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The case of the missing dots: AI and SNR loss

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Recent experiments with directional microphones produced a surprising result: Subjects with sloping loss—who generally had the greater loss of speech-to-noise ratio (SNR)—obtain more improvement than subjects with flat loss or normal hearing.[1] We were able to explain those results with the help of the Articulation Index. That inquiry led in turn to a characterization of hearing loss in terms of the number of "missing dots" corresponding to a given SNR loss. This paper presents those results.

REVIEW OF AI

The development of the Articulation Index (AI) goes back to the work of Harvey Fletcher at Bell Labs in the 1920s, with the full details released in reports by French and Steinberg in 1947 and Fletcher and Galt in 1950 after WWII security had been lifted.[2-5] Most readers today are familiar with the AI in one form or another. The Count-the-Dots version shown in Figure 1 is taken from an earlier paper of Mueller and Killion.[6]

Each dot in Figure 1 represents 1% of the speech cues, shown on an audiogram form. To decide which dots are audible to someone with a hearing loss, imagine that each dot represents a tone at that frequency and intensity. Someone with a 45-dB flat loss, for example, would hear the 14 dots lying below an imaginary horizontal line at 45 dB HL in Figure 1. (The reader will understand that in this context we sometimes casually speak of "hearing 14 dots," as a convenient shorthand for "hearing 14% of the speech cues," and that most of us don't really hear dots.)

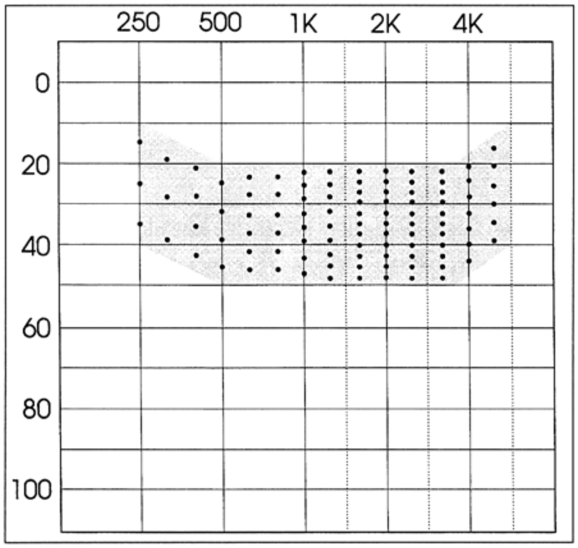

Figure 1. *Count-the-Dots audiogram form for calculation of the Articulation Index (from Mueller and Killion[6])*

Mueller and Killion originally intended the dots in Figure 1 to represent conversational speech at 50 dB HL (65 dB SPL). Several readers have pointed out, however, that a person with 50-dB-HL thresholds should hear enough speech cues to score 50% correct on spondee words like "sidewalk" and "baseball," even though none of the speech-cue dots in Figure 1 would be audible to that person. The level of speech represented by the dots in Figure 1 is clearly less than 50 dB HL.

The Mueller and Killion error allows us a good introduction to the present topic. The left-hand curve in Figure 2 shows the relationship between the percentage correct score for spondee words and sentences and the AI.[7,8] A 50% correct score on spondees requires 14 dots (more formally, requires an AI of 14%). In other words, 14% of the speech cues must be heard to get 50% of sentences or spondee words correct. Since the 100 dots shown in Figure 1 for constant-level conversational speech are spread out over the 30-dB range of speech-cue intensities, 14 dots correspond to the most intense 4 dB of dots.

For the formula-minded, 30x(14/100) = 4.2 dB. Rounding to 5 dB, we conclude that our original Count-the-Dots figure really corresponds to 45-dB-HL (60-dB-SPL) speech: slightly on the quiet side of the normal conversational-speech range. Fortunately, no less an authority than Skinner and her colleagues have recently urged that conversational speech testing be carried out at 60 dB SPL[9], so our error may have been relatively innocent.

Of more interest for our present purposes is the number of dots (percentage of speech cues) required to obtain a 50% correct score for words in sentences. One would expect the percentage of speech cues to lie somewhere between the 14% required for sentences (left-hand curve in Figure 2) and the 38% required for isolated words (right-hand curve in Figure 2). We took 26%, marked with a circle on the middle curve in Figure 2, as a reasonable guess.

We are interested in words in sentences because of our interest in the SIN test[10], which scores the five key words in sentences such as "The lawyer tried to lose his case." The signal-to-noise ratio (SNR) required by normal-hearing subjects to obtain a 50% correct score on the SIN test is about 2 dB.[11] We have chosen that 2-dB value as the reference for the SNR labeling at the top of Figure 2. The shape of the curve was taken from SIN-test data for normal-hearing subjects. Although the curve for words was taken as the average of the two curves from a previous paper[7], it was pleasant to see that it nearly coincided with the 1950 data of Daniel Martin.[12]

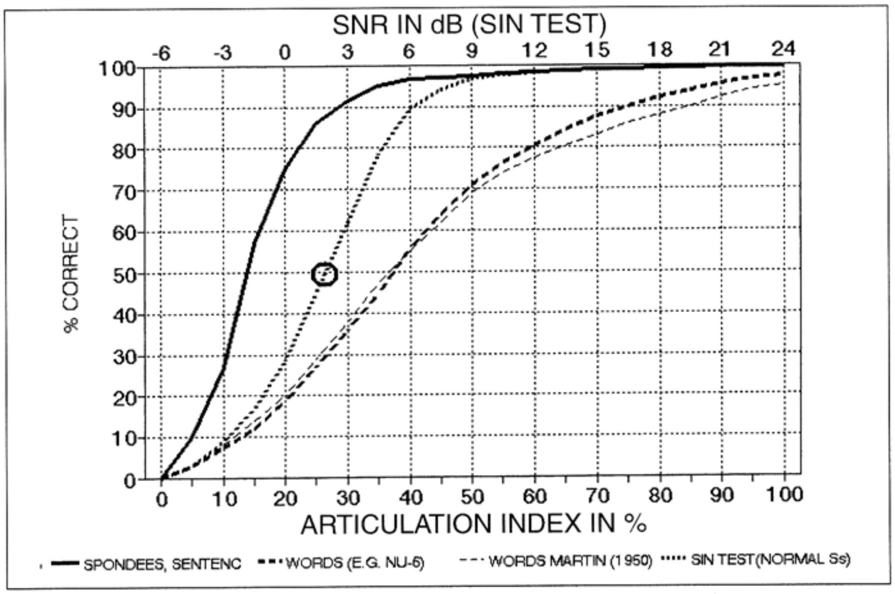

Figure 2. *Intelligibility of words and sentences vs. SNR or Articulation Index.*

SNR LOSS AND HEARING LOSS

Elsewhere, we have distinguished between audiometric hearing loss and SNR loss.[13] The pure-tone average (PTA) audiometric loss, for example, is the average of the increase in SPL required for threshold at 500 Hz, 1000 Hz, and 2000 Hz, over normal values. SNR loss is expressed as the dB increase in SNR, over the SNR required by a normal listener, for a 50% correct score on words in sentences (if that is the task). A person with a 40-dB-PTA loss may typically have a 5-dB-SNR loss, i.e., may require an SNR of 7 dB rather than the normal 2 dB.[11]

At a noisy party, the person with normal hearing can carry on a conversation at a 2-dB SNR. As indicated in Figure 2, this means only 26 of the dots remain audible above the noise of the party. Even so, the ongoing conversational context allows the hearer to fill in the gaps and understand approximately 85% of the sentences (see the left-hand curve in Figure 2.) The person with a 5-dB SNR loss, on the other hand, needs to hear additional speech cues—in effect, clearer speech—in order to understand the same number of sentences.

For ease of discussion, we can translate a 5-dB SNR loss into the number of additional dots required by such a person. Since the AI covers 100 dots in 30 dB, we expect 3.33 dots per 1-dB increase in SNR. Increasing the SNR by 5 dB to a 7-dB SNR should thus uncover 5x3.33, or 17, additional dots.

The reasoning of the last paragraph can be checked approximately on Figure 1 by drawing a line representing a masking noise that covers up all but the 26 highest-intensity dots, and then drawing another line 5 dB above (lower intensity) that line and counting the dots between the two lines, or counting the total of 43 dots now audible.

MISSING DOTS

The person with a 5-dB SNR loss needs to hear 43 dots (43% of the speech cues) to reach the same level of intelligibility that those with normal hearing obtain with 26 dots. When those 43 dots are presented, that person behaves as if only 26 dots are available for decoding in the auditory centers.

As we change SNR, we might expect the same proportion of dots to be passed on to the brain. If we put in 43 dots and 17 dots are lost somewhere between the eardrum and the brain, for example, the ratio 26/43=0.6 suggests that this auditory system may pass along only 6 of every 10 dots that come into the ear. Casually speaking, this person is missing 40 dots: The dots go in, but they don't all come out.

We could visualize our example above in terms of a switchboard with 43 telephone lines for answering customers' calls, but 17 of the lines are either cut (lost calls), weak, or so full of static that no ordering information can be safely taken. Whatever the cause, 17 of the total 43 lines are effectively out of service.

In the auditory system, the obvious analog of the cut telephone lines would be "nerve loss," but Dallos and Berlin suggest that most SNR loss results from a loss of inner hair cells.[14] This would be more analogous to defective or missing microphones in the telephone handpieces.

Fletcher and others used a "proficiency factor" multiplier to the calculated AI to account for hearing loss, English as a second language, or lack of proficiency at speech tasks. Several modifications to the Articulation Index have been made to improve its ability to predict speech-in-noise performance for those with hearing impairment.[15-17]

The modification that occurred to us follows in the footsteps of its predecessors but is more visual. We propose to modify the Count-the-Dots graph to distinguish "intact dots" from "missing dots." Figure 3 shows such a modification, where groups of normal inner hair cells are shown as solid square dots, while groups of missing or badly damaged inner hair cells are depicted as open squares.

Cochlear microphotographs of noise-damaged cochleae suggest the missing-dots representation may have a solid physical basis. In the 4000-Hz frequency region, for example, we expect a feeble but non-zero data stream to the brain from the cochlea of someone with a noise-induced hearing loss of 60 dB to 70 dB.

Both Skinner and Rankovic found that some subjects with severe high-frequency losses did *worse* when high-frequency speech cues were restored to complete audibility (by making the Articulation Index equal to 1.0), compared to a lesser amount of high-frequency amplification.[18,19] Speech cues at those frequencies appeared to convey little information even when they were completely audible. Indeed, some of those dots appear to act as "black holes," absorbing (and destroying) information in nearby dots that would otherwise be available to the brain. For a person with such a loss, the complaint, "I can *hear* all the dots, but I can't understand *speech*," makes sense.

Lest the present argument lead to misunderstanding, we note that it is the person with an auditory system that doesn't pass on all the incoming dots to the brain who most needs excellent hearing aid fittings. Restoring audibility may still leave

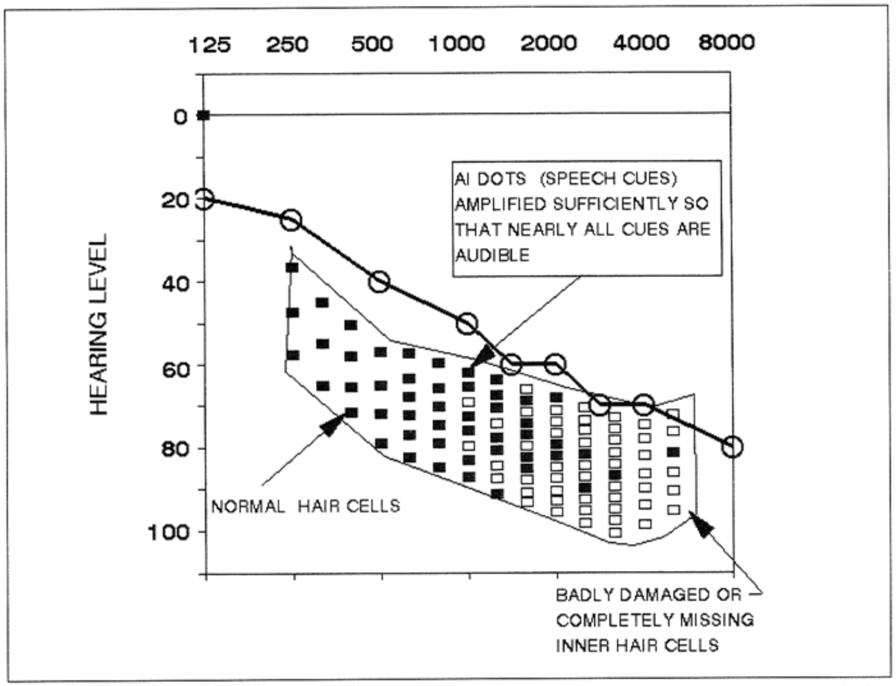

Figure 3. *Visual illustration of amplified speech that is completely audible, but only half of the speech cues reach the brain.*

a substantial SNR deficit, but *failure* to restore audibility is criminal: When only half the incoming dots reach the brain, the fitter who provides audibility for only half of the available dots doubles the handicap. (It is only in rare cases, such as those reported by Skinner and Rankovic, that full audibility is less than optimum. In the vast majority of cases, better audibility gives better hearing; it is the first thing to do right in hearing aid fitting.)

MISSING DOTS AND INTELLIGIBILITY

It turns out that we can calculate the expected SNR deficit from the data in Figure 3, which shows 50 intact dots and 50 dots missing. The elegant contribution of AI theory is that it doesn't matter which dots are missing because they have been made equally important, at least for a first approximation. With half the dots missing, twice as many audible speech cues (incoming dots) will have to be presented before a given number reach the brain. Instead of requiring 26 AI dots of audibility to reach a 50% correct score on the SIN test, a person with half the dots missing would require 52 dots.

As illustrated in Figure 4, providing an extra 26 dots will always require an increase in SNR of (26/100)x30dB, or 8 dB. A person with 32 dots missing will require a 10-dB SNR instead of the normal 2-dB to obtain a 50% correct score. Such a person should thus show an 8-dB SNR loss.

As an aside, it is interesting to note that the predicted 8-dB SNR loss for the person represented in Figure 3 is 2 dB greater than the 6-dB SNR loss expected for someone with a pure-tone average audiometric loss of 50 dB, based on the *average* data presented by Bentler, Niquette, and others.[11] The number of empty dots in Figure 3 was somewhat arbitrarily chosen as 50 for the sake of a simple illustration, rather than chosen to match available SNR-loss data.

WHERE ARE THE MISSING DOTS? (FILTERED SPEECH TESTS)

Figure 5 illustrates the case of speech low-pass filtered at 1600 Hz. If we count the dots below and above 1600 Hz, we see 50 dots each (reflecting decades of filtered-speech AI studies showing that roughly half the speech information lies above about 1600 Hz and half below[2]). If we tested someone with normal hearing using a filtered version of the SIN test, the person would no longer be able to obtain 50% correct words at a 2-dB SNR because filtering would remove half the 26 dots needed for 50% intelligibility.

To obtain a 50%-correct score with 1600-Hz high-pass or low-pass filtered speech, we would need to increase the SNR enough in the low band to restore the 13 dots lost to filtering. By the reasoning illustrated in Figure 4, this would require an 8-dB increase in SNR, from 2 dB to 10 dB, just as in the hypothetical case illustrated in Figure 3, where we presumed to know how many dots were missing.

We tried the filtered-speech experiment using both low-pass and high-pass speech in babble, repeating experiments done by Fletcher and his colleagues 70 years ago. We had the advantage of commercially available SIN-test material[20] and a 100-dB/octave brick-wall filter).

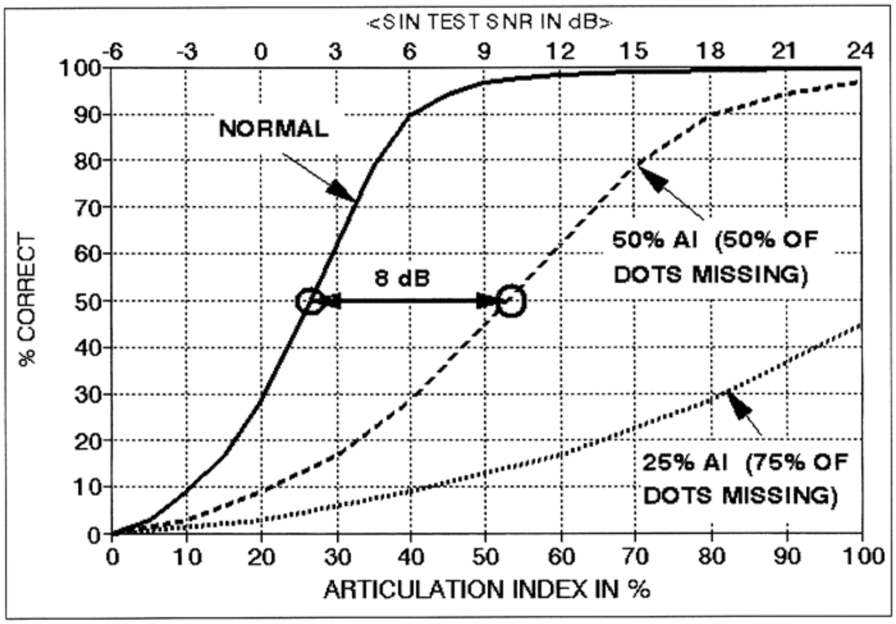

Figure 4. *Intelligibility of SIN test words in sentences for persons with normal hearing (——), 50% dot loss (– – –), and 75% dot loss (·····).*

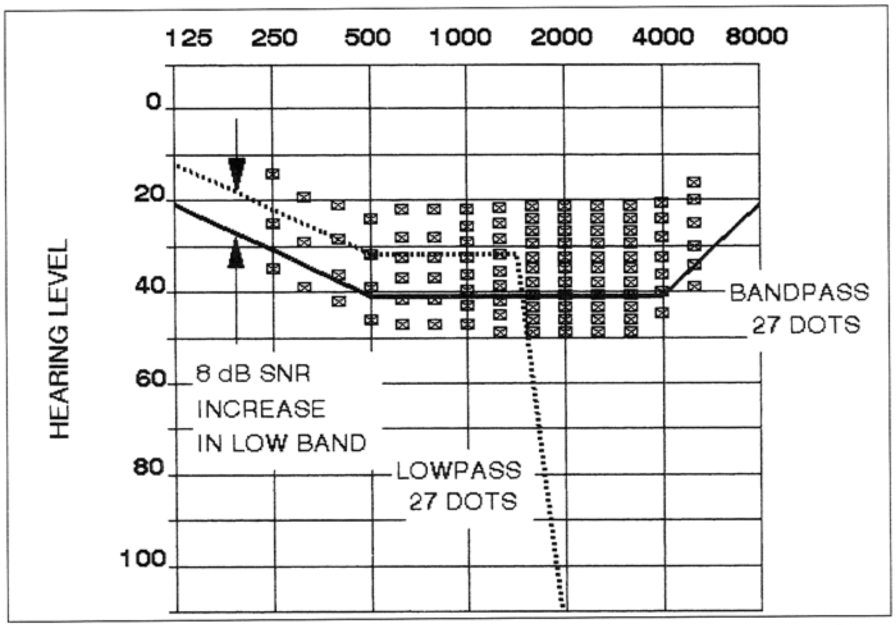

Figure 5. *Estimated increase in SNR required for 1600-Hz low-pass SIN test compared to full-band SIN test.*

Figure 6 shows the results from two sites for three groups of subjects: listeners with normal hearing and listeners with mild-moderate sloping loss. Each group was tested on full-band (FB), low-pass (1600-Hz LP), and high-pass (1600-Hz HP) CD recordings of the SIN test. The results for the listeners with normal hearing are averaged over the 70-dB-HL and 40-dB-HL conditions. Results for the listeners with hearing impairment are for the 70-dB-HL condition only.

Two bands each of the 1600-Hz LP and 1600-Hz HP lists are reproduced on Bands 27–28 and 29–30 of the CD that was contained in the April 1998 issue of *The Hearing Journal.* Bands 25 and 26 contain full-band SIN-test material, but the signal and babble are recorded on different tracks and must be combined by the user. Alternately, the SIN test CD contains similar full-band material.

No dots lost on normals

Our normal subjects required a 2.1-dB SNR for a 50% correct score on the full-band test, nearly identical to the 2 dB reported elsewhere for the SIN test.[11] Our normal subjects required an SNR of 9.3 dB for the low-pass condition and 11.2 dB for the high-pass condition, nearly identical to the value of 10 dB predicted for either condition. It was pleasant but hardly surprising that the AI calculations predicted our results with normal listeners. If we had chosen a slightly lower frequency than 1600 Hz, consistent with the importance function for words in sentences[21], we would presumably have obtained exactly 10 dB for both HP and LP tests.

Lost dots with SNR loss

Our hearing-impaired subjects required a 4.8-dB SNR for a 50% correct score, a 2.7-dB increase in SNR compared to normal. Thus, our hearing-impaired subjects required 37 dots instead of the normal 27 dots. Extrapolating to 100 dots, we speculate that on average our hearing-impaired subjects had lost the use of 27 dots. In the future, with histological data available on subjects who had been tested with the SIN or similar tests while they were alive, we may be able to speculate that 27% of their inner hair cells are missing.

Figure 7 provides a simple estimate of the number of missing dots as a function of SNR for the full-band SIN test (solid curve). A subject requiring a 10-dB SNR for a 50% correct score on the full-band SIN test, for example, would have lost the use of 50 dots.

As an example of the use of Figure 7, our tests with high-pass and low-pass filtered lists showed that hearing-impaired subjects at both Louisiana State University and Northwestern University required approximately a 15-dB SNR for the 1600-Hz LP condition and approximately a 23-dB SNR for the 1600-Hz HP condition (see Figure 6). Using the dashed curve in

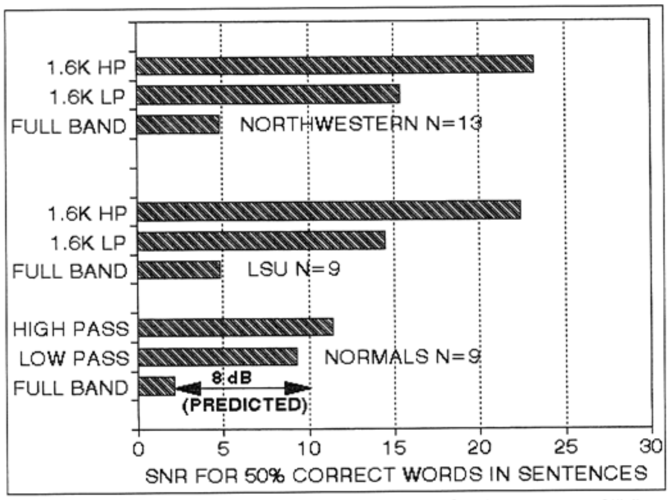

Figure 6. *Results of full-band, 1600-Hz LP and 1600-Hz HP SIN tests with three groups of subjects, two with mild–moderate sloping loss.*

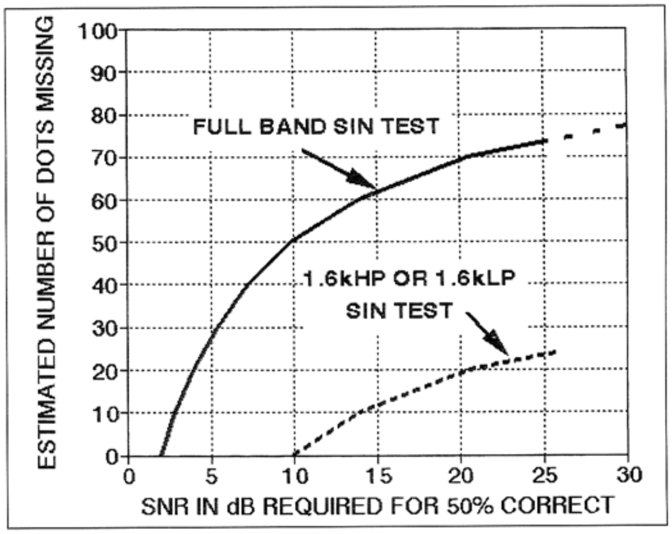

Figure 7. *Graph for estimating missing dots from full-band and 1600-Hz LP or HP SIN test.*

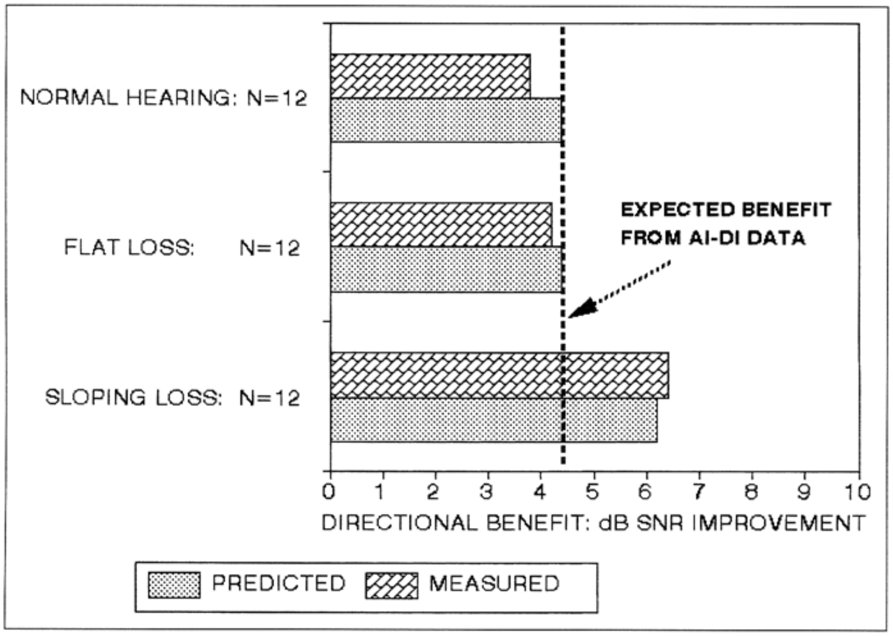

Figure 8. *Effective noise reduction from D-MIC directional microphone measured on subjects with normal hearing, flat loss, and sloping loss.*

Figure 7, which corresponds to our half-band tests, we deduce that our average subject was missing 12 dots at low frequencies and 21 dots at high frequencies, for a total of 33 dots missing. Using Figure 7 in reverse, missing 33 dots predicts a full-band SNR of 6 dB, which is within 1 dB of the measured full-band SNR for these subjects.

Although our average sloping-loss subject did not show a dramatic difference between high-pass and low-pass SNRs, some individual subjects showed dramatic differences, with low-band SNRs near 10 dB (normal) and high-band SNRs at the 28-dB upper limit of our extrapolation scheme.[22]

The CD in last month's issue of *The Hearing Journal* contains the full-band and filtered SIN test blocks used to obtain these data, as well as other potentially useful SIN-test-like recordings for research.[23]

EXPLAINING UNEXPECTED BENEFIT

The original purpose of this exercise was to explain the data in Figure 8: Our normal and flat-loss subjects obtained approximately a 4-dB benefit in noise from D-MIC™ directional microphone recordings, but our sloping-loss subjects—who had a greater SNR deficit—obtained a 6.3-dB benefit. As reported earlier, the 12 normal-hearing subjects required an average of a 0.7-dB SNR to obtain 50% correct scores on the omni-microphone recordings made at Lou Malnati's restaurant. The 12 flat-loss and sloping-loss subjects required 5.3 dB and 8.2 dB, respectively. Because of the larger benefit for the sloping-loss subjects, their average SNRs dropped to 1.9 dB, which is 0.1 dB better than the 2 dB of normal listeners.

The explanation? Although the directivity is highest at high frequencies in the D-MIC directional microphone, the directivity in the omni setting also rises at high frequencies, with the result that the *difference* is greatest at *low* frequencies. We found the average difference was only 3.4 dB above 1600 Hz, while it was 6.2 dB below 1600 Hz. Since the hearing of the sloping-loss subjects was more damaged at high frequencies, where they required an 8-dB greater SNR, it is reasonable to assume that they obtained little benefit from the high-frequency improvement. If so, they depended primarily on the low-frequency information, where the improvement was greatest, and the high-frequency SNR improvement made little difference.

For normal and flat-loss subjects, the AI-DI rating discussed earlier[1] remains the appropriate performance predictor. Figure 8 shows a comparison between predicted and measured performance for 36 subjects. The predicted performance was based on AI-DI for the normal and flat-loss subjects and based on the low-frequency average DI difference for sloping-loss subjects. The agreement is good.

The average audiograms for the three subject groups are found in Table I.

SUMMARY

We used a simple Count-the-Dots approach to estimate the loss of information flow accompanying a given amount of SNR loss at low and high frequencies. Not only does this method nicely predict the reduced slope in the graph of percentage correct vs. SNR for hearing-impaired subjects, but helps explain how hearing-impaired persons with high-frequency loss—those who often have the greatest SNR losses—will often obtain the greatest benefit in noise from the use of high-performance directional microphones. In the experiment reported here, this benefit exceeded the previously predicted benefit by nearly 2 dB. For once, it appears, those who need the most help may receive the most benefit. HJ

Table I. *Average thresholds in dB HL for subjects used to obtain data shown in Figure 8.*

FREQUENCY In Hz	250	500	1000	2000	4000	Pure-tone average
NORMAL	10	12	11	5	5	9
FLAT LOSS	43	45	50	50	53	48
SLOPING LOSS	23	28	43	56	61	42

NOTE: The standard deviation of thresholds for the hearing-impaired subjects ranged from 5 dB to 14 dB, with an rms value of 11 dB. Two-thirds of the subjects in each group, therefore, had thresholds within approximately 11 dB of the average thresholds shown.

ACKNOWLEDGMENTS

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23. Obtaining SNR estimates from SIN test scores can be done in two ways: (a) estimating the SNR for 50% correct from a graph of the percentage correct vs SNR data, or (b) adding up *all* the percentage correct scores in a block and subtracting that number divided by 20 from 17.5 dB (following the method recommended by Tillman and Olsen for spondee thresholds[24]). A graph of 100% for the first five sentences at 15-dB SNR and 0% for the next five at 10-dB SNR would intercept 50% at 12.5-dB SNR, for example. If all the other scores were 0%, the Tillman-Olsen method would also give a 12.5-dB SNR (17.5—100/20). In actual practice, small differences are sometimes encountered, so one or the other method should be used consistently. The Tillman-Olsen method uses all available data and gives a slightly lower standard deviation. Recent statistical analyses indicate the variability of each five-sentence, 25-key-word SIN test sub-block, scored with half credit for partially correct words, is equivalent to that of a 25-word list with whole-word scoring: Scores near 50% have a standard deviation of 10%. (Note: In Bands 31-36 on the accompanying CD, the constant in the formula should not be 17.5 dB but the highest SNR+2.5 dB. The appropriate constants are: 19.5 dB for Bands 31-32, 24.5 dB for Bands 33-34, and 29.5 dB for Bands 35-36.)
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