EFFECTS OF ELECTROACOUSTIC CHARACTERISTICS OF HEARING AIDS ON SPEECH UNDERSTANDING [a]

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INTRODUCTION

Research under this contract is broadly concerned with the relationship between the electroacoustic characteristics of hearing aids and their successful use by the hearing-impaired. We seek the elusive link between the physical and the behavioral: the extent to which differences in electroacoustic factors affect the listener's ability to understand speech through the aid.

The present report is specifically concerned with the relationship between speech understanding and the electroacoustic parameters of frequency response, effective bandwidth, and harmonic distortion in a sample of 21 commercially available hearing aids. The overall design was to obtain a representative sample of commercially available aids and derive measures of physical performance. Speech intelligibility test materials were then recorded through each aid and the resulting tapes used to test various groups of listeners. Detailed correlational analyses were carried out between behavioral test results and the various electroacoustic indices of hearing-aid performance. Subsequent sections describe, in detail, the sample of hearing aids, the procedures used to measure speech understanding, and correlations between electroacoustic measurements and psychoacoustic performance data for both normal and hearing-impaired listeners.

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HEARING AIDS

Our aim in the selection of hearing aids was to obtain a representative sampling of gain category, frequency response, and harmonic distortion. Accordingly physical data supplied to VA by the National Bureau of Standards (NBS) for (specific samples tested at Houston) all aids under VA contract in fiscal year 1966 were carefully studied. From this list 21 aids were selected as representative of the various continua that we sought to sample. Ten of the 21 aids were body-type, 10 were "over-the-ear" models, and one was mounted in an eyeglass frame. Other electroacoustic characteristics are detailed below.

Certain electroacoustic measures used in the present study are taken from data supplied to VA by NBS (Burnett & Priestley, 1964). Other measures were made in our own laboratory using standard instrumentation for the measurement of hearing-aid performance (hearing-aid test box, B & K type 4214; beat-frequency oscillator, B & K type 1014; microphone amplifier, B & K type 2602; audio-spectrum analyzer, B & K type 2109; harmonic wave analyzer, HP type 300 A).

Subsequent sections clearly indicate whether electroacoustic data under consideration were gathered by the National Bureau of Standards (NBS) or in our own laboratory (Houston Speech and Hearing Center).

Frequency response. The twenty-one frequency response curves are shown in Figure 1. These response curves were supplied by NBS. The aid number appears in the upper left-hand corner of each box. All types of frequency responses—flat and gradually sloping, extended and short frequency range, smooth and jagged—were represented in the sample.

Effective bandwidth. Two methods were used for abstracting the effective bandwidth from the frequency response curve, the United States of America Standards Institute (USASI) method (USASI, 1967) and our own method which will henceforth be denoted HSHC (Houston Speech and Hearing Center).

The procedure for the USASI method was to determine the average of the 500, 1000, and 2000 Hz values on the frequency response curve and draw a straight line, parallel to the frequency axis, 15 dB below the average value determined. The points at which the horizontal line intersected the response curve defined the effective bandwidth. In the Appendix, Table A, the bandwidths below 1000 Hz, above 1000 Hz, and the total bandwidth are shown for each of the 21 hearing aids.

With the HSHC method, bandwidth was determined by placing a line parallel to the frequency axis 10 dB below the highest point on the response curve. The distance between the points intersected on the response curve defined the total bandwidth. On three of the aids, bandwidth below 1000 Hz was a negative value because the lowest point intersected on the

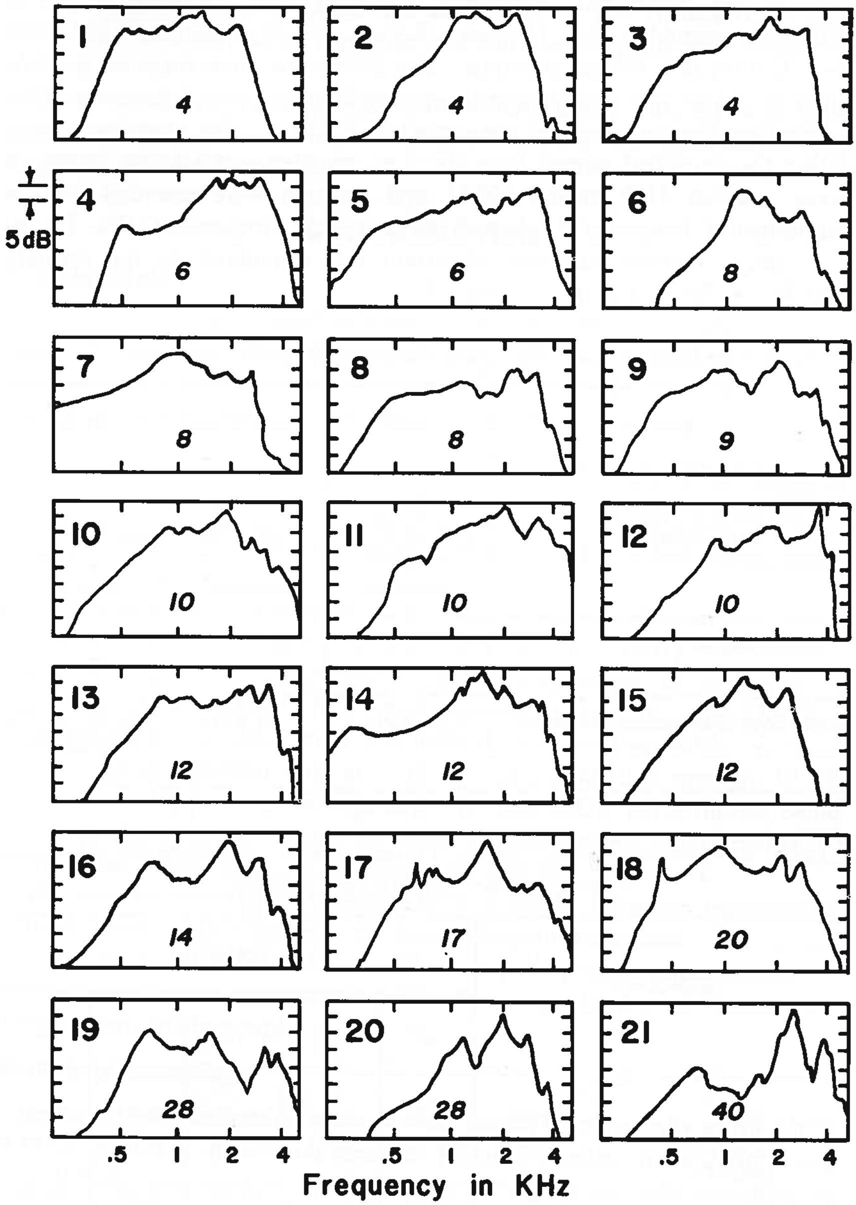

FIGURE 1.—Frequency Response Curves of the 21 experimental aids (data of NBS). Number under each curve is Index of Response Irregularity (IRI) score for that aid.

response curve was above 100 Hz. Appendix, Table B, summarizes measurements by this method.

Harmonic distortion. Harmonic distortion was measured by three different methods: the National Bureau of Standards (NBS), the S–3–X–48[b], and HSHC methods. The NBS data were supplied by VA. Data by latter two measurements were gathered in our laboratory. The procedures for each method are shown in Table 1. For each input condition the amplified output from the 2 cc. coupler was led to a harmonic wave analyzer (HP, model 300A) and voltages were recorded for the fundamental frequency (P_1) and all harmonic frequencies (P_2, P_3, P_4 . . . etc.). Percent harmonic distortion was calculated by the formula $100(P_2^2 + P_3^2 + P_4^2 + \ldots / P_1^2)^{1/2}$.

TABLE 1.—*Procedures for Measuring Harmonic Distortion by Various Methods*

Item	NBS	S–3–X–48	HSHC
To set gain			
Input signal frequency	1000 Hz	700 Hz	1000 Hz
Input signal level	62.5 dB SPL	75 dB SPL	60 dB SPL
Gain set to	< 10% total distortion	10 dB below saturation	10 dB below saturation
Test frequencies	500, 700, 900 Hz	500, 700, 900 Hz	500, 700, 900 Hz
Input level of frequency under test	75 dB SPL	75 db SPL	60, 65, 70, 75, 80 dB SPL

TABLE 2.—*Intercorrelations Among Various Indices of Harmonic Distortion (Averaged Over 500, 700, and 900 Hz)*

	S–3–X–48	HSHC				
		60	65	70	75	80
NBS	0.30	0.25	0.56	0.45	0.36	0.27
S–3–X–48	—	0.61	0.65	0.66	0.64	0.61
HSHC						
60	—	—	0.72	0.62	0.42	0.36
65	—	—	—	0.91	0.69	0.57
70	—	—	—	—	0.90	0.80
75	—	—	—	—	—	0.96

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[b] Tentative procedure developed by exploratory group S–3–X–48, USASI Methods of Measuring and Expressing Hearing Aid Distortion, S. F. Lybarger, Chairman.

The measurements obtained are contained in the Appendix, Tables C–I. The intercorrelations among the various methods are shown in Table 2.

Other Measures. Data for gain, maximum power out, signal-to-noise ratio and signal-to-hum ratio obtained from NBS are contained in the Appendix, Tables J and K.

BEHAVIORAL TESTS

Test Materials

In designing a behavioral task for measuring speech understanding, we placed primary emphasis upon three factors. First, we wanted the listening situation to be similar to one encountered in everyday life. Second, we wanted conditions which created difficulty for the hearing-aid user. Third, we felt it desirable to have a machine-scored task.

The use of synthetic sentence identification (SSI) (Speaks and Jerger, 1965) provided a reasonable solution to the problem. The synthetic sentence is an approximation to a real English sentence. It has a linguistic pattern but little meaning.

The message set we selected had already been developed and tested in our laboratories. Speaks, Karmen, and Benitez (1967) had demonstrated how sentence identification performance varied as functions of both sound pressure level (SPL) and message-competition ratio (MCR). Since we wanted a task which was difficult, but not impossible, we fixed the message-competition ratio at −12 dB (i.e., competing message 12 dB higher than the primary message set). At this MCR performance could be varied from approximately 10 to 95 percent correct identification by varying the overall level of the combined signal.

The primary message set consisted of 10 synthetic sentences representing a third order approximation to actual English sentences. The actual message set is listed in Table 3. The competing message, a passage of continuous discourse concerned with the early history of Texas, was recorded on another tape.

Method of Recording

Sentences and competing message were mixed electronically at an MCR of −12 dB in a speech audiometer (Grason-Stadler, model 162) and recorded through each of the 21 experimental hearing aids according to a procedure illustrated in Figure 2. The exact procedure was as follows:

1. The aid was positioned in a hearing-aid test box (B & K, model 4214).
2. A 1000 Hz tone was introduced into the test chamber at an SPL of 60 dB.
3. The gain control of the aid was adjusted to a level 10 dB below the maximum output of the aid at 1000 Hz.

TABLE 3.—*Closed Message Set Containing Ten Alternative Synthetic Sentences Constructed as Third-Order Approximations to Real English Sentences*

Alternative sentences
1. SMALL BOAT WITH A P'CTURE HAS BECOME
2. BUILT THE GOVERNMENT WITH THE FORCE ALMOST
3. GO CHANGE YOUR CAR COLOR IS RED
4. FORWARD MARCH SAID THE BOY HAD A
5. MARCH AROUND WITHOUT A CARE IN YOUR
6. THAT NEIGHBOR WHO SAID BUSINESS IS BETTER
7. BATTLE CRY AND BE BETTER THAN EVER
8. DOWN BY THE TIME IS REAL ENOUGH
9. AGREE WITH HIM ONLY TO FIND OUT
10. WOMEN VIEW MEN WITH GREEN PAPER SHOULD

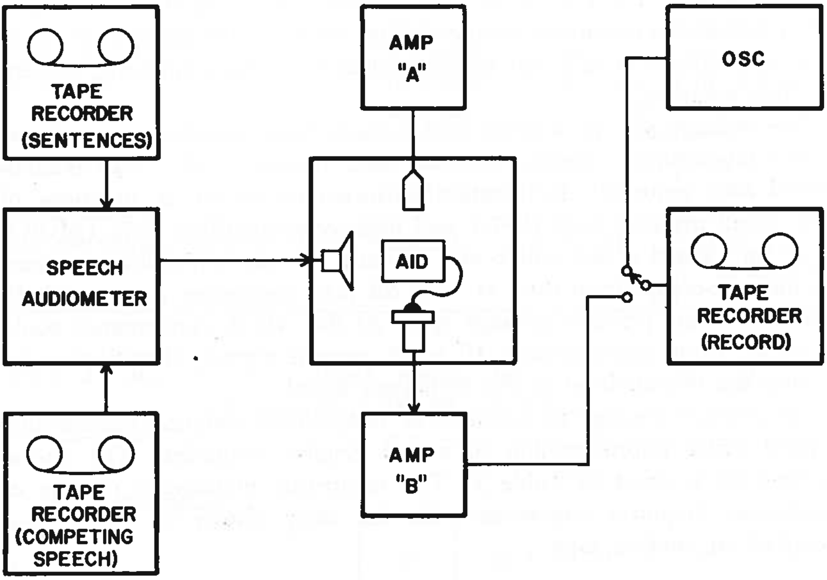

FIGURE 2.—Instrumentation for recording SSI materials through each hearing aid. Sentences and competing speech are mixed in speech audiometer at an MCR of −12 dB and fed to hearing-aid test box. Amplifier "A" reads input SPL to aid. Amplifier "B" reads output SPL in 2 cc. coupler. Calibration tone is dubbed onto tape after speech has been recorded through the aid.

4. The 1000 Hz tone was replaced by the output of the speech audiometer.
5. The input level of the speech to the hearing aid test chamber was adjusted for an average input level of 75 dB SPL.

6. The output from the hearing aid was fed through a 2 cc. coupler and appropriate amplification to a third tape recorder (Magnecord, model 728–44) in the record mode.
7. After speech materials had thus been recorded through the aid, a 1000 Hz calibrating tone was dubbed onto the tape at the average level of frequent peaks of the recorded speech.

It is important to note that the calibrating tone itself was not recorded through the hearing aid. Such a procedure would have introduced a biasing effect depending upon the frequency response characteristics of each aid. In the procedure we used, the calibrating tone reflected the average level of frequent peaks after transduction by the hearing aid.

Test Procedure

Each subject was seated in a sound-treated booth before a response panel. On the response panel was placed a card with the ten synthetic sentences and a push button corresponding to each sentence. The subject heard the sentence materials monaurally through earphones. A light at the top of the panel indicated the presence of a sentence embedded in the continuous competing message. Upon completion of the sentence, a respond light was turned on for the duration of the response interval. Both "listen" and "respond" intervals were 5 seconds in duration.

The subject was instructed to watch the listen light, and then, when the respond light came on, press the button corresponding to the sentence heard. If the subject was not certain which sentence he heard, he was instructed to make the best possible selection.

System instrumentation is shown in Figure 3. The tape for a particular aid was placed on the playback tape recorder (Magnecord model 728–44). Sentence materials were channeled through a speech audiometer (Grason-Stadler, model 162) to the subject's earphone (Telephonic, model TDH–39).

EXPERIMENT I

The purpose of this experiment was to explore the relationship between physical characteristics and behavioral test results in normal listeners.

Subjects

Five subjects with normal hearing served in this phase. Three were female and two were male. Their ages ranged from 19 to 30 years, with a mean age of 24 years.

Procedure

During an initial practice period subjects heard the test tapes at intensity levels high enough to permit nearly perfect sentence identification.

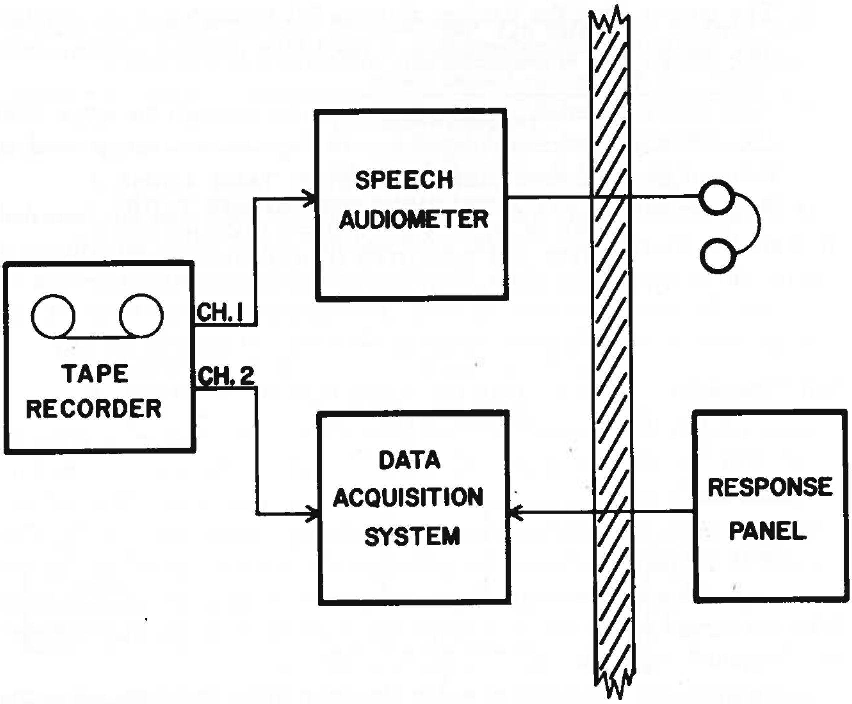

FIGURE 3.—Instrumentation for administering SSI test procedure to each subject. Previously recorded sentences mixed with competing speech (channel 1) are played through speech audiometer to subject's earphone. Pulses coding correct answer (channel 2) program data acquisition system to accept only correct button pushes from subject's response panel.

Then the speech level was varied until approximatly 75 percent correct performance was achieved. This level varied slightly among subjects. For any given subject it was held constant in all subsequent testing. The practice period was not rigidly defined, but most subjects were at ease with the task after about 100 identifications.

Each subject was now tested on each of the 21 experimental tapes. The previously determined intensity level was held constant, tapes were presented in a random order, and the final score for each tape was based on 10 blocks of the 10-item message set or a total of 100 identifications.

Results

Synthetic sentence identification (SSI) scores, averaged across the five subjects, are detailed in the Appendix, Table L. For each aid, scores are shown cumulatively over successive 10-item test blocks. We can observe that the SSI procedure did yield significant differences among aids. Scores ranged from 64.8 percent for aid #21 to 82.4 percent for aid #2. The average score for all aids was 75.3 percent.

Our next step was a systematic correlational analysis (product-moment coefficient) between the SSI scores and various physical measures. This procedure necessarily involved comparisons among pairs of variables differing in respect to the expected sign of the correlations. Bandwidth, for example, would be expected to show positive correlation with SSI. As bandwidth increases we would expect SSI to increase. On the other hand a variable such as percent harmonic distortion would be expected to show an intrinsically negative correlation with SSI. As distortion increases we would expect SSI to decrease. In the present data, however, we found several correlations in which direction did not conform to expectation. Occasionally a negative sign appeared where a positive sign was expected, and vice versa. In order to avoid confusion on this point, we have adopted the convention that a positive sign on the coefficient of correlation means that the relationship was in the direction conforming to expectation, and a negative sign means that the relationship was opposite to expectation. For our purposes expectation is defined to mean simply that we expect any departure from an ideal speech amplifier to have an adverse effect on speech understanding. We would expect, for example, that as harmonic distortion increased, SSI would decrease, and would assign a positive sign to such a relationship. Throughout the remainder of this report, then, a negative sign before a coefficient of correlation should be interpreted to mean that the observed relationship was contrary to expectation irrespective of the direction in which the respective numbers actually change.

We turned first to measures of effective bandwidth. Table 4 details these correlations. Here we note an extraordinarily interesting result. By both USASI and HSHC methods the correlation of SSI with bandwidth above 1000 Hz is negative. This was a quite unexpected finding. It implies that high frequency response was actually detrimental to SSI performance. However, correlations with bandwidth below 1000 Hz are positive, being stronger by the HSHC method than USASI.

TABLE 4.—*Correlations of SSI Scores with USASI and HSHC Measures of Effective Bandwidth*

	Below 1000 Hz	Above 1000 Hz	Total
USASI	0.15	−0.58	−0.57
HSHC	0.57	−0.49	−0.09

These results are understandable when one considers that the frequency region important for SSI performance is well below 1000 Hz (Speaks, 1967).

The traditional use of monosyllabic word (PB) materials in speech intelligibility testing has conditioned us to attach considerable weight to high frequency response as a significant factor in speech understanding through hearing aids. Such a relationship is entirely predictable when one considers the critical role of frequencies above 1000 Hz in the intelligibility of monosyllabic words (French and Steinberg, 1947).

It does not follow, however, that other speech intelligibility measures will necessarily show the same dependence on high-frequency response. Indeed the results detailed in Table 4 suggest that, for the SSI task, response below 1000 Hz is the more critical range. Speaks (1967) has shown, for example, that, in the sentence identification task, high-pass and low-pass filtering functions intersect at about 725 Hz. The analogous frequency for monosyllabic words (French and Steinberg, 1947) is 1900 Hz.

It is not surprising, therefore, that Table 4 shows positive correlations between SSI and bandwidth below 1000 Hz. Since the SSI task is heavily loaded with low-frequency information it follows that aids with good low-frequency response will perform better on SSI than aids with relatively poorer low-frequency response.

It is also understandable that the correlation should be higher by the HSHC method than by the USASI method since the former gives a more stringent definition of bandwidth than the latter. We may note in the Appendix, Table A, for example, that by the USASI method, bandwidth below 1000 Hz ranged from +510 to +900 Hz, whereas by the HSHC method the range was considerably greater: from −1050 to +595. These data suggest that the USASI method for expressing effective bandwidth might serve as a more realistic index of hearing-aid performance if the horizontal axis were dropped 10 dB or perhaps only 5 dB below the average response for 500, 1000, and 2000 Hz, rather than the present 15 dB. Interestingly enough the Northwestern group, although using speech materials different from ours, confirm the critical importance of bandwidth (Progress Report X, p. 121).

Somewhat more difficult to explain are the negative correlations with bandwidth above 1000 Hz. If it were simply a question of high frequencies being less important to SSI than to PB words, then we might reasonably expect low or zero correlations. But there must be an additional factor in operation to produce a negative correlation. A possible clue to the source of this factor lies in our next analysis.

Cursory examination of the 21 frequency response curves in relation to SSI scores for each aid suggested a fairly strong correlation between speech understanding and a factor that can best be described as "irregularity" of frequency response. We noted that the best aids in terms of SSI were also the aids with the smoothest frequency response by visual inspection. Conversely the poorest aids by SSI invariably showed extremely jagged and irregular response curves.

This jaggedness, or irregularity factor, has been previously considered by VA. It is presently expressed by the index known as "uniformity of slope." And, indeed, this uniformity-of-slope index showed a correlation of 0.38 with SSI.

Our visual inspection convinced us, however, that a far stronger relationship existed. Further scrutiny suggested that the VA uniformity-of-slope index was not sufficiently sensitive to response irregularity because of the manner in which it is defined. Deviations from uniform slope are determined only at fixed predetermined discrete frequencies. In consequence major irregularities that may occur between the discrete points of measurement are lost.

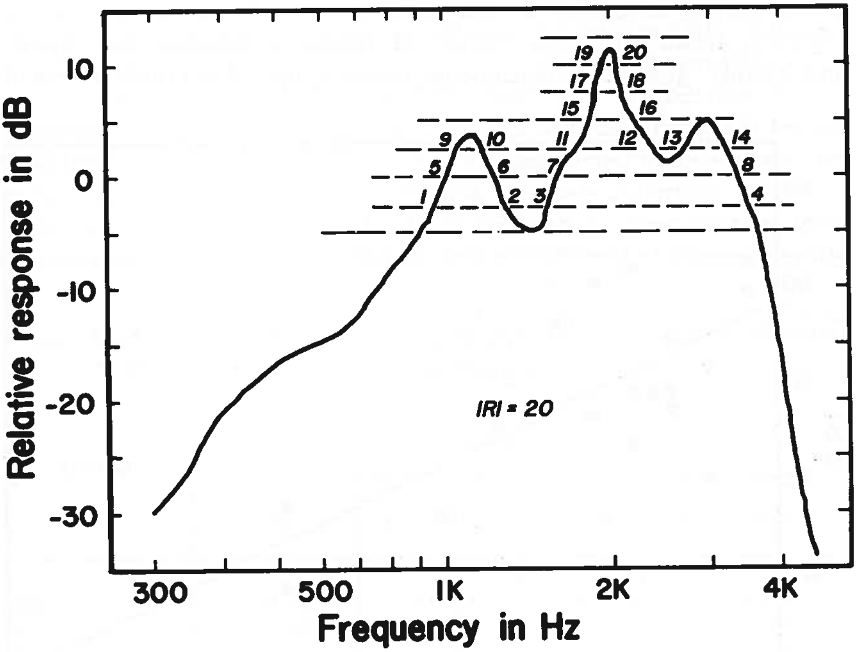

FIGURE 4.—Method for calculating Index of Response Irregularity (IRI). A reference line is drawn parallel to the horizontal axis at the level of the lowest point between the curve boundaries. Additional horizontal lines are positioned at 2.5 dB intervals above the reference line. The number of times that the frequency rsponse curve intersects this grid is counted. The total count is the IRI.

We set out, therefore, to devise a new index of response irregularity (IRI) that would take into account departure from uniformity at any point on the response curve. The procedure for obtaining an IRI value for a hearing aid was as follows (see Fig. 4):

1. a reference line was drawn parallel to the frequency axis at the lowest reversal of the response curve of more than 2.5 dB, 2. parallel lines were drawn at 2.5 dB intervals above this reference, 3. the number of crossings of the response curve lines above the reference were then counted. The hearing aid in Figure 4 has an IRI value of 20. The number located inside each of the frequency response curves in Figure 1, is the IRI value for that aid.

The correlation between SSI and the new IRI score was 0.80. The actual scatter diagram is shown in Figure 5.

We regard this as a very significant result. It suggests that one of the most important electroacoustic characteristics of a hearing aid is simply the relative smoothness of the frequency response.

At first glance this result would appear to be in striking contradiction to the earlier conclusion of Harris et al. (1961) who found only a negligible relation between flatness of frequency response and speech intelligibility. It must be remembered, however, that of the three indices of

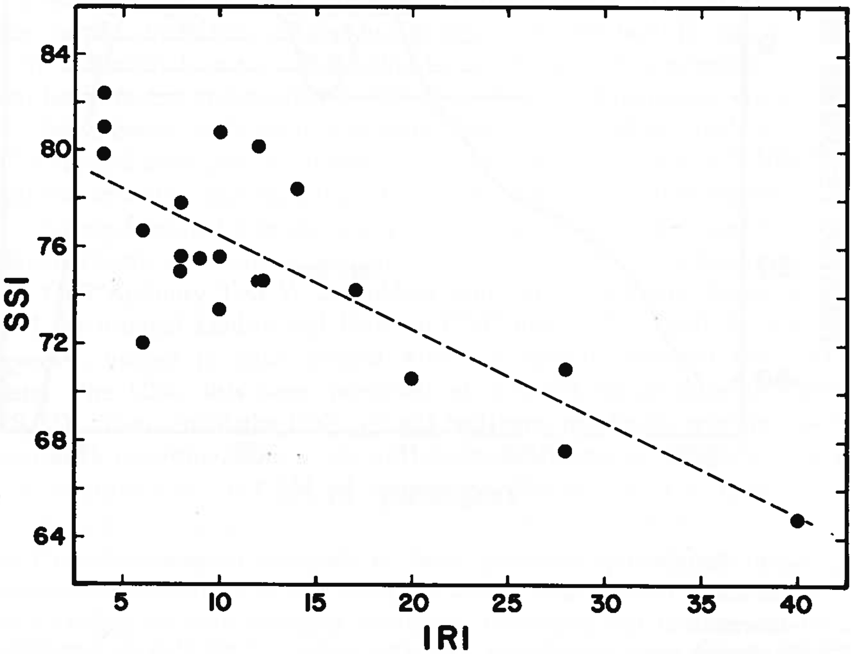

Figure 5.—Scattergram relating SSI and IRI scores for the 21 aids.

frequency response flatness employed by Harris et al., two were based on the VA method, thereby suffering the disadvantage of discrete frequency analysis. The third was essentially an area measure, presumably relatively insensitive to irregularity of the area boundary.

The principal difference between IRI and previously devised indices is that it is concerned solely with irregularity and does not concern itself directly with uniformity of slope.

Correlation of IRI with effective bandwidth above 1000 Hz (HSHC method) yielded an r of −0.28. In other words the aids with the broadest high-frequency response also showed a moderate tendency to be the aids with the most irregularity in their response curves. Here we see a possible clue to the unexpected negative correlations between SSI and bandwidth above 1000 Hz (Table 4). We suggest that high-frequency response correlated negatively with SSI because the aids with best high-frequency response tended to fairly irregular response curves. The high-frequency response did not help SSI but the high IRI value hurt it.

Continuing our correlational analysis we turned next to measures of harmonic distortion. Table 5 summarizes correlation coefficients between SSI and harmonic distortion at each of three frequencies (500, 700, and 900 Hz) and the distortion averaged across all three frequencies. The most alarming finding in this table is that with only one exception every coefficient is negative. In other words the aids with least distortion tended to be the aids with poorest SSI scores. This unexpected result was true no matter what method was used to express harmonic distortion.

On first inspection this result seems to stand in contradiction to a considerable body of previous research on the relationship between hearing-

TABLE 5.—*Correlation of Sentence Identification Score (SSI) with Harmonic Distortion According to Various Methods of Measurements*[a]

Method	Frequency in Hz			
	500	700	900	Avg.
NBS	−0.32	−0.33	−0.08	−0.30
S-3-X-48	−0.32	−0.44	−0.40	−0.43
HSHC 60	0.08	−0.07	−0.21	−0.04
65	−0.31	−0.36	−0.08	−0.36
70	−0.48	−0.31	−0.17	−0.40
75	−0.54	−0.33	−0.27	−0.46
80	−0.47	−0.31	−0.23	−0.45

[a] Negative sign indicates that harmonic distortion increased as SSI score increased.

aid performance and harmonic distortion. Investigators both in this laboratory (Jerger et al., 1966), in the Washington, D.C., group (Kasten et al., 1967), and others (Harris et al., 1961) have previously noted a positive rather than negative relation between speech intelligibility and harmonic distortion. It must be recalled however, that in each of these studies, harmonic distortion was deliberately manipulated over an unusually large range in order to create artifically difficult listening conditions.

In the present study, however, harmonic distortion was measured under comparable circumstances for all aids. The aim was to obtain a representative sampling of the variation in harmonic distortion when a large group of aids is subjected to the same input signals, and the gain is set by a common rule. In other words we sought only to sample the actual or real-life harmonic distortion likely to be encountered by the hearing-aid user.

When variation in harmonic distortion is bounded by such limits it would appear that this parameter of electroacoustic performance is not a significant source of degradation in speech understanding in the typical modern hearing aid. In the present sample average distortion at 500, 700, and 900 Hz ranged from 1.3 percent to 36 percent in the NBS data (Appendix, Table C), and from 8.15 percent to 69.36 percent by the HSHC method for 80 dB input (Appendix, Table I). Yet we observed no significant positive relation between harmonic distortion and SSI. Indeed the general trend of the relationship is distinctly negative. Interestingly enough a similar conclusion was reached by the Northwestern group in its Progress Report X (p. 76) for nonlinear distortion by the Burnett method.

Summary

Synthetic Sentence Identification (SSI) test materials were recorded through each of 21 commercially-available aids on VA contract for fiscal year 1966. The 21 tapes were then played to five normal listeners at a level yielding approximately 75 percent correct performance. For any given subject playback level was constant for all tapes.

SSI results were then correlated with various electroacoustic measures of hearing-aid performance. Results may be summarized as follows:

1. The physical measure yielding the highest correlation with SSI ($r = 0.80$) was a newly devised index of frequency response irregularity (IRI). This index is roughly proportional to the jaggedness or overall departure from smooth uniform slope in the frequency response.
2. The physical measure yielding the next highest correlation with SSI ($r = 0.57$) was the effective bandwidth below 1000 Hz, when bandwidth was defined in fairly stringent fashion.
3. Correlations of SSI with various measures of harmonic distortion failed to implicate the latter as a significant source of degradation in speech

understanding in modern hearing aids. Obtained correlations were, in fact, negative, indicating that SSI scores tended to be somewhat better in aids with greatest distortion.

EXPERIMENT II

Experiment I explored the relationship between behavioral and physical results in normal-hearing listeners. The purpose of Experiment II was to extend the same overall design to hearing-impaired listeners.

Subjects

In this phase the experimental group consisted of 10 subjects with essentially symmetrical sensorineural hearing loss. They were chosen to represent a typical cross section of hearing-aid users. Table 6 summarizes age and sex distributions, average sensitivity loss on the better ear (PTA), and slope of audiometric contour of these 10 subjects. For control purposes six fresh normal subjects were run under the same procedure used with the hearing-impaired subjects. They were all female and ranged in age from 16 to 50 years. The median age was 20 years.

Procedure

Testing procedure in Experiment II was identical to that of Experiment I with two exceptions. First, the number of 10-item test blocks per hearing aid was reduced from 10 to 3 so that each subject's score for a given aid was based on his response to 30 items rather than the 100 items employed in Experiment I. The 100-item test procedure was deemed desirable in

TABLE 6—*Description of Hearing-Impaired Subjects in Experiment II*

Age	Sex	PTA[a]	Slope of audiometric contour
78	M	47	Steep
66	M	12	Steep
47	M	27	Steep
80	F	62	Gradual
63	M	32	Gradual
37	F	35	Gradual
36	F	47	Gradual
65	M	45	Flat
36	F	38	Flat
29	F	45	Flat

[a] Average loss at 500, 1000, and 2000 Hz in test ear (ISO–64).

Experiment I in order to assure completely stable final percentages. Block-by-block analysis of these results suggested, however, that the score based on the first 30 items correlated well with the score based on the entire 100-item procedure ($r = 0.88$), and could be effectively substituted with considerable saving in experimental time.

The second procedural change was the incorporation of instrumentation for measuring the latency of each behavioral response. This was achieved by letting the first code pulse for each sentence initiate an interval timer set to time intervals of 0.2 second repetitively until inhibited by the subject's button push. The number of 0.2 second intervals which elapsed between onset of the sentence and button push was counted automatically on a mechanical counter. A light of 8 seconds defined both listen and respond intervals. The subject could press as soon as he knew which sentence he had heard. In this way response latencies to all responses made while listening to a particular aid were cumulated. Correct response latencies were tabulated separately from incorrect response latencies for later analysis. Subjects were not informed that response latencies were being measured. They were instructed exactly as in Experiment I to listen for the sentence, find it on the response panel, and press the appropriate button. It was presumed, therefore, that the incorporation of the circuitry for measuring response latency had no biasing effect on the percent correct response measures.

In all other respects the testing procedure for Experiment II followed exactly the procedure used in Experiment I. Each subject heard the 21 tapes in a unique random order and at a constant playback level as in Experiment I. This level was chosen on the basis of an initial practice period in which the level producing approximately 75 percent correct performance was sought. Some hearing-loss subjects could not reach the 75 percent criterion at any level tested. For these subjects the level yielding optimal performance was chosen. For all hearing-impaired subjects the test ear was always the better ear.

Results

Table 7 summarizes average SSI results in Experiment II. Previous data on the five normal listeners in Experiment I are included for comparison. We may note that, in comparison with the results of Experiment I, the six normals in Experiment II showed a somewhat lower average score (65.3 percent versus 75.3 percent) and a broader range (25.6 percent versus 17.6 percent).

The correlation between scores on individual aids for the two groups was 0.75, indicating that, in spite of the reduction in test length, aids retained their rank orders fairly well in the two normal groups.

The 10 hearing-impaired subjects of Experiment II have been divided into three groups according to audiometric configuration. Three subjects

TABLE 7.—*Summary of SSI Results in Experiments I and II, Averaged Across All Aids*

	Experiment I	Experiment II			
	Normal	Normal	Flat	Gradual	Steep
Average percent correct	75.3	65.3	49.3	60.8	48.7
Range	17.6	25.6	36.6	25.0	21.1

had flat losses, four had gradual slopes, and three had fairly steep slopes. This categorization was based on the difference between audiometric thresholds at 500 and 4000 Hz on the test ear. For the flat group this difference averaged 3.3 dB. For the gradual group the average slope was 20.0 dB, and for the steep group 38.3 dB.

The SSI score averaged across all aids varied from 49.3 percent in the flat group, to 60.8 percent in the gradual group, and 48.7 percent in the steep group. Interestingly the range across subjects systematically decreased from 36.6 percent for the flat group to only 21.1 percent for the steep group.

Our principal purpose, in Experiment II, was to explore the extent to which differences in hearing aids, as reflected in the SSI scores of normal subjects, can be generalized to the hearing-impaired. The principal finding was that the degree of correspondence depended critically on the slope of the audiometric contour. Subjects with flat losses yielded results in good agreement with normals, but as the audiometric slope changed from gradual to steep, the correlation with the performance of normals became progressively weaker.

Table 8 summarizes intercorrelations of SSI scores on individual hearing aids among the four groups of Experiment II. When subjects with flat losses are compared with normals the correlation is quite good ($r = 0.77$) indicating that subjects with flat losses rank ordered the 21 aids in much the same fashion as the normal group. However, when subjects with gradual slopes are compared to normals the correlation drops to 0.60, and when subjects with steep slopes are compared to normals the correlation drops further to 0.28. The other intercorrelations confirm this pattern of decreasing correlation with increasing slope.

The significance of this finding is that one cannot generalize from behavioral results on normals to behavioral results on all hearing-impaired

TABLE 8.—*Correlations of SSI Scores Among Various Groups Within Experiment II*

	Slope		
	Flat	Gradual	Steep
Normal	0.77	0.60	0.28
Flat	—	0.39	0.01
Gradual	—	—	0.65

subjects. The extent to which generalization is warranted depends on the slope of the audiometric contour. Subjects with flat losses can be expected to rank aids about the same as normals, but subjects with steeply sloping losses cannot be expected to show the same rank ordering.

There are at least two possible explanations for this important finding. One is that there are aspects of the physical performance of hearing aids that are important to individuals with steeply sloping audiometric contours but not important to either normals or individuals with flat losses.

If this explanation were true we should expect at least some indices of physical performance to correlate strongly with SSI in the steep group, but not in the normal or flat groups. In other words, the steep group should rank order the aids according to some critical physical dimension that is not important to either the normal or the flat group.

A converse possibility is that steeply sloping hearing loss imposes a limitation on the extent to which the individual can benefit from subtle differences in the physical performance of hearing aids.

If this explanation were true we should expect at least some indices of physical performance to correlate well with SSI in the normal and flat groups, but not in the steep group. In other words, any relation between behavioral and physical performance should become progressively attenuated as the audiometric slope changes from flat to gradual to steep.

The present data favor the latter explanation. We find meaningful relations between SSI and physical performance data in the normal and flat groups, but we have been unable to identify in any aspect of physical performance hearing even a moderate correlation with SSI in the steep group.

Table 9 summarizes correlations between SSI and the three physical measures identified as important to normal listeners in Experiment I (IRI, bandwidth below 1000 Hz, and bandwidth above 1000 Hz). In the normal group we note results similar to those obtained earlier. The correlation with IRI is 0.73, with low-frequency bandwidth, 0.51, and with high-frequency bandwidth, −0.29.

TABLE 9.—*Correlation of IRI and Bandwidth Measures With SSI Scores for Normal and Hearing-Impaired Subjects*

	Normal	Hearing-impaired		
		Flat	Gradual	Steep
IRI	0.73	0.60	0.39	0.23
Bandwidth below 1000 Hz	0.51	0.51	0.16	−0.10
Bandwidth above 1000 Hz	−0.29	−0.28	−0.15	0.01

As we move horizontally across each row from flat to gradual to steep we note a systematic reduction in the strength of the relationship between SSI and each of the three measures. The correlation with IRI declines from 0.73 to 0.23. The correlation with bandwidth below 1000 Hz drops from 0.51 to −0.10, and the correlation with bandwidth above 1000 Hz drops from −0.29 to 0.01.

Further extensive correlational analysis failed to uncover any other aspect of physical performance that yielded a significant correlation with SSI in the steep group.

We conclude, therefore, that there are physical indices of hearing-aid performance that relate strongly to behavioral results, namely response irregularity (IRI) and effective bandwidth, but that the relationships are most important for normal listeners and least important for hearing-impaired patients with steeply sloping losses.

In particular, we were unable to find any index of physical performance relating to frequency response or harmonic distortion that showed even a weak correlation with behavioral data in the steep group.

As noted earlier an additional feature of Experiment II was the measurement of response latency. By averaging the latencies of all responses by all subjects for each aid, we obtained a single average response latency for each of the 21 aids. In the normal group the correlation between this response latency and SSI was 0.85. For the total group of hearing-impaired subjects the correlation was 0.74. Both correlations are strong and indicate that response latency is closely related to successful behavioral performance. As the SSI score decreased, average latency increased in reasonably systematic fashion.

Summary

Extension of the procedure used in Experiment I to six normal and 10 hearing-impaired subjects revealed that:

1. The test procedure could be reduced from 100 items to 30 items without appreciable effects on hearing-aid rank order in normals.
2. Audiometric contour had a profound effect on the relationship between physical and behavioral results. As slope became steeper correlations between SSI, IRI, and effective bandwidth became progressively weaker.
3. Efforts to find meaningful physical correlates of behavioral performance in the group with steeply sloping loss were unsuccessful.
4. Total average response latency to SSI materials correlated strongly with actual percent correct scores.

EXPERIMENT III

The purpose of this experiment was to construct psychometric functions for SSI in order to explore hearing-aid performance at varying levels of difficulty. Accordingly five aids were selected from the original pool of 21 for intensive study. They were chosen on the basis of the SSI score obtained in Experiment I in order to represent points along the continuum from best to worst performance. Original SSI scores ranged from 82.4 percent for aid 2 to 64.8 percent for aid 21. SSI scores and corresponding IRI values for each of the five aids chosen are shown in the first two columns of Table 10.

TABLE 10.—*Relations Among IRI Scores, SSI Scores, and Latency Measures in Experiments I and III (Rank Order of Each Score is Indicated in Parentheses)*

Aid no.	IRI	Exper. I	Experiment III			Average latency [d]		
		SSI	SSI [a]	Latency-level [b]	Latency-percent [c]	Correct	Incorrect	Total
1	4 (1.5)	79.8 (2)	56.2 (1.5)	4.82 (1)	4.64 (1)	4.24 (2)	5.70 (2)	4.85 (2)
2	4 (1.5)	82.4 (1)	56.2 (1.5)	4.84 (2)	4.68 (2)	4.19 (1)	5.62 (1)	4.80 (1)
2	10 (3)	73.4 (3)	50.7 (3)	4.97 (3)	4.82 (4)	4.42 (4)	5.78 (3)	4.98 3)
19	28 (4)	67.6 (4)	42.0 (4)	5.15 (4)	4.73 (3)	4.41 (3)	5.84 (5)	5.03 (4)
21	40 (5)	64.8 (5)	40.0 (5)	5.22 (5)	4.86 (5)	4.47 (5)	5.83 (4)	5.15 (5)

[a] Measurements in percent correct based upon speech level of 35 dB.

[b] Total average latency in seconds plotted as a function of level; measured at 35 dB.

[c] Total average latency in seconds plotted as a function of percent correct; measured at 75 percent correct.

[d] Average latencies in seconds for correct, incorrect, and total responses for a given aid.

Subjects

Ten new subjects with normal hearing served in this phase. Six were male and four were female. Ages ranged from 16 to 36 years with a mean age of 24 years.

Procedure

Subject instructions and practice sessions were identical to those employed in Experiments I and II. In the present experimental procedure, however, the speech level was varied for each aid in order to define responses over the range from 10 percent to 100 percent. Each datum point was based on a total of 20 identifications and complete functions usually required 6–8 points for adequate definition. Response latency data were also collected in the same manner as Experiment II.

Results

Figure 6 shows complete performance-intensity (PI) functions for the five aids studied. Least squares straight lines have been fitted to the actual

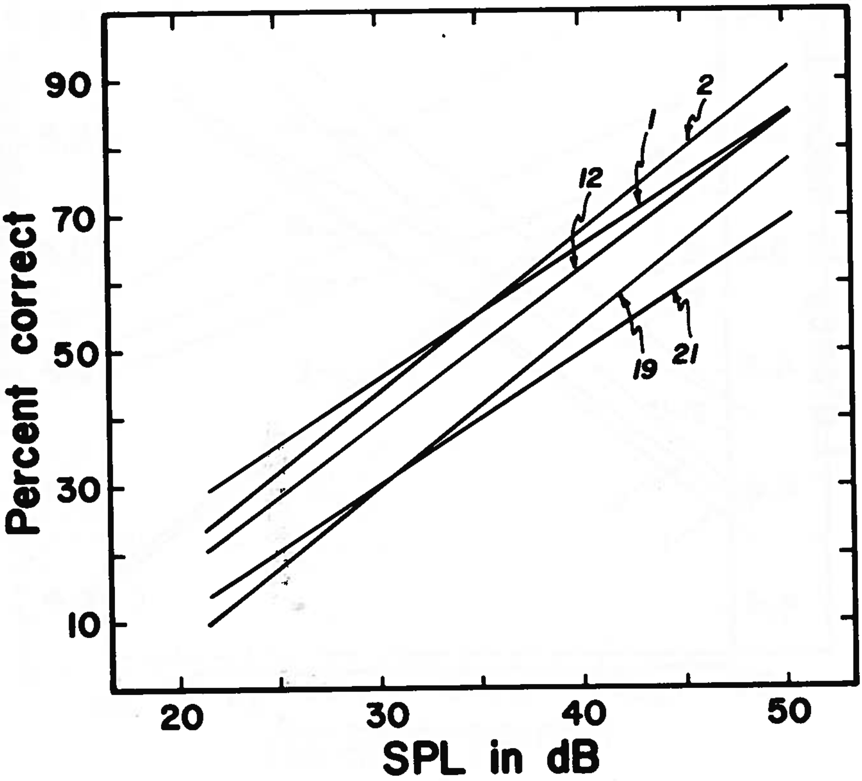

Figure 6.—SSI score as a function of speech level for five selected aids.

data points in order to clarify the relations among aids. We note that aids 1 and 2 perform best, aid 12 is intermediate, and aids 19 and 21 perform worst. In addition, there is no significant variation in slope from best aid to worst aid. Results are consistent with expectation from the findings in Experiment I. They illustrate the further point, however, that aids may be rank-ordered in two dimensions: either by contrasting the SSI score at a fixed speech level, or by contrasting speech levels necessary to achieve a constant SSI score. Figure 6 shows that, by either criterion, rank orders are fairly constant no matter what the level of difficulty of the task. There is, in other words, no critical performance level at which differences among aids are maximized or minimized.

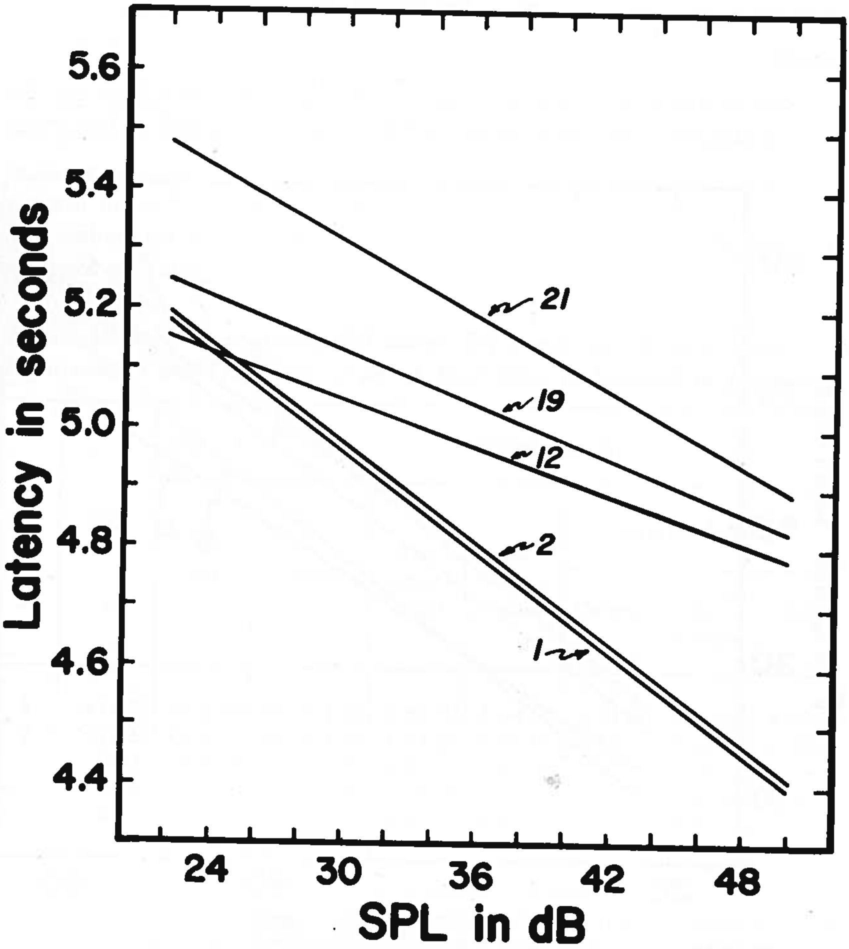

FIGURE 7.—Response latency as a function of speech level for five selected aids.

In this experiment response latencies could be analyzed according to three dimensions: speech level, percent correct, and correct versus incorrect answers.

Figure 7 shows latency as a function of speech level for each of the five aids. Latencies of both correct and incorrect responses have been pooled. Findings are consistent with expectation. Latencies rank order the five aids in a manner consistent with SSI results. Aids 1 and 2 yield shortest latencies, aid 12 and 19 are intermediate, and aid 21 shows the greatest latencies. For all aids latency decreases as speech level increases.

Figure 8 plots average latency for all responses as a function of the percent correct score on SSI. Here differences among aids due to varying

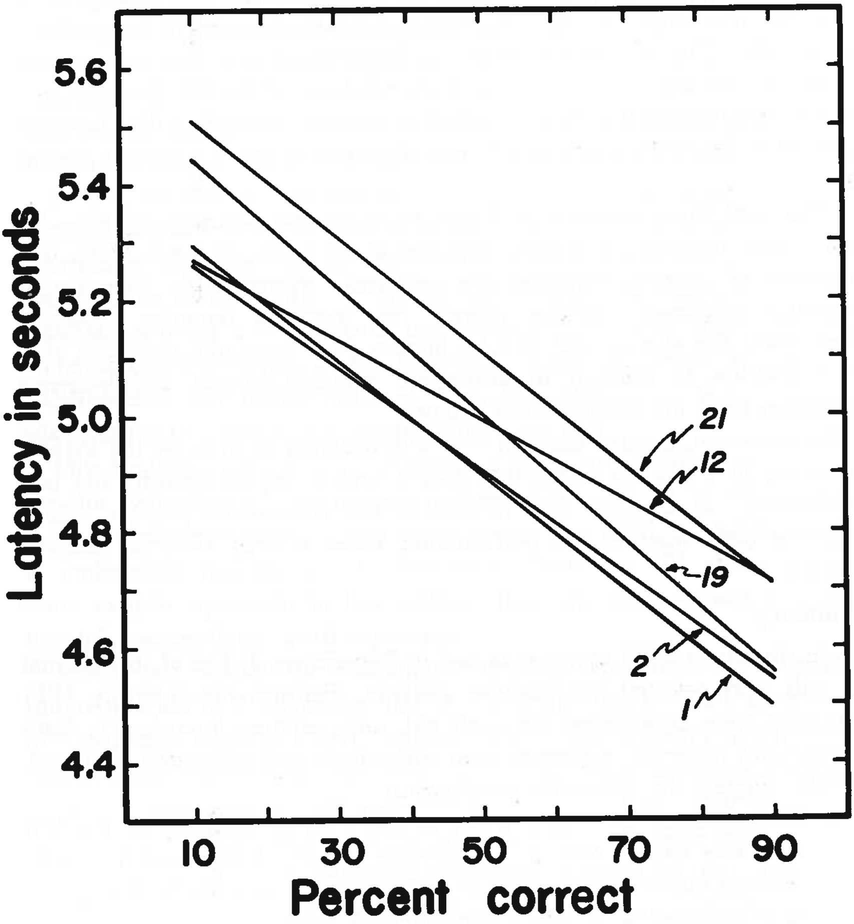

FIGURE 8.—Response latency as a function of SSI score for five selected aids.

level have been eliminated. All aids are equated in terms of SSI score. Nevertheless we still see the aids rank ordered in the expected fashion. Even at the same behavioral performance levels, latencies for aids 1 and 2 are shorter than for aid 21. This finding suggests an added dimension for the exploration of differences among aids. Figure 8 suggests that response latency may be a more sensitive index of performance differences than SSI. It suggests that the same performance levels were more easily achieved by subjects when listening through the better aids.

This finding supports a suggestion made to the writers some years ago by Dr. Eugene F. Murphy of VA. It is a pleasure to acknowledge his stimulus to our thinking in this regard.

Table 10 summarizes the various measures of response latency obtained on the five aids and the rank orders in which they place the aids, along with the IRI score for each aid, and SSI scores obtained in Experiments I and III. The SSI scores listed for Experiment III were interpolated from the functions of Figure 7 at a speech level of 35 dB. Latency-level scores were interpolated from Figure 8 at a speech level of 35 dB. Latency-percent scores were interpolated from Figure 8 at the 75 percent correct level.

The final three columns of Table 10 summarize average latencies for all correct, incorrect, and total responses at all levels. We note, first, that latencies of correct responses are uniformly shorter than latencies of incorrect responses. Neither correct nor incorrect latencies, however, rank order the aids as well as total latency. We conclude, therefore, that it is fruitless to attempt to distinguish between correct and incorrect responses from the standpoint of latency.

In any event, careful study of the rank ordering of aids, by the various measures in Table 10 shows that aids 1 and 2 are consistently the best performers. In contrast aids 19 and 20 are consistently poorest. These relations hold whether the performance index is SSI, IRI, or response latency.

Summary

On the basis of SSI scores obtained in Experiment I, five of the original 21 aids were selected for intensive analysis. Performance-Intensity (PI) functions were constructed for each aid, and response latencies for both correct and incorrect responses were collectively and separately analyzed. Results suggest the following conclusions:

1. Aids retained their rank order as the level of difficulty of the SSI task was varied over a considerable range. Aids could be rank-ordered either by SSI score at a fixed speech level or by the speech level required to obtain a constant SSI score.
2. Response latency decreased with increasing speech level for all aids, but aids retained their rank orders at all levels.

3. Even at constant SSI performance levels, aids were meaningfully rank-ordered according to merit by response latency.
4. Comparison of latencies to correct and incorrect responses yielded no advantage over total latency for all responses.
5. SSI, IRI, and response latency are essentially interchangeable indices of hearing-aid performance.

DISCUSSION

The specific findings of the three experiments described above have several important implications not only for our own future research activities but for the general area of hearing-aid research.

First, the SSI procedure used in these experiments was quite successful in separating aids behaviorally. The basic technique of sentence identification coupled with the competing message concept can well be recommended as a point of departure for the design of new approaches to hearing-aid evaluation in the clinical context. The procedure is easily automated and, with proper choice of competing message level, yields stable performance differences among aids with varying physical characteristics.

Second, the present results strongly suggest that the observed relationship between physical characteristics of hearing aids and speech understanding is critically dependent on the nature of the speech task used to measure performance behaviorally. In the present results, for example, the SSI materials showed a dependence on effective bandwidth that was quite understandable in terms of the frequency region important for sentence identification, but rather different from the relationship between bandwidth and performance on a monosyllabic word task.

This finding highlights the importance of a standardized speech task for the evaluation of hearing-aid performance. Central to the problem is the definition of what constitutes a reasonably valid test of the ability to understand running speech. We believe that the SSI procedure is a more realistic approach to this problem than the conventional approach through monosyllabic word repetition.

Third, our search for meaningful physical correlates of behavioral differences led to a surprising finding. A simple index of the irregularity of frequency response (IRI) turned out to be a better predictor of performance differences than any of several other measures explored. In fact it correlated so well with SSI scores ($r = 0.80$) that we are led to question whether the search for other physical correlates might well be abandoned in favor of extended systematic analysis of this apparently critical dimension of hearing-aid performance. It may well be that this factor of response irregularity is of such overriding importance that it effectively obscures the effects of variation in other physical dimensions.

Fourth, the present results confirm our previous finding that differences in hearing aids are at least as important for normal listeners as for the hearing-impaired. In previous reports, we showed that differences among aids diminished with degree, slope, and type of loss, being least for subjects with loss configurations typifying the problem case from the standpoint of hearing-aid fitting. The present results suggest that the slope of loss is the most critical factor. As slope increased, relations among physical and behavioral measures became progressively weaker.

The significance of these findings is that we have failed to discover dimensions of physical performance that are important for the hearing-impaired but not for the normal. On the contrary the normal ear seems to be a more sensitive instrument for hearing-aid comparison than the impaired ear. In consequence we suggest that subsequent research relating electroacoustic parameters to speech understanding can be most profitably carried out on normal rather than hearing-impaired subjects.

Finally, response latency emerges as a very promising tool for the comparative evaluation of aids. The present results lend support to the notion that differences among aids may be reflected in the ease with which a listening task is accomplished, even when the task itself is not capable of separating aids. We suggest that future effort be devoted to the design of listening tasks specifically constructed to measure not only conventional performance but the time required to carry out the task.

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APPENDIX

TABLE A.—*Effective Bandwidth (Hz) by USASI Method*

Aid no.	Bandwidth below 1,000 Hz	Bandwidth above 1,000 Hz	Total bandwidth
1	640	1,900	2,540
2	550	2,100	2,650
3	650	2,300	2,950
4	590	3,500	4,090
5	720	3,300	4,020
6	540	3,200	3,740
7	900	2,300	3,200
8	690	3,000	3,690
9	680	2,600	3,280
10	690	3,700	4,390
11	550	4,000	4,550
12	620	3,100	3,720
13	610	3,400	4,010
14	810	3,000	3,810
15	680	2,000	2,680
16	590	3,100	3,690
17	610	3,800	4,410
18	630	2,600	3,230
19	630	3,700	4,330
20	510	3,000	3,510
21	680	4,200	4,880

TABLE B.—*Effective Bandwidth (Hz) by HSHC Method*

Aid no.	Bandwidth below 1,000 Hz	Bandwidth above 1,000 Hz	Total bandwidth
1	560	1,525	2,085
2	150	1,700	1,850
3	400	2,000	2,400
4	−200	2,800	2,600
5	500	2,700	3,200
6	50	2,000	2,050
7	540	2,000	2,540
8	590	2,350	2,940
9	550	2,350	2,900
10	300	1,950	2,250
11	180	3,000	3,180
12	230	2,500	2,730
13	330	2,700	3,030
14	50	2,400	2,450
15	300	1,550	1,850
16	380	2,300	2,680
17	360	1,100	1,460
18	595	2,150	2,745
19	430	3,100	3,530
20	−25	2,000	1,975
21	−1,050	2,900	1,850

Table C.—*Percent Harmonic Distortion (NBS Data)*

Aid no.	Frequency in Hz			
	500	700	900	Avg.
1	27	19	7	17.6
2	6	3	1	3.3
3	1	14	17	15.0
4	21	21	21	21.0
5	30	45	33	36.0
6	26	30	10	22.0
7	8	2	1	3.7
8	35	28	16	26.3
9	31	10	1	14.0
10	24	16	14	18.0
11	1	20	40	23.3
1	4	0	0	1.3
13	12	5	5	7.3
14	10	10	5	8.3
15	5	40	8	17.7
16	9	4	5	6.0
17	8	3	9	6.7
18	3	0	1	1.3
19	2	0	6	2.7
20	5	6	3	4.7
21	0	1	9	3.3

TABLE D.—*Percent Harmonic Distortion by S–3–X–48 Method*

Aid no.	Frequency in Hz			
	500	700	900	Avg.
1	8.45	6.67	3.50	6.21
2	12.08	5.74	8.81	8.88
3	7.32	10.66	9.19	9.06
4	13.13	6.30	6.47	7.63
5	19.13	8.58	5.40	11.04
6	4.25	5.50	5.79	4.85
7	6.10	3.58	4.37	4.68
8	10.10	7.46	6.50	8.02
9	30.38	4.17	8.58	14.38
10	55.42	19.06	19.90	31.46
11	10.53	6.15	12.20	9.63
12	9.85	2.72	3.59	5.39
13	7.01	1.41	4.26	4.23
14	30.48	22.79	15.34	22.95
15	7.24	30.08	7.66	14.99
16	3.28	2.27	4.83	3.46
17	7.84	4.41	5.91	5.93
18	9.44	1.03	6.54	5.67
19	2.18	1.09	0.97	1.41
20	3.59	4.05	3.56	3.73
21	1.78	2.41	4.68	2.96

Table E.—*Percent Harmonic Distortion by HSHC Method (60 dB Input)*

Aid no.	Frequency in Hz			
	500	700	900	Avg.
1	6.47	6.55	3.83	5.62
2	5.07	2.62	1.39	3.03
3	3.92	2.43	2.03	2.79
4	8.06	4.77	4.71	5.85
5	7.28	3.61	2.57	4.49
6	8.05	4.66	7.47	6.73
7	3.94	2.07	0.71	2.24
8	7.98	5.00	5.42	6.13
9	23.85	9.22	3.36	12.14
10	8.96	5.68	10.51	8.38
11	3.47	3.13	2.90	3.17
12	1.77	1.12	1.60	1.50
13	3.09	1.83	1.96	2.29
14	19.24	14.23	10.33	14.60
15	3.38	16.40	3.03	7.60
16	4.35	1.07	1.98	2.47
17	1.42	1.16	2.10	1.56
18	1.68	0.58	1.73	1.33
19	1.48	1.99	0.92	1.46
20	19.33	13.04	2.10	11.49
21	1.51	1.10	1.00	1.20

TABLE F.—*Percent Harmonic Distortion by HSHC Method (65 dB Input)*

Aid no.	Frequency in Hz			
	500	700	900	Avg.
1	21.57	13.49	6.28	13.78
2	10.00	5.00	2.69	5.90
3	3.94	3.80	3.31	3.68
4	22.84	10.96	9.65	14.48
5	9.54	5.37	4.97	6.63
6	14.21	7.47	12.91	11.53
7	6.71	3.78	1.34	3.94
8	11.82	8.32	7.61	9.25
9	24.47	7.91	4.76	12.38
10	23.11	10.75	8.11	13.99
11	5.93	3.60	4.92	4.82
12	1.90	1.15	1.55	1.53
13	5.21	1.20	4.04	3.48
14	12.71	17.39	13.51	14.54
15	5.51	32.69	4.73	14.31
16	7.10	1.71	4.08	4.30
17	2.40	2.19	6.34	3.64
18	3.19	1.58	3.28	2.68
19	2.77	3.56	2.09	2.81
20	7.01	2.83	2.46	4.10
21	0.67	2.31	3.13	2.04

TABLE G.—*Percent Harmonic Distortion by HSHC Method (70 dB Input)*

Aid no.	Frequency in Hz			
	500	700	900	Avg.
1	19.92	10.99	6.59	12.50
2	17.95	6.00	3.80	9.25
3	4.44	6.63	6.38	5.82
4	22.39	19.60	17.54	19.84
5	12.77	8.36	6.41	9.18
6	24.85	11.39	10.70	15.65
7	8.01	2.81	2.12	4.31
	14.53	12.69	12.20	13.14
9	19.36	13.10	6.12	12.86
10	26.11	15.22	12.58	17.97
11	10.00	7.45	12.43	9.96
12	5.10	1.39	2.60	3.03
13	9.81	2.42	6.94	6.39
14	19.12	30.82	14.96	21.63
15	10.72	61.95	13.68	28.78
16	13.34	3.27	1.41	6.01
17	4.48	3.97	5.73	4.73
18	7.50	2.49	1.93	3.97
19	2.55	1.81	3.91	2.76
20	2.21	3.53	2.99	2.91
21	1.57	1.54	3.55	2.22

TABLE H.—*Percent Harmonic Distortion by HSHC Method (75 dB Input)*

Aid no.	Frequency in Hz			
	500	700	900	Avg.
1	25.99	10.76	5.93	14.23
2	35.52	12.56	7.09	18.42
3	5.99	8.20	8.39	7.53
4	24.80	23.13	18.76	22.23
5	18.63	16.51	12.74	15.96
6	27.36	10.92	9.00	15.76
7	6.06	3.99	2.90	4.32
8	17.03	14.64	7.87	13.18
9	19.36	8.70	6.39	11.48
10	44.62	20.96	22.24	29.27
11	19.30	15.21	26.93	20.48
12	8.69	2.23	8.04	6.32
13	30.04	19.03	11.02	20.03
14	35.36	38.13	16.92	30.14
15	24.94	106.12	24.43	51.83
16	15.72	8.62	10.78	11.71
17	11.55	6.35	10.08	9.33
18	18.12	2.01	5.93	8.69
19	2.79	4.90	10.73	6.14
20	3.97	4.12	4.06	4.05
21	1.34	1.64	5.05	2.68

Table I.—*Percent Harmonic Distortion by HSHC Method (80 dB Input)*

Aid no.	Frequency in Hz			
	500	700	900	Avg.
1	34.34	13.06	8.26	18.55
2	63.90	24.67	12.56	33.71
3	1.72	14.38	15.73	10.61
4	29.88	29.96	22.45	27.43
5	28.30	24.31	15.94	22.85
6	22.23	12.74	10.18	15.05
7	13.16	7.22	4.07	8.15
8	22.40	19.17	12.83	18.13
9	26.02	16.85	8.14	17.00
10	65.43	23.84	21.10	36.79
11	35.50	28.63	48.67	37.60
12	13.02	7.21	11.02	10.42
13	48.32	11.79	9.84	23.30
14	50.94	55.98	22.76	43.23
15	30.26	138.12	40.53	69.36
16	24.48	20.62	24.64	23.25
17	20.03	14.18	20.00	18.07
18	38.49	10.76	9.98	19.74
19	10.58	8.31	10.66	9.86
20	5.74	15.66	10.90	10.77
21	5.08	5.27	10.20	6.85

Table J.—*Maximum Power Output for Full Volume Control Setting: Maximum RMS Output Level in dB (NBS Data)*

Aid no.	Frequency in Hz			
	500	750	1,000	2,000
1	142	143	145	138
2	124	125	126	116
3	137	137	136	135
4	131	130	130	133
5	137	138	138	139
6	130	131	131	124
7	127	129	130	119
8	132	132	132	131
9	123	128	131	126
10	116	120	119	117
11	103	108	109	113
12	115	123	119	110
13	121	126	125	116
14	138	138	140	137
15	124	125	126	122
16	120	126	122	121
17	119	124	118	111
18	118	121	118	111
19	105	113	105	102
20	113	113	115	116
21	117	119	113	109

TABLE K.—*Gain, Signal-to-Noise Ratio, and Signal-to-Hum Ratio Measurements in dB (NBS Data)*

Aid no.	Max. gain 10% dist.	Gain full vol.	S/N ratio	S/H ratio
1	81.0	81.0	42.5	59.5
2	51.5	51.5	47.0	66.0
3	70.5	73.5	43.0	36.0
4	51.0	66.5	47.0	30.0
5	71.0	71.0	45.5	30.0
6	63.5	69.0	47.0	30.0
7	54.0	54.0	36.0	30.0
8	60.0	66.0	48.0	—
9	61.0	61.0	48.0	30.0
10	47.5	47.5	47.0	52.0
11	34.5	34.5	48.5	30.0
12	37.0	41.0	40.5	30.0
1	51.0	59.0	41.5	40.0
14	67.0	67.0	53.0	30.0
15	46.0	46.0	37.0	30.0
16	45.5	49.5	36.0	54.0
17	43.5	43.5	41.5	—
18	45.0	45.0	45.5	62.0
19	29.5	29.5	40.0	48.5
20	37.0	37.0	42.5	56.5
21	25.5	30.5	34.5	40.0

TABLE L.—*SSI Scores in Percent Correct for Test Blocks 1 Through 10 (The Score is Cumulative Across Blocks)*

Aid no.	Test block									
	1	2	3	4	5	6	7	8	9	10
1	74.0	79.0	78.7	78.0	77.6	78.0	79.4	80.8	79.8	79.8
2	86.0	89.0	86.7	85.0	83.6	82.0	83.4	84.2	82.4	82.4
3	90.0	86.0	84.7	83.5	83.2	85.7	83.1	82.2	81.6	81.0
4	80.0	75.0	74.0	73.0	71.6	71.7	75.1	74.0	72.7	72.0
5	84.0	81.0	78.7	76.5	76.4	77.3	78.3	79.0	77.6	76.6
6	80.0	77.0	77.3	76.0	72.4	71.3	73.1	75.5	74.4	75.4
7	74.0	77.0	79.3	79.0	78.8	79.3	78.6	79.0	78.4	77.8
8	74.0	78.0	78.0	77.0	74.8	74.7	76.0	77.0	75.1	75.0
9	72.0	77.0	76.7	77.0	73.6	72.7	74.8	77.5	74.7	75.4
10	78.0	80.0	81.3	80.5	79.2	79.3	81.1	81.7	80.6	80.8
11	74.0	75.0	74.7	76.5	76.8	76.7	77.4	77.5	76.9	75.6
12	84.0	82.0	80.7	79.5	75.6	74.0	74.9	74.5	73.8	73.4
13	64.0	74.0	74.0	74.0	72.0	72.7	75.1	75.8	75.1	74.6
14	78.0	75.0	71.3	74.0	70.0	71.3	73.7	74.2	73.1	74.6
15	74.0	81.0	80.7	81.0	79.6	79.3	80.3	80.0	79.6	80.2
16	70.0	78.0	76.0	77.0	76.0	77.7	79.1	79.5	78.7	78.4
17	76.0	79.0	78.0	79.5	77.2	77.0	77.7	76.8	75.3	74.2
18	74.0	72.0	68.7	72.0	70.4	71.0	73.1	72.5	71.3	71.6
19	66.0	71.0	70.7	71.0	70.4	69.7	70.3	71.5	70.2	71.0
20	66.0	72.0	69.3	71.0	70.4	68.7	70.0	70.0	67.8	67.6
21	64.0	67.0	64.0	63.5	62.4	62.3	64.8	64.8	64.2	64.8

Table M.—*Correlation Matrix; SSI Score Versus VA Indices of Hearing-Aid Performance (Experiment I)*

	Total performance	Raw index of effectiveness	Raw uniformity of slope
SSI	−0.07	0.25	0.38
Total Performance		0.69	0.46
Raw Index of Effectiveness			0.41

Table N.—*Correlation Matrix; SSI Scores Versus Gain and Power Output Factors (Experiment I)*

	Maximum gain for 10% distortion	Gain at full volume	Maximum power output at 1,000 Hz
SSI	0.57	0.48	0.49
Maximum gain for < 10% distortion		0.96	0.95
Gain at full volume			0.95

Table O.—*Correlation Matrix; IRI Versus Effective Bandwidth (Experiment I)*

	Bandwidth below 1,000 Hz	(HSHC method) Bandwidth above 1,000 Hz	Total bandwidth
IRI	0.56	−0.28	−0.11
Bandwidth below 1,000 Hz		−0.30	0.39
Bandwidth above 1,000 Hz			0.76