been able to obtain APHAB (Abbreviated Profile of Hearing Aid Benefit) data from only four patients at this writing. All of them showed benefit on the "Noise" subscale, two of them by 30 percentage points or more, significant at the 90% level.[22] It is unusual to see such large APHAB differences in hearing aid comparisons unless directional microphones are involved.

SIMULATED REAL-WORLD RECORDINGS

Finally, Figure 6 compares SNR data obtained from real-world recordings with SNR data from simulated-real-world recordings. The simulations were described above. The agreement is not perfect, but is certainly encouraging.

SUMMARY

High-performance directional-microphone ITE hearing aids provide an estimated noise reduction (SNR improvement) of 4 dB to 5 dB over conventional omni-microphone aids, based on laboratory AI-DI measurements. We tested hearing-impaired subjects in four cities using on-site recordings that we made in restaurants, at parties, and outdoors. Our subjects typically experienced an improvement that often equaled or exceeded the laboratory AI-DI number. In word scores, they experienced 20 to 60 percentage points of improvement.

Since previous data indicate that the typical hearing-impaired person with a 40-dB pure-tone loss will exhibit a deficit in SNR of 5 dB[20], our measurements indicate that such persons, wearing high-performance ITE directional-microphone hearing aids, should now be able to communicate in many noisy situations with little more difficulty than normal-hearing persons. On Bourbon street, they might be able to hear more easily. Those with greater SNR loss will still have difficulty, but will be brought significantly closer to normal functioning in noise.

While these results were obtained with a particular type of ITE directional microphone, we expect future experiments will show they apply to any hearing aid directional microphones with the same AIDI ratings. Hearing aid array microphones available in the future should nearly double these AIDI ratings. Circuits haven't solved the noise problem; directional microphones can.

ACKNOWLEDGMENTS

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APPENDIX A

To imitate the SIN test[19], which changes the SNR 5 dB after each five sentences, we used a live talker who changed vocal effort after each five sentences. (See subject testing for a description of SIN test scoring using the different SNRs.) Unlike the SIN test recordings, where the overall level was held constant as the SNR was changed, we allowed the overall level to change to mimic the real-world situation in which the listener keeps saying, "What?". In that situation, the talker progressively raises his or her voice until adequate intelligibility is reached; the overall SPL generally increases in the process.

We reversed the typical real-life process, instructing the talker to progressively *decrease* vocal effort. The highest vocal effort was used on the first sentences in each block, making it easier for the subject to identify the target talker.

The talkers were equipped with a small boom microphone so they could monitor their own level in high levels of background noise. The boom microphone was wired into a Radio Shack sound level meter (SLM) that the talker monitored while reading the sentences.

For each block of sentences, the talker established a suitable level for the highest vocal effort, producing an estimated +10-dB to +15-dB SNR according to a precision sound level meter held near the listener's ear. While the talker maintained that effort, the mouth-to-boom-mic distance was adjusted until the monitor SLM read peaks of 85 dBA (FAST scale). The talker then read the first five of the IEEE sentences used in the SIN test while trying to produce frequent peaks of 85 dB on the meter. Next, by reducing vocal effort, the talker tried to produce peaks of 80 dB for the next five sentences. The meter was then switched to the 70-dB scale; five more sentences were read to 75-dB peaks, and the last five to 70-dB peaks.[23]

The above process produced a series of test sentence blocks modeled after the SIN test: On the omni-microphone recordings, the first five sentences in each block had an SNR of approximately 10 dB, the next five sentences an SNR of 5 dB, the next 5 an SNR of 0 dB, and the last five an SNR of −5 dB. The directional-microphone recordings showed SNRs of about 15 dB, 10 dB, 5 dB, and 0 dB.

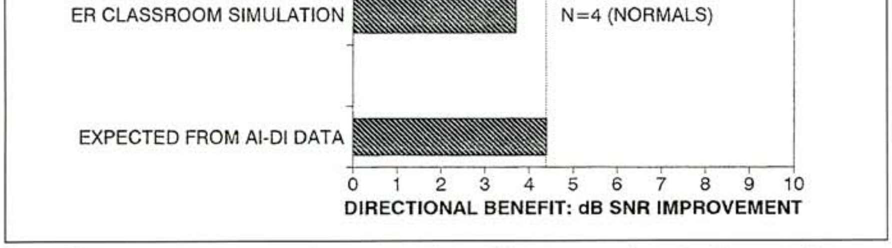

Figure 6. *Comparison of results from two real-world locations with results from simulations of those situations.*

For three of the real-world locations, we made a sentence-by-sentence SNR analysis of the directional-microphone recordings as a check on the SNRs designed for each test block. Most talkers managed to drop each set of sentences close to the planned 5 dB relative to the previous one. The deduced SNRs for 50% correct were thus not much different using either the measured or nominal values of recorded SNR.

Recordings in location #5 (Mayo Clinic) were modified from the five-loudspeaker setup described by Voss[24], in an attempt to simulate the conditions in location #2. Voss used Danish words coming from a front loudspeaker in an audiological test booth, with speech-envelope-modulated speech-spectrum noise fed equally to each of four loudspeakers located as described in our location #5. Voss reported word-recognition scores for omni and directional conditions, each condition with the same frequency response. A plot of those data revealed that the scores grew at 5.6% per dB of SNR improvement (as one would expect for NU-6), and that the "directional" curve relative scores virtually coincided with the "omni" curve after it had been replotted as if the SNR was 3.9 dB worse. From this, one deduces a 3.9-dB directional improvement in that experiment.

The tables in the Elizabethan restaurant (location 2) were arranged in a checkerboard layout, with a distance from the listener to the nearest frontal interfering talker of 9 feet at an angle of approximately 45°. The distance to the nearest rear talker was 5 feet at an angle of approximately 135°. By reducing the output level of the two front test booth loudspeakers by 5 dB relative to that of the rear speakers, we approximated the expected sound levels from equal-energy talkers at the distance ratio of 5:9 found in that restaurant.

Recordings at location #6 (ER Classroom) were made in an attempt to simulate a crowded party. The attendees were encouraged to make lots of noise while they carried on "conversations." Of the five live-talker locations, there appeared to be more enthusiastic front noise people in location #6 than elsewhere. (This is relevant because the response of both omni and directional head-worn microphones is nearly identical for sounds within ±30° of the front: A dominant frontal noise source will not be rejected by either microphone, eliminating the directional microphone advantage.) The use of separate recordings for the babble and the talker meant that the female talker—experienced at monitored-live-voice testing—could maintain a constant level, a somewhat easier task, throughout. The SNRs were set by the mixing attenuators at a later date, so they could be more precise than those produced in the fully live situations.

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