DEVELOPMENT OF TEST PROCEDURES FOR EVALUATION OF BINAURAL HEARING AIDS

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The Auditory Research Laboratory of Northwestern University has been conducting a research project, supported by the Prosthetics and Sensory Aids Service, designed to provide the Veterans Administration with test tools that would facilitate the recommendation of binaural hearing aids for veterans who benefit more from this type of amplification than from monaural amplification.[a] This work has led, among other things, to a better understanding of: 1. the head shadow effect and its influence on speech understanding in noise, 2. the binaural squelch effect, 3. the general effect of noise and competition on the understanding of speech by hard-of-hearing persons with and without a hearing aid, and 4. the effect of differences in electroacoustic reproduction on discrimination of speech. The following report deals with each of these topics.

HEAD SHADOW EFFECT

A paper presented by Tillman, Kasten, and Horner at the 1963 Convention of the American Speech and Hearing Association (Asha 5, 1963, 778–779 A) demonstrated a 6.4 dB head shadow effect. During their experiment, Tillman and his associates tested 24 young normal hearing persons in sound-field-listening conditions. Each listener was seated by himself in a sound-treated room between two loudspeakers which were to his right and left at azimuths of 45 deg. Figure 1 shows

[a] Numerous investigators have participated in this experimental work, which has been carried on under VA Contract V1005M–1926. A number of papers emerging from the project have been presented at professional meetings. This report draws from the work of many who have been involved in this work, and their papers are cited at appropriate points in the text.

the physical arrangement and demonstrates the fact that the listener was equidistant from the two loudspeakers. In order to achieve monaural listening conditions for the listener one ear was covered with a Willson muff. Speech reception thresholds were then established using spondee words as the test material. Thresholds were determined: 1. for the situation in which the spondaic words originated from the loudspeaker on the side of the open ear and 2. in another condition in which the words were generated by the loudspeaker on the other side, that is, on the side away from the open ear. The first of these two listening conditions was labeled monaural direct by Tillman and his colleagues, since the speech was presented directly to the monaural open ear. The second listening situation was called monaural indirect, since here the speech had to come around the head of the listener and thus reached the open ear circuitously. The signal strength developed by each of the loudspeakers was defined in terms of a speech spectrum noise generated by each loudspeaker independently as measured, with the listener absent, at the center of the position occupied later by the listener's head.

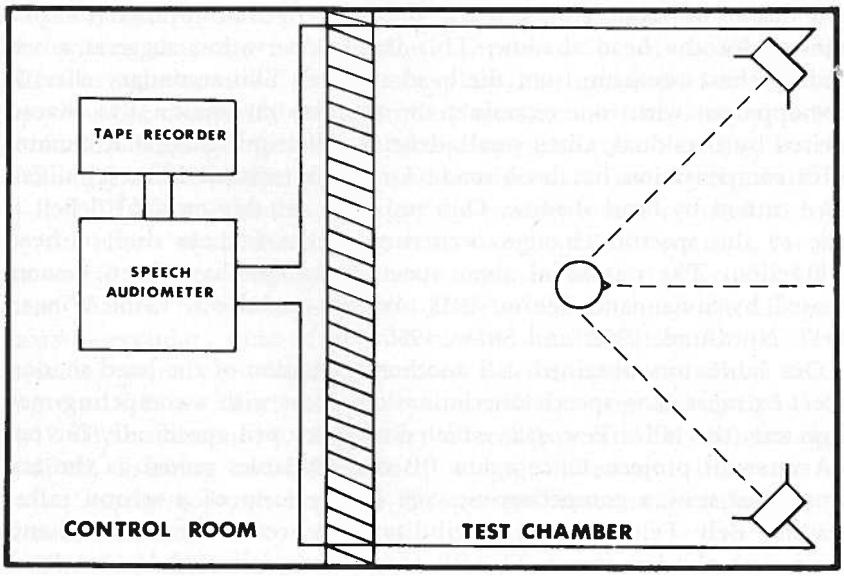

FIGURE 1.—Diagram showing listener positioned equidistant from two loudspeakers to his left and right at azimuths of 45 deg.

The average results for the 24 listeners showed that the signal level had to be increased by 6.4 dB for them to perceive the spondee words during monaural indirect listening as compared to monaural direct

listening. These data indicate that when the head is interposed between the signal source and the single monitoring ear, the acoustic shadow which it casts, i.e., the head shadow effect, produced a difference of this magnitude between the spondee thresholds obtained when competing sounds were absent.

The same physical arrangement shown in Figure 1 was also used to test speech discrimination for monaural direct and monaural indirect listening conditions in quiet. During this phase of the experimentation, all PB materials were presented at a sensation level of 30 dB relative to the monaural direct spondee threshold. Consequently, in the monaural indirect listening situation the head shadow reduced the effective sensation level by about 6.4 dB. Therefore, a second discrimination test was also administered in the monaural indirect condition, but now the intensity of the PB items was increased by 6.4 dB to compensate for the loss in intensity due to the head shadow effect. This latter condition was referred to as the adjusted monaural indirect condition. The average discrimination scores are shown in Table 1. It is seen here that a decrease of 5.2 percent occurred for monaural indirect listening, but note also that only 2.4 percent of this deficit was restored when the signal strength is adjusted to compensate for the head shadow. This latter observation suggests a secondary effect resulting from the head shadow. This secondary effect is not apparent when one examines the spondee threshold. It is characterized by a residual, albeit small, deficit in discrimination that remains after compensation has been made for the interaural intensity difference caused by head shadow. One suspects that this residual deficit is due to the spectral changes occurring at the far ear due to head diffraction. The nature of these spectral changes have been demonstrated by Sivian and White, 1933; Wiener and Ross, 1946; Wiener, 1947; Nordlund, 1962; and Shaw, 1966.

Our laboratory obtained still another evaluation of the head shadow effect by measuring speech discrimination scores with a competing message test (the N.U. Test #2) which was developed specifically for our VA research project. Once again PB monosyllables served as the test items, but now a competing message in the form of a second talker reading Bell Telephone Intelligibility Sentences occurred simultaneously with the test items. The PB words were delivered by one loudspeaker while the competing message was generated by the second loudspeaker. During the present experiment, the competing message was emitted at a nominal level 6 dB weaker than the PB materials. (Nominal level refers to the measurement of the signal level as the point in space occupied by the listener's head, but with the head absent.) Discrimination scores were then obtained in this sound field under three listening conditions: namely, monaural direct, monaural

indirect, and adjusted monaural indirect. During the monaural direct listening, the monosyllabic words originated from the loudspeaker to the side of the head with the open ear while the competing sentences came from the loudspeaker on the opposite side of the head. In the two monaural indirect conditions, the situations were reversed in that now the PB items came from the loudspeaker on the side away from the open ear and the competition was developed by the loudspeaker on the side of the open ear. However, in the adjusted monaural indirect the intensity of the monosyllables was increased by an average of 6.4 dB and the level of the competition was decreased by the same amount. These two adjustments were made so as to compensate for the head shadow effect described earlier. Note that in this instance dual compensation was necessary because two signals were involved and they were shadowed at opposite ears.

The results for these test conditions are shown in Table 2. Observe the sharp reduction (34 percent) in the speech discrimination score for the monaural indirect condition. This reduction represents a decrease of discrimination by virtue of simply shifting from monaural direct to monaural indirect listening. The marked difference in monaural direct versus monaural indirect listening is reasonable, however, when one remembers that the head shadow operates twice in modifying the effective signal-to-noise ratio. To explain, the nominal ratio of 6 dB between the monosyllables or primary message and the competition or secondary message (primary-to-secondary ratio of +6 dB) in the monaural direct condition must be considered as an effective ratio of +12.4 dB because in this situation the competition is reduced in level by the effects of the head shadow by about 6 dB. In contrast, for the monaural indirect condition, the primary message is affected by the head shadow by about 6 dB and thereby results in an effective primary-to-secondary ratio of approximately —.4 dB. Thus, for the same nominal primary-to-secondary ratio of +6 dB, monaural direct listening results in an effective primary-to-secondary ratio of approximately +12 dB and of about 0 dB primary-to-secondary ratio for the monaural indirect listening condition. Such a large interaural difference in ratios easily accounts for the 34 percent interaural difference in discrimination.

The discrimination score for the adjusted monaural indirect condition given in Table 2 indicates that the procedure of increasing the level of the primary signal by 6.4 dB and also simultaneously reducing the level of the competing signal for monaural indirect listening to the same degree almost returned the discrimination score to the good efficiency achieved in the monaural direct listening situation. However, the finding that performance in the adjusted indirect condition remains an average of 5.6 percent poorer than the mean score for

TABLE 1.—*Mean Discrimination Scores Obtained in Quiet for 24 Subjects in Three Conditions of Monaural Listening*

Monaural direct	98.1
Monaural indirect	92.4
Adjusted monaural indirect	95.3

TABLE 2.—*Mean Discrimination Scores in Percent Obtained in a Competing Message Situation for 24 Subjects in Three Conditions of Monaural Listening*

Monaural direct	92.8
Monaural indirect	59.3
Adjusted monaural indirect	87.2

monaural direct listening is probably attributable to the spectrum changes at the far ear due to the differential attenuation there of high frequency components. Such spectrum changes cannot be counteracted merely by adjusting levels at the two ears so as to eliminate the discrepancies in overall signal intensity induced by the head shadow.

Results such as these help us understand the complaints of unilateral hearing loss cases. These people report great trouble in noisy situations. Their problem becomes clear when one remembers that a unilateral hearer listening in everyday environments where noises or competing speech are rampant cannot help but be at a serious disadvantage compared to the binaural listener whenever the speech to which he wishes to attend originates on the side away from his good ear. Stated in the reverse, a person with bilaterally normal hearing is almost never faced with having to rely upon the far ear, since one of his two ears will always be favorably positioned with respect to the speech of interest at the moment. The ear that is the advantageous one will shift from side to side as the important sources in the environment change from side to side; but having to shift the ear on which one is momentarily relying is no hardship. By contrast, having only one ear which is on the wrong side of the head about half the time is a real burden.

The same type of practical disadvantage cannot help but beset the monaural hearing-aid user; and one would expect that a major benefit to be derived from using two hearing aids is that monaural indirect listening is thereby eliminated.

These considerations are a part of the next section of this report, which also considers the further benefits which accrue from binaural interaction per se.

BINAURAL SQUELCH EFFECT

Past studies of binaural hearing generally have presented stimuli to the two ears via earphones and then have manipulated the intensities, phase angles, and/or time delays of these signals to achieve whatever interaural differences were required by the research protocol being followed. Many of these investigations have tested speech intelligibility when the speech was presented in noise and while one or more of the above mentioned parameters of the speech or noise were systematically varied at the two earphones. Very little work has been done, however, to study binaural hearing for speech intelligibility in everyday situations.

Some of the early work performed by our group which dealt with this facet of binaural hearing has already been discussed by Carhart (1965). Carhart's report considers the question as to whether the imbalance in the signal-to-noise ratios at the two ears that is produced by the head shadow nullifies any potential binaural advantage. In other words, did subjects understand speech equally well monaurally and binaurally providing that the single ear for monaural listening was favorably positioned with regard to the speech of interest? If not, then there must have been an advantage which accrued from binaural interaction per se and the issue before us is, "How great was the binaural advantage?"

The critical comparison here is between optimal monaural listening (direct) and binaural listening. The data covering this comparison which Carhart reviewed revealed improvement of about 10 percent in speech discrimination for PB words in the presence of a competing message (N.U. Test #2). Carhart converted this difference into subjective reduction in masking effectiveness of the competing speech, expressed in dB. Carhart termed this reduction the binaural squelch factor. The data he reviewed revealed the binaural squelch was equivalent to the reduction for masking which a 2.8 dB drop in competing sound would have produced during monaural direct reception.

We have since obtained new data for 12 normal hearing listeners. These subjects listened to a new set of test materials, which are identified as N.U. Test #20S. The N.U. Test #20S is also of the competing message type. The items it employs are a series of CNC [consonant, nucleus, consonant] words that our laboratory has organized under the heading of N.U. Test #6 (Tillman and Carhart, 1966). Bell Telephone Intelligibility Sentences have been added as competition. The entire sequence has been recorded on magnetic tape with test words on one channel and competition on the other.

In broad outline, the experimental conditions employed in gather-

ing data on binaural squelch with N.U. Test #20S were similar to those used in our earlier investigation of the head shadow effect. Each listener was seated in the center of a sound-treated room with two loudspeakers equally distant from him and at 45-deg. azimuths to his right and left. Monaural direct and monaural indirect listening conditions as described previously were employed, as was a binaural listening situation. Both ears were open for all binaural listening, but during all monaural listening the non-test ear was masked with white noise delivered by an insert receiver at 60 dB sound pressure level and this same ear was also covered with a Willson muff. The test words were presented in the sound field only at 54 dB sound pressure level. The competing sentences were presented at 4 levels. One level was nominally equal to the CNC words, and the other levels were such that competition was nominally 6, 12, and 18 dB more intense than the monosyllabic words, respectively. These relations were such that the sound field's monaural primary-to-secondary ratios were —18, —12, —6, and 0 dB.

TABLE 3.—*Mean Discrimination Scores in Percent for N.U. #20S Obtained for 12 Listeners on Three Listening Situations and Four Primary-to-Secondary Ratios*

Listening situation	Nominal primary-to-secondary ratio in dB			
	—18	—12	—6	0
Monaural indirect	15.8	33.2	56.2	70.8
Monaural direct	58.3	76.2	90.7	95.8
Binaural	73.0	87.8	95.3	97.7

The means of the speech discrimination scores for the four primary-to-secondary ratios during three different listening situations of the experiment are given in Table 3. The same results are plotted in Figure 2.

The first thing one notices is that these data demonstrate again the head shadow effect. There was a marked difference in monaural discrimination ability dependent upon the location of the source of the

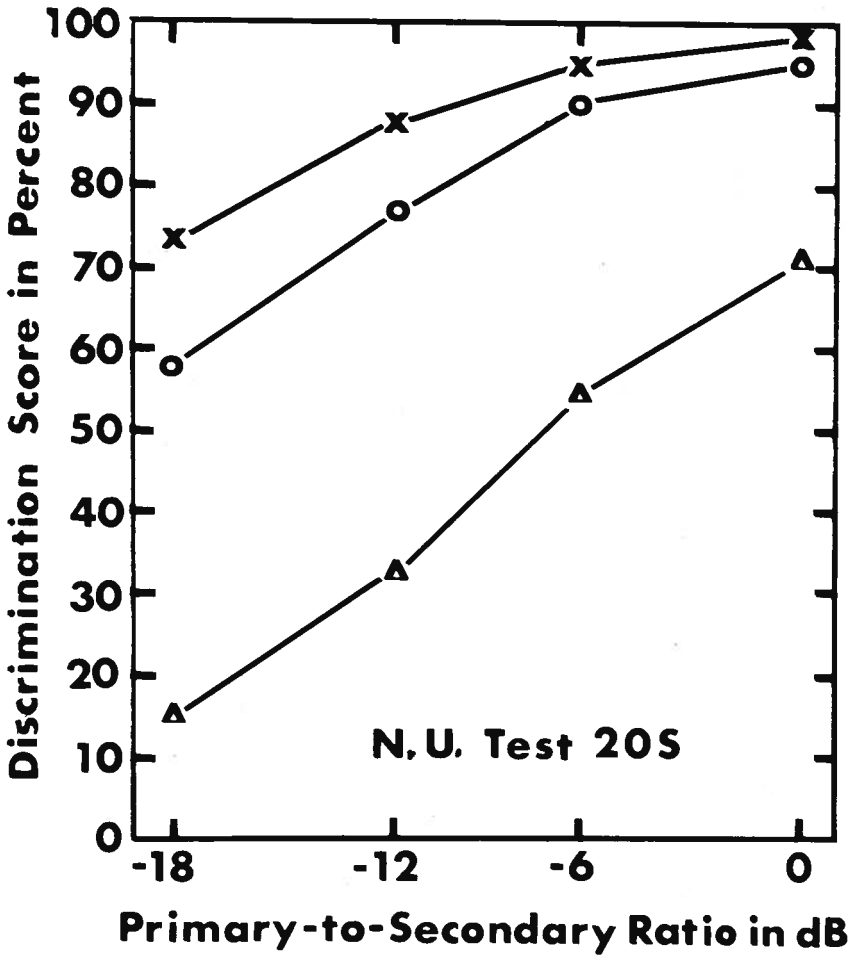

FIGURE 2.—Mean speech discrimination scores achieved by 12 normal hearers for N.U. Test #20S plotted as a function of the nominal intensity ratios of the monosyllables versus competing sentences (primary-to-secondary ratio in dB). Δ Monaural indirect; O Monaural direct; × Binaural.

primary signal, i.e., whether it be on the side adjacent to the open ear (monaural direct) or on the side away from the open ear (monaural indirect). Here, too, the average scores show differences of about 40 percent between monaural direct and monaural indirect listening for the same nominal primary-to-secondary ratio. Thus, the new findings provided good supportive evidence of the magnitude of the head shadow effect.

When one corrects the nominal primary-to-secondary ratios used in this experiment for the changes in ratio on the two sides of the head

induced by shadowing, the actual signal-to-competition ratios at which subjects were operating during monaural listening were approximately —24, —18, —12, and —6 dB during the indirect condition (far ear) and —12, —6, 0, and +6 dB during the direct condition (near ear). Figure 3 presents the monaural results after this correction. Note how closely the data points for monaural direct and monaural indirect conditions fit a single function whose linear portion has a slope of 3.1 percent per dB. It is clear that in this particular study, at least, monaural performance was determined almost exclusively by the signal-to-competition ratio at the test ear and that changes in intelligibility resulting from spectral modifications due to head diffraction effects were minimal.

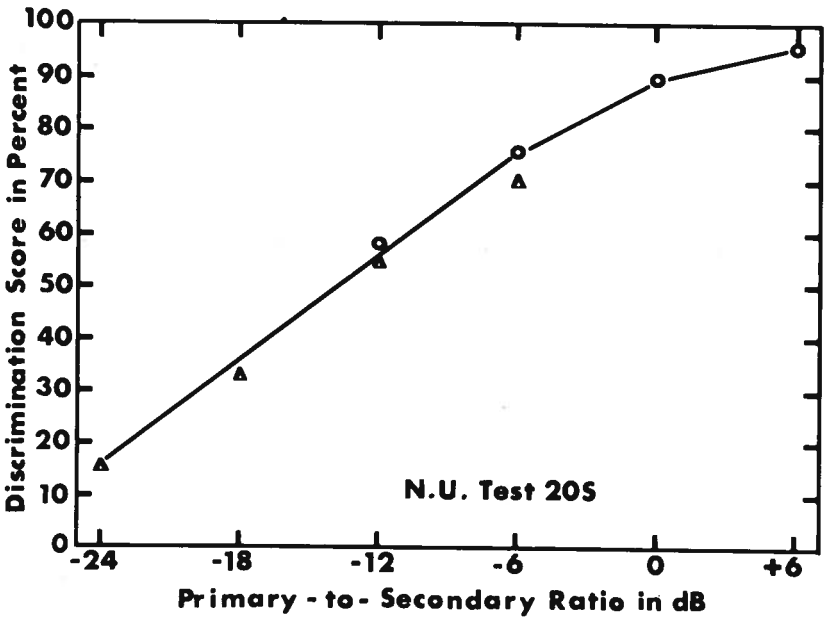

FIGURE 3.—Mean speech discrimination scores achieved by 12 normal hearers for monaural indirect and monaural direct listening conditions plotted as a function of effective primary-to-secondary ratio in dB, i.e., after correction for the head shadow effect.

This last observation allows one to use only monaural direct data in making immediate comparisons between monaural and binaural performance, since using monaural indirect will yield the same relations after signal levels are corrected for head shadow influence. Hence, observe in Table 3 that all binaural means are consistently superior

to their monaural direct counterparts. Morever, for the —18 dB and —12 dB primary-to-secondary ratios, which involve scores lying within the linear range of the function depicted in Figure 3, the binaural scores are better than monaural direct scores by an average of about 13 percent (the means of the —6 dB and 0 dB primary-to-secondary ratios are not considered here since the binaural function begins to plateau in these easier listening conditions). Dividing the slope of 3.1 percent per dB mentioned above into the 13 percent difference between monaural direct and binaural scores shows an average binaural enhancement of about 4 dB. The enhancement represents the magnitude of the binaural squelch as it exhibited itself in the present experiment. The amount of binaural squelch observed here is only slightly greater than either the 2.8 dB binaural advantage (mentioned above) which Carhart noted or than the 3 dB average binaural gain which we have found reflected in the data obtained by Harris (1965) and Nordlund and Fritzell (1963). The small differences in the foregoing four estimates of binaural squelch could easily be due to differences in the test materials, the procedural differences and the sample size employed. The important generalization deriving from these studies is that a modest binaural advantage over the favorably placed single ear is obtained in sound-field-listening situations where head shadow effects operate to modify adversely the signal levels reaching the far ear. Stated in another way, remember that the favorably placed ear during monaural direct listening is the same ear as the one receiving the less disruptive signal during binaural listening. Moreover, the speech-to-competition ratio will be the same at this ear whether or not the second ear is active. Consequently, any binaural advantage which appears in the experimental data must be attributed to interaural interactions that occur when the second ear participates. This contribution is sufficient to produce the 3 to 4 dB binaural squelch even though the second ear is shadowed so that it is plagued by a much more adverse speech-to-competition ratio than exists simultaneously at the favored ear.

COMPOSITE OF EFFECTS

The fact that masking is squelched by 3 to 4 dB when the listener is permitted to use both ears must not be misinterpreted to mean that binaural efficiency in everyday situations is never more than a little superior to monaural efficiency. Monaural success is critically dependent upon the moment to moment signal-to-noise ratio occurring in ordinary environments at the active ear. Whenever sound sources are located so that the active ear is directed toward important sounds (i.e., monaural direct listening), the addition of a second ear would

merely introduce the 3 to 4 dB decrease in masking brought about by binaural squelch. However, when the reverse is true (i.e., monaural indirect reception), addition of the second ear would combine binaural squelch with a 12 to 13 dB release from unfortunate head shadowing. In this circumstance the two forms of release from masking would summate momentarily to a 15 to 17 dB advantage for binaural reception. In other words, when comparison is made between monaural indirect and binaural listening, an effective reduction in masking of about 16 dB can accrue for the binaural condition, whereas during comparison between monaural direct and binaural listening the reduction will be only about 3 dB.

The practical implication here, since everyday happenstances shift the monaural auditor back and forth between the two monaural states, is that when his single ear is unfavorably situated, such an auditor is plagued with much greater masking from background noise than plagues his binaural companion. However, at the next moment this severe handicap may largely disappear merely because the monaural listener has turned his head or the critical sound sources have moved to his good side. Stated in another way, binaural hearing brings each of us dramatic everyday advantage over monaural listening because with two active ears we *never* have to rely on our adversely placed ear to achieve receptive efficiency. When one of our ears is not fortunately placed the other ear will be. Thus, the possession of a second ear saves each of us from a multitude of frustrating experiences that would arise because of adverse head shadowing. Added thereto we each achieve a binaural squelch effect, which is a welcome bonus of limited magnitude—*but the escape from shadowing is the large benefit we get from binaural reception.*

Of course, the question arises as to whether persons with hearing loss exhibit these foregoing relations in the same way while wearing hearing aids. Experimental results gathered in our laboratory indicate that they do. The subjects in these experiments were persons with bilaterally symmetrical hearing deficits. These subjects listened through instruments at ear level. They exhibited magnitudes of head shadowing and of binaural squelch that were about the same both while using hearing aids and while unaided as normal listeners had previously manifested. In fact, the relations were so similar for the two groups that nothing would be added by reporting here the data for the hard-of-hearing subjects.

These findings, and the concepts they embody, have important implications for research with monaural and binaural hearing aids. Gross misjudgment of the relative benefit of a binaural instrument will occur if one compares such an instrument with a monaural hearing aid placed in an unfavorable location as in monaural indirect

listening. Whenever one makes such a comparison a large portion of the advantage exhibited by the binaural system is merely the escape from head shadow which occurs with binaural reception because one of the two aids was in a more favorable listening position than the single monaural aid had been.

The only fair comparison, when one wishes to evaluate the contribution of interaural interaction which is embodied in a binaural hearing aid, is the comparison between monaural direct and binaural listening conditions.

SPEECH DISCRIMINATION WITH DIFFERENT HEARING AIDS

We made a rather startling observation in our early work on discrimination for speech via hearing aids. Discrimination deteriorated when heard through a hearing aid as contrasted to direct reception at a comparable sensation level, provided there was competition from background sound. This was true for both monaural and binaural listening. To illustrate, we found that average discrimination scores were reduced by as much as 40 percent (70 to 30 percent) for N.U. Test #2 materials not only with two groups of persons with sensorineural loss but also with a group of cases with conductive hearing loss (Tillman and Carhart, 1963; Carhart, 1964). In other words, during the same signal-to-noise conditions where speech was reasonably intelligible despite the competition (70 percent discrimination for monosyllables) unaided, interpretation became highly unmanageable (30 percent discrimination) when materials were delivered to the listener via a hearing aid.

This observation became the impetus for an extensive investigation which we have recently completed on the relations between the electroacoustic performance characteristics of hearing aids and relative deterioration in discriminations for speech received against competing sound. This investigation employed as its frame of reference measurement of discrimination in the absence of competition. It was carried out with hard-of-hearing subjects. It explored both monaural and binaural reception. The study and its findings are discussed in some detail below.

Three pairs of over-the-ear hearing aids were purchased in order to conduct the study. Instruments were selected on the basis of data available from the National Bureau of Standards. Choices were made so as to sample permutations in performance of contemporary wearable hearing aids as these permutations have been revealed by the evaluation of hearing aids which the Bureau performs for the Veterans Administration. Each pair of aids happened to be of different manufacture.

The physical performance of the two instruments constituting a pair were matched to one another as closely as possible. It was found

that satisfactory matching could be achieved only by trial and error after several extra insert receivers had been purchased. Once this goal was achieved, the two instruments within a pair were sufficiently similar so that the physical response characteristics reported below apply to either member of the pair. The three pairs of instruments are referred to throughout this paper as hearing aids A, B, and C rather than by brand and model.

The frequency response curves of the three different makes of instruments are shown in Figure 4. It is seen here that of the three hearing aids, hearing aid A had the widest frequency response, hearing aid C showed the narrowest band width and hearing aid B was intermediate. The width of the frequency response for each aid as designated by the HAIC [Hearing Aid Industry Council] method (Lybarger, 1961) is also given in this Figure. These latter values reflect the differences between instruments in frequency response in a second way.

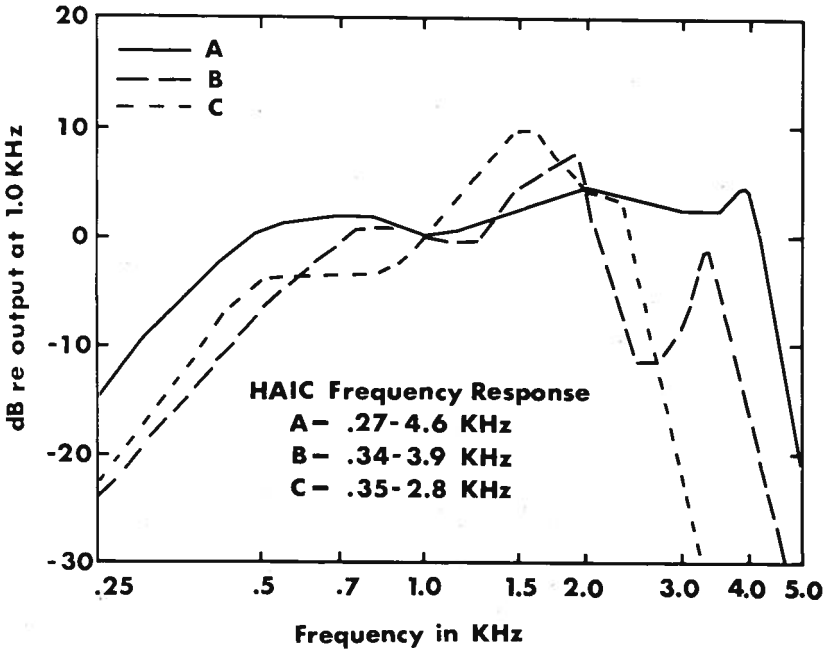

FIGURE 4.—Frequency response curves for three makes of hearing aids used in the investigation. Band width of each instrument as determined according to HAIC recommendations also given.

Harmonic distortion was measured according to the procedures employed by the National Bureau of Standards with regard to input level (75 dB SPL) and frequencies (500, 700, and 900 Hz and fre-

quency of maximum distortion) (Burnett and Priestly, 1964). The gain control for each instrument was set to 5 dB below its maximum gain at 1000 Hz for these measurements. This designation for gain settings was chosen because the same gain settings were used for the experimental work with these instruments. The bar graphs in Figure 5 report the harmonic distortion values in percent. It is apparent that hearing aid B shows very little harmonic distortion. Hearing aids A and C show some distortion at 500, 700, and 900 Hz but differ in the frequency of maximum distortion. Overall, it appears that hearing aid A generated the greatest amount of harmonic distortion.

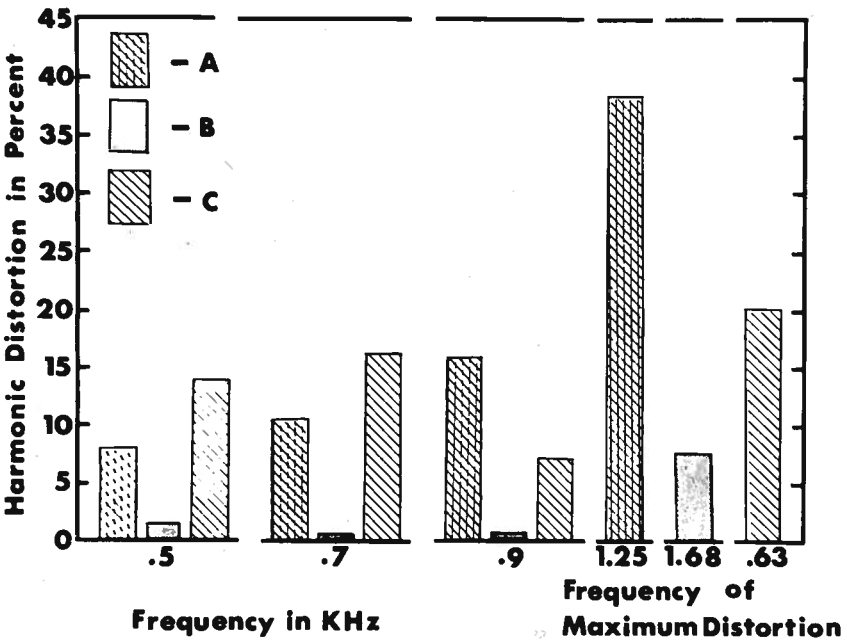

FIGURE 5.—Harmonic distortion in percent at 500, 700, and 900 Hz, and at frequency of maximum distortion as measured for the three makes of hearing aids used in the investigation.

The CCIF method was used for measuring intermodulation distortion in these instruments. This method combines two input frequencies of equal amplitude. The level of the difference frequency developed by the instrument is taken as the indicator of intermodulation distortion. We employed six pairs of input frequencies in our measurements. These pairs are listed in Table 4. Note that in three instances the lower frequency of the pair was one we also had used for harmonic distortion measurements (500, 700, and 900 Hz, respectively) while the higher frequency of the pair was chosen so as to produce a difference

of 1000 Hz. The other three pairs all had 2000 Hz as their higher frequency, and their lower frequencies were selected to produce differences of 500, 700, and 900 Hz, respectively. The table reports the intermodulation distortion percentage measured for each hearing aid with each pair of probe frequencies. Hearing aids A and B exhibited essentially equal intermodulation distortion when the input signal pairs were inputs of 500–1500 and 700–1700 Hz, while hearing aid C developed more. When the input pair was 900–1900 Hz, hearing aid A showed least distortion, C greatest intermodulation, and B was intermediate. For the remaining three input pairs hearing aid A again showed least intermodulation distortion, but now B developed the most distortion and C was intermediate.

TABLE 4.—*Intermodulation Distortion in Percent for the Three Hearing Aids*

Hearing aid	Input frequencies Hz					
	500 1500	700 1700	900 1900	1500 2000	1300 2000	1100 2000
A	3.8	4.5	4.7	12.6	7.6	4.1
B	3.3	3.5	9.8	35.8	45.6	23.4
C	9.8	14.6	20.3	26.4	15.8	7.0

After the three pairs of instruments had been demonstrated to sample the differences in performance called for by the plan for the investigation, the problem was to achieve a quick method for controlling the required permutations in presenting test materials through these aids. It became rapidly apparent that the only way to do so was to record these permutations on magnetic tape. Experimental subjects then listened to reproductions from the tape rather than to sound fields set up anew while each subject was present.

The procedure for making the tapes was simple. In order to simulate monaural direct, monaural indirect, and binaural listening with hearing aids, the two instruments constituting one matched pair were placed behind the pinnae of a dummy head, just as they would be

worn binaurally by a human listener. The output of each hearing aid was coupled to a condenser microphone via a standard 2 cc cavity. One condenser microphone and its associated amplifier in turn was connected to one input of a dual channel tape recorder, while the second condenser microphone fed the second channel. The dummy head was placed in the center of a sound-damped room (IAC 1205 A booth). Two loudspeakers were located in two corners of the room in front of the dummy head at azimuths of 45 deg. These loudspeakers generated the sound field which we wished the hearing aids to encounter, and which, after reproduction through the hearing aids, was recorded on magnetic tape.

Stimulus conditions of four kinds were produced in the sound field, namely: 1. spondee words free from background noise, 2. monosyllabic words in similar quiet, 3. monosyllables in the presence of competing speech (Bell Telephone Intelligibility Sentences), and 4. monosyllables in speech spectrum noise. These sound fields were set up by having all spondees and monosyllables emitted through the loudspeaker to the right of the dummy head. The competing sounds, when present, were developed by the loudspeaker to the left of the dummy head. The signal levels used were such that the spondees and monosyllables possessed a sound pressure level of 70 dB at the point where the dummy head was situated (measured with the head absent at the spot where the center of the head would later be). The competing sounds, when present, were at the level of 58 dB SPL (measured in the same way). Thus, the nominal primary-to-secondary ratio employed in this experiment was +12 dB. Of course, since the test words (spondees and monosyllables) originated from the right loudspeaker and the competition when present came from the left loudspeaker, head shadow effects modified this ratio. The hearing aid on the right side of the dummy head received and amplified the test materials as in monaural direct listening (the effective primary-to-secondary ratio being about 18 dB), while the instrument on the left side of the dummy head received, amplified, and reproduced the test signals as in monaural indirect listening (the effective ratio being about +6 dB).

Tape recordings were made in the foregoing manner through each of the three pairs of hearing aids and also directly from the condenser microphones to the tape recorder. The last set of recordings was obtained so that we would have available a substantially higher fidelity reproduction of the sound field than was possible when reception was through the hearing aids. In this instance the procedure was to mount the condenser microphones at the entrances to the ear canals of the dummy head.

The various test materials thus recorded were played back under earphone during the experiment proper. One ear was selected per

subject for monaural testing. This ear was the one which most logically would be used if the subject were fitted with a single hearing aid. The equipment used to present materials under earphone included appropriate intensity and switching controls so that the subject could be allowed to hear only the signal that originally had reached the right side of the dummy head (which replicated monaural direct listening), only the signal that had been picked up at the left side of the dummy head (monaural indirect), or the two signals simultaneously. During the binaural conditions, the monaural indirect signal was administered to the ear not used for monaural testing.

Three groups of adult listeners were tested with all four sets of materials via the three pairs of hearing aids and the good fidelity system. One group consisted of 9 subjects with conductive hearing loss, the second consisted of 12 younger adults with sensorineural hearing loss, and 12 persons with hearing loss due to presbycusis comprised the third group. Eight of the 9 conductive loss cases were hearing-aid users, as were 9 of the persons with sensorineural hearing loss and 9 of the presbycusics.

Each subject underwent every experimental condition twice. The resulting test and retest data are so similar that the results for the two runs have been combined here to shorten the presentation.

The means of discrimination scores for the several test conditions are given for each group of subjects in Table 5. It is immediately apparent from this table that the scores align themselves in an orderly manner, with those for the high fidelity system almost always being best and those for materials reproduced via hearing aids being progressively poorer from instrument A through instrument C. However, performance did differ sufficiently from one group of subjects to another so as to warrant more detailed discussion.

Most of the monaural direct and binaural listening conditions proved to be so easy for the conductive loss group that performance was excellent for all four patterns of electroacoustic reproduction. The clearest clue to a possible difference is that the mean discrimination scores with hearing aid C are slightly but systematically poorer than for any of the other three sets of scores. The situation is changed when one considers results for monaural indirect listening, which obviously was more taxing as evidenced by the fact that mean discrimination scores were consistently lower than the companion means for monaural direct and binaural presentations. The feature of significance for us, however, is that performance varied in an orderly manner with the pattern of electroacoustic reproduction. The means for the high fidelity presentation were slightly better than for hearing aid B and sharply better than for hearing aid C.

The results for both the younger persons with sensorineural loss

TABLE 5.—*Mean Speech Discrimination Scores in Percent for Combined Test and Retest Sessions Achieved by Each of Three Groups When Listening to Speech in Quiet and in Competition of N.U. #20S and N.U. #20N as Reproduced by a High-Fidelity System and Three Different Makes of Hearing Aids*

Speech reproducing system	Quiet	N.U. Test #20S			N.U. Test #20N		
		MI	MD	Bin	MI	MD	Bin
Conductive group (N=9)							
High fidelity	98.0	85.6	97.3	96.8	77.3	95.8	95.4
Hearing aid A	98.6	80.6	96.6	96.8	75.2	95.0	93.8
Hearing aid B	97.4	73.5	95.8	97.2	64.8	93.8	92.8
Hearing aid C	94.4	61.0	92.8	93.1	47.1	88.8	88.1
Sensorineural group (N=12)							
High fidelity	83.4	61.3	82.5	83.7	58.2	81.9	82.8
Hearing aid A	85.6	57.2	82.5	82.7	50.0	78.4	80.8
Hearing aid B	82.5	53.1	78.5	80.0	42.7	74.4	76.9
Hearing aid C	75.5	41.3	70.5	70.4	29.0	62.6	66.5
Presbycusic group (N=12)							
High fidelity	81.0	58.0	78.3	83.2	52.7	76.5	82.2
Hearing aid A	77.4	39.1	77.1	78.8	38.1	70.2	76.0
Hearing aid B	73.7	37.5	71.6	74.1	27.6	63.6	67.8
Hearing aid C	66.4	27.1	60.7	64.1	20.2	49.4	53.2

MI=Monaural indirect MD=Monaural direct Bin=Binaural

and the presbycusic group show this same hierarchy of dependence upon electroacoustic pattern. Here the superiority of the high-fidelity system is evident during both types of monaural listening and during binaural reception. Again, the drop in efficiency as gaged by discrimination scores was only slight with hearing aid A, moderate with hearing aid B, and greatest with hearing aid C. The relationships are again most dramatically revealed by the data for the monaural indirect

presentations, which represented the conditions of greatest difficulty.

The effects of pattern of electroacoustic performance upon discrimination scores can be epitomized graphically by recording the results for monaural listening as has been done in Figures 6 through 8. Here the technique has been to plot the mean scores for monaural indirect listening as those at the +6 dB primary-to-secondary ratio, which is approximately the ratio that existed because of head shadowing at the left ear of the dummy head during the recording of test materials, and the mean scores for monaural direct at the +18 dB primary-to-secondary ratio, which was the ratio that existed at the right ear of the dummy head. Means obtained when competition was absent (in quiet) are also shown. This method of plotting allows part of an intelligibility function to be graphed for the results obtained with each pattern of electroacoustic reproduction. Note that two figures embodying such results are shown for each group of experimental subjects, one figure summarizing behavior when the competing sounds were sentences (N.U. Test #20S) and the second when background was speech spectrum noise (N.U. Test #20N). Each of the figures also includes a curve showing the behavior of normal hearers receiving the same test materials under the same listening conditions via the high-fidelity system.

One relationship which is apparent in Figures 6 through 8 is that the discrimination exhibited by any single experimental group did not vary much either in quiet or in the +18 dB primary-to-secondary ratio as the pattern of electroacoustic performance was changed. The hierarchy of efficiency mentioned earlier is apparent. Results are aligned with the best scores obtained via high-fidelity reproduction and the poorest via the hearing aid C reproduction. A third relation is that this hierarchy, as already stressed in discussion of Table 5, was very definite when the ratio was +6 dB (that is, during reproduction of the monaural indirect sound field). Thus, we are justified in reaching three conclusions as to the performance which hard-of-hearing subjects of screened types achieved with electroacoustic reproduction embodying characteristics typical of contemporary instruments. The first conclusion is that performance deteriorated with all instruments in contrast to that achieved with high-fidelity reproduction. The second conclusion is that this deterioration achieved practical importance and became clearly visible when competing sounds became more pronounced. The third conclusion is that this deterioration of performance was definitely greater with some combinations of hearing-aid characteristics than with others. This last finding constitutes clear justification for the position that: 1. the Veterans Administration must consider physical characteristics of hearing aids in establishing criteria

for the purchase of hearing aids and 2. audiologists must know these characteristics as they cope with the problem of selecting a hearing aid for a particular veteran.

Another set of relationships having high practical importance is revealed by Figures 6 through 8. Recall that each figure includes a curve showing behavior of normal hearers when listening via high fidelity reproduction during the three conditions reported in the figures. Note that, except when the conductive loss group was listening to the monosyllables in quiet or the +18 dB primary-to-secondary ratio, hard-of-hearing subjects obtained poorer scores for high-fidelity reproduction than did normals. The difference was very substantial both for the younger adults with sensorineural loss and for the presbycusics. The difference is not unexpected nor, in itself, remarkable, but when one realizes that it is combined with further deterioration when reproduction is via a hearing-aid system, one is forced to recognize that when hard-of-hearing subjects are listening via hearing aids in conditions where there is moderate background competition, understanding may be grossly inferior for them as compared to normal hearers, who are privileged to receive the sound field without any form

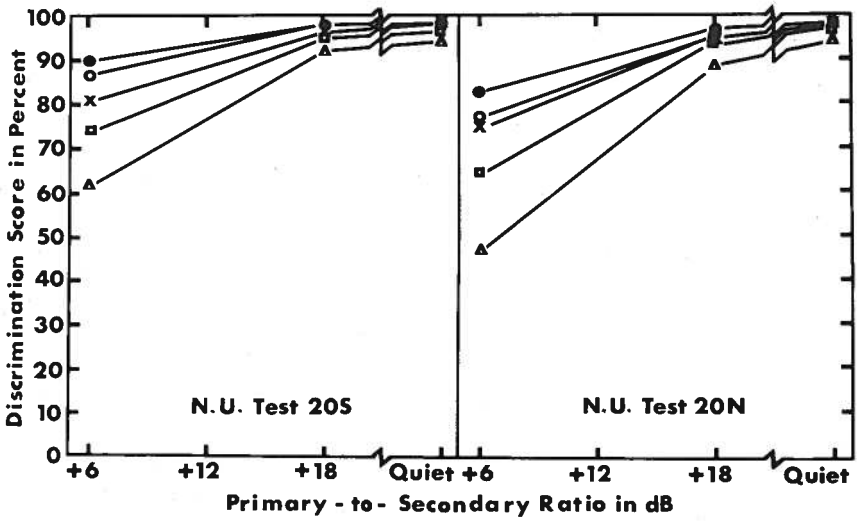

FIGURE 6.—Mean speech discrimination scores achieved by 9 conductive hearing loss cases for N.U. Test #20S and N.U. Test #20N when listening to speech as reproduced by a system with good fidelity and by three hearing aids. Scores achieved by 12 normal hearers for good fidelity system shown for comparison purposes. Scores are plotted as a function of effective primary-to-secondary ratio in dB. Normal hearers: • High fidelity. Conductives: O High fidelity; × Hearing aid A; □ Hearing aid B; △ Hearing aid C.

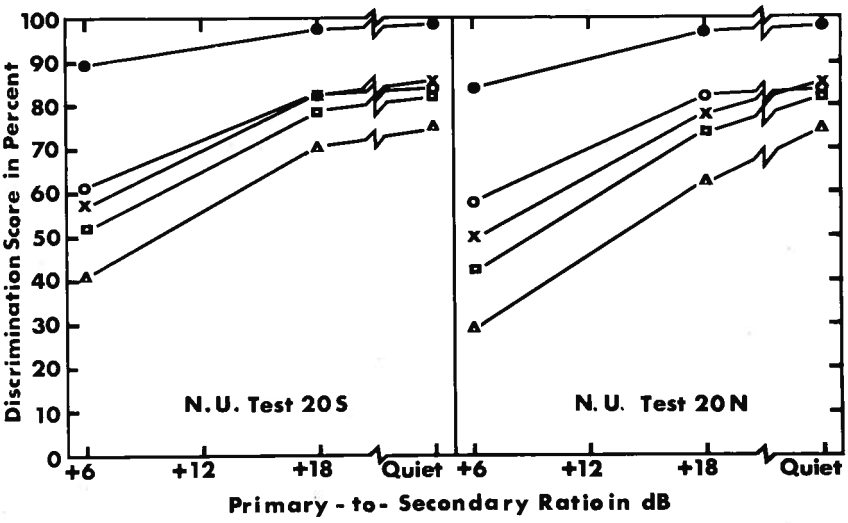

FIGURE 7.—Mean speech discrimination scores achieved by 12 sensorineural hearing loss cases for N.U. Test #20S and N.U. Test #20N when listening to speech as reproduced by a system with good fidelity and by three hearing aids. Scores achieved by 12 normal hearers for good fidelity system shown for comparison purposes. Scores are plotted as a function of effective primary-to-secondary ratio in dB. Normal hearers: ● High fidelity. Sensorineurals: O High fidelity; × Hearing aid A; □ Hearing aid B; △ Hearing aid C.

of electroacoustic intervention. Moreover, our data indicate that this same problem plagues, to a limited degree, the hearing-aid user who has conductive loss.

Summarizing all of the discussion in this section in a somewhat different way, four observations common to all three groups can be made here: 1. In easy listening conditions such as in quiet or a +18 dB primary-to-secondary ratio, all the discrimination scores are at the plateau of the discrimination ability of the groups and consequently differences in the speech reproduction system are not sharply differentiated in speech discrimination testing. 2. Binaural scores here are only equal to or slightly better than their monaural direct counterparts, thereby indicating little binaural superiority when the monaural direct scores are already at the plateaus of the discrimination ability of the listener. In other words, the binaural squelch effect did not operate here because background sound was not intense enough to interfere with discrimination. Hence, adding the information from the monaural indirect signal from the second ear to the monaural direct signals reaching the other ear did not significantly improve speech discrimination in the present investigation. The scores for monaural direct listening were already equivalent to the scores achieved

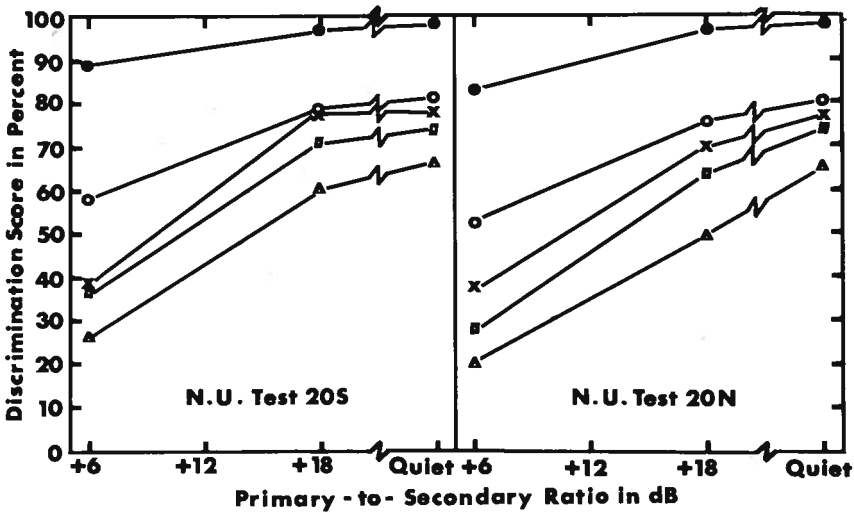

FIGURE 8.—Mean speech discrimination scores achieved by 12 persons with hearing loss due to presbycusis for N.U. Test #20S and N.U. Test #20N when listening to speech as reproduced by a system with good fidelity and by three hearing aids. Scores achieved by 12 normal hearers for good fidelity system shown for comparison purposes. Scores are plotted as a function of effective primary-to-secondary ratio in dB. Normal hearers: • High fidelity. Presbycusics: O High fidelity; × Hearing aid A; □ Hearing aid B; △ Hearing aid C.

by the listeners in quiet listening conditions. 3. The best speech discrimination scores were consistently achieved with the high-fidelity system when the listening conditions were sufficiently taxing to demonstrate differences in speech understanding with different reproduction systems. In these same conditions the discrimination scores consistently showed important differences in speech discrimination with different hearing aids. 4. Speech discrimination scores obtained by hard-of-hearing subjects under the higher level of competition (+6 dB primary-to-secondary ratio) were clearly inferior when heard via hearing aid than normal auditors achieve via high-fidelity system and, thus by implication, via direct listening.

RELIABILITY OF AIDED DISCRIMINATION

During the investigation with hearing aids just described, each listener participated in two identical test sessions. Thus, the test-retest reliability of each group of subjects during the several experimental conditions could be assessed by computing coefficients of correlation. The Pearson product-moment method was used for this purpose. Table 6 reports the results.

TABLE 6.—*Correlation Coefficients for Test-Retest Speech Discrimination Scores Obtained by Each of Three Groups When Listening to Speech in Quiet and in Competition of N.U. Test #20S and N.U. Test #20N as Reproduced by a High-Fidelity System and Three Different Makes of Hearing Aids*

Speech reproducing system	Quiet	N.U. Test #20S			N.U. Test #20N		
		MI	MD	Bin	MI	MD	Bin
Conductive group (N=9)							
High fidelity	.080	*.727	—.375	—.093	.466	.371	.598
Hearing aid A	.453	**.809	—.209	—.135	.474	.581	.207
Hearing aid B	.087	**.899	.623	*.772	**.818	.547	*.676
Hearing aid C	.380	*.728	.309	.640	**.877	.289	.588
Sensorineural group (N=12)							
High fidelity	**.936	**.774	**.976	**.951	**.786	**.891	**.900
Hearing aid A	**.953	**.784	**.901	**.884	**.900	*.658	*.690
Hearing aid B	**.926	**.798	**.804	**.898	**.848	**.759	**.867
Hearing aid C	**.858	**.846	**.932	**.922	*.692	*.655	**.718
Presbycusic group (N=12)							
High fidelity	**.865	**.916	**.940	**.918	**.885	**.978	**.914
Hearing aid A	**.917	**.863	**.723	**.831	**.824	**.741	**.776
Hearing aid B	**.908	**.961	**.945	**.949	**.928	**.900	**.842
Hearing aid C	**.874	**.901	**.902	**.855	**.844	**.877	**.894

MI=Monaural indirect MD=Monaural direct Bin=Binaural
* Significant at .05 level.
** Significant at .01 level.

Note that only a few of the coefficients obtained for the conductive loss group reach statistical significance and that these coefficients are clustered in more difficult listening conditions, i.e., either during monaural indirect listening or for reception via hearing aids B and C. This outcome is logical, since it was only when the task was sufficiently

taxing to produce an appreciable spread in the scores obtained by these subjects that systematical individual differences in scores were distinctive enough to manifest themselves through a high coefficient of correlation.

On the other hand, note the very high correlation coefficients derived for all conditions for the sensorineural and presbycusic groups. Speech discrimination ability as tested for these groups varied considerably among individuals and therefore a good range of scores was seen for all test conditions. With a reasonably large range of scores it is possible to achieve good correlation coefficients if measures of a given type of performance(s) or ability(s) are related. The correlation coefficients shown here for the test-retest sessions indicated that test-retest reliability was very good. In other words, scores achieved in the test session were quite closely repeated in the retest session so that individuals who obtained the better speech discrimination scores in the test session also achieved the better speech discrimination scores in the retest session. Correlation coefficients as seen here are highly encouraging in that they demonstrate that speech discrimination testing is reliable and further that speech discrimination scores achieved with speech reproduced by hearing aids also can be repeated closely. Moreover, even conductive loss cases showed these relations when the listening task was sufficiently difficult.

INFLUENCES OF DIFFERENT ELECTROACOUSTIC CHARACTERISTICS

Having demonstrated differences in the physical performance characteristics of the hearing aids used here, differences in speech discrimination scores achieved with these hearing aids, and good test reliability for these discrimination scores, it is now of interest to attempt to relate the physical performance characteristics to the speech discrimination scores. Remember that the best speech discrimination scores were obtained with hearing aid A, the poorest scores were achieved with hearing aid C, and scores of hearing aid B were intermediate. The question of interest now is which of the several physical performance characteristics these results parallel, since one may properly assume that the characteristics which did demonstrate such parallel were the electroacoustic features most intimately influencing discrimination as here explored.

The data reported in Figure 4 on the frequency responses of the instruments used in this experiment show hearing aid A to have the broadest response, with B having the intermediate, and C the narrowest band width. Thus, we see here a parallelism between greater width of frequency response and better discrimination.

With regard to harmonic distortion, hearing aid B produced the

least, while hearing aid A developed more distortion than hearing aid C (see Figure 5). This ordering of instruments does not match the hierarchy of performance established by the discrimination scores listeners achieved, and one must conclude that harmonic distortion was not the electroacoustic variable of maximal significance within the range of distortion characteristics encompassed by the investigation.

Similarly, the results of the intermodulation distortion measurements revealed no clear relation to the speech discrimination scores. With inputs of 900 and 1900 Hz, hearing aid A showed the least intermodulation distortion followed by hearing aid B and C in ordering from least to greatest intermodulation distortion, in other words the same order of best to poorest that was obtained in speech discrimination testing. However, for lower frequency inputs hearing aids A and B were essentially equal in intermodulation distortion, while for higher input frequencies hearing aid B generated more intermodulation distortion than did hearing aid C.

Thus, the only physical measurement which showed any wholly consistent relationship to speech discrimination performance for a given hearing aid was the width of the frequency response. This statement must be restricted, however, to the instruments studied here and to the performance characteristics achieved during the present study. Our experimental conditions were chosen to typify use settings and signal levels representative of everyday demands. Obviously, additional investigations employing different forms and balances of acoustic stimuli and looking into the question of weighing various characteristics of physical performance must be conducted before we have an overall picture of the correlation between details of electroacoustic performance and perception of speech in the relatively difficult listening situations often encountered by the hearing-aid user in everyday life.

It is clear, however, from our studies so far that hearing aids of different makes and models do present substantially different physical performance characteristics. The instruments employed in this experiment showed sharp differences in frequency response, harmonic distortion, and intermodulation distortion. Speech discrimination performance of hearing-impaired listeners with these instruments also revealed important differences between instruments. These differences were more apparent when speech had to be perceived in the presence of moderate competition than when heard during easier listening conditions. Finally, it must also be emphasized that with all combinations of electroacoustic performance, hearing-impaired listeners experienced considerably more difficulty in understanding speech in the face of other competing sounds than would have been predicted either from their own speech discrimination scores in quiet or from the speech

discrimination scores obtained by normal hearers in similarly difficult listening conditions. Realization of this last fact makes clear that hearing-impaired listeners are at a more serious disadvantage than generally realized in many everyday listening situations which are only slightly taxing for a normal hearer.

SUMMARY

Research conducted in our laboratory for the Veterans Administration has led to a better understanding of the difficulties encountered by monaural listeners due to the head shadow effect which occurs when competing sounds are present. Head shadowing reduces the level of the speech signal reaching the ear on the side away from the source (monaural indirect or far ear) by slightly more than 6 dB. When competing sounds are in the environment, the head shadow effects can cause a difference of as much as 13 dB between the signal-to-noise ratios existing at the near ear and at the far ear, respectively. This difference leads to much greater masking at the far ear than at the near ear. Binaural hearing offers an additional release from masking, over near ear efficiency, of approximately 3 dB. The most dramatic advantage of binaural hearing, however, is that it allows the listener to almost always have one ear favorably located with reference to the speech of interest to him. In other words, a binaural hearer does not encounter the disadvantages of monaural indirect listening wherein his head is shadowing him from the sounds he wishes to interpret.

Subsequent research demonstrated that head shadow influences continued when persons were wearing ear-level hearing aids. This research also indicated that the binaural advantage of about 3 dB over monaural direct listening persisted with hearing-aid use. Thus, head shadowing and the binaural squelch effect must be accepted as important phenomena during use of an ear-level hearing aid.

Our studies also demonstrated that there was sharp reduction in speech discrimination scores whenever monosyllables and competing background sound were amplified by a hearing aid. This finding led to comparison of performances with three pairs of over-the-ear hearing aids. Each pair of aids was closely matched, but each pair differed from the other pairs in physical performance characteristics. Tape recordings of speech in quiet and in competition, as amplified and reproduced by these hearing aids and by a system with good fidelity, were presented to three groups of hearing-impaired listeners. Test and retest sessions were completed. Test findings indicated that speech discrimination scores were essentially the same both in quiet and when competition was mild, for reproduction via the high-fidelity system as

for reproduction via the three hearing aids. In more difficult listening situations (i.e., where the speech of interest was only 6 dB stronger than the competition), however, the scores for the high-fidelity system were consistently best. Here, too, the scores obtained with hearing aids varied substantially from one type of instrument to the next. The width of the frequency response appeared to be the only physical characteristic among those we studied that was directly related to the discrimination scores achieved with a given instrument. Neither the degree of harmonic distortion nor of intermodulation distortion affected discrimination scores systematically. However, this statement must not be understood to apply to all types of hearing aids and to all listening tasks. Instead it must be restricted to the test conditions and hearing-aid characteristics encompassed in our studies.

Finally, our results indicate that hearing-impaired persons experience considerably more difficulty in understanding speech in the face of competition than generally has been realized. This statement holds true even when speech is made loud enough for them with a good fidelity system. The imperfections in reproduction introduced by hearing aids further complicate their listening task. This added disadvantage is particularly apparent for cases with sensorineural loss (including presbycusis) and it can reach dramatic proportions when substantial competition is imposed by background sounds.

REFERENCES

TILLMAN, T. W., R. N. KASTEN, and J. S. HORNER: Effect of Head Shadow on Reception of Speech. Asha, 5:778–779, 1963 (A).

SIVIAN, L. F. and S. O. WHITE: On Minimum Audible Sound Fields. J. Acoust. Soc. Am., 4:288–321, 1933.

WIENER, F. M. and D. A. ROSS: The Pressure Distribution in the Auditory Canal in a Progressive Sound Field. J. Acoust. Soc. Am., 18:401–408, 1946.

WIENER, F. M.: On the Diffraction of a Progressive Sound Wave by the Human Head. J. Acoust. Soc. Am., 19:143–146, 1947.

NORDLUND, B.: Physical Factors in Angular Localization. Acta Oto-Laryngol., 54:75–93, 1962.

SHAW, E. Q. G.: Earcanal Pressure Generated by a Free Sound Field. J. Acoust. Soc. Am., 39:465–470, 1966.

CARHART, R.: Monaural and Binaural Discrimination against Competing Sentences. International Audiology, 4:5–10, 1965.

TILLMAN, T. W. and R. CARHART: An Expanded Test for Speech Discrimination Utilizing CNC Monosyllabic Words (Northwestern University Auditory Test No. 6). Technical Report No. SAM–TR–66–55. USAF School of Aerospace Medicine, Aerospace Medical Division (AFSC), Brooks Air Force Base, Texas, 1966.

HARRIS, J. D.: Monaural and Binaural Speech Intelligibility and the Stereophonic Effect Based on Temporal Cues. Laryngoscope, 75:428–446, 1965.

NORDLUND, B. and B. FRITZELL: The Influence of Azimuth on Speech Signals. Acta Oto-Laryngol., 56:632–642, 1963.

TILLMAN, T. W. and R. CARHART: Effect of Competing Speech on Aided Discrimination of Monosyllabic Words. J. Acoust. Soc. Am., 35:1900, 1963, (A).
CARHART, R.: Speech Discrimination with a Hearing Aid in a Competing-Message Situation. Asha, 6:407, 1964, (A).
LYBARGER, S. F.: A New HAIC Standard. The Hearing Dealer, February 16, 1961.
BURNETT, E. D. and B. J. T. PRIESTLEY: NBS Report 8154: Hearing Aid Test Methods. National Bureau of Standards, Washington, D.C., 1964.