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ABSTRACT

Reported were studies measuring residual auditory capacities of deaf persons and investigating hearing aids which transpose speech to lower frequencies where deaf persons may have better hearing. Studies on temporal and frequency discrimination indicated that the duration of a signal may have a differential effect on its detectability by sensorineural hearing-impaired persons compared to normal, but that temporal effects on frequency discrimination and perception of temporal order seem normal, and therefore provide scant explanation of low speech discrimination abilities. Problems involved in doing research with long-term hearing impaired Ss were identified. Studies of speech pattern perception yielded the following conclusions: sensorineural hearing-impaired listeners have better residual reception for low-frequency speech patterns than the middle- and high-frequency patterns; and the superiority of low-frequency pattern reception holds over a rather wide range of degrees and types of sensorineural impairment. Data was reported concerning the hypothesis that acoustic transposition of phonemic differences could make them indistinguishable at least until discrimination could be retrained. Also presented were data showing that speech discrimination performance is higher for transposer amplification than for conventional amplification. Theoretical aspects of frequency transposition were discussed. (GW)

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RESEARCH ON FREQUENCY TRANSPOSITION FOR HEARING AIDS

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INTRODUCTION

The purpose of this research is to develop and test methods for altering speech signals so as to better compensate for severe deafness. Severe deafness of early onset produces grossly deficient speech communication. This deficit pervades all aspects of deaf education with the result that there is severe retardation of intellectual development. If better means can be found for alleviating the deficient speech communication of deaf persons, large improvements would occur in their education. The present research is focussed on those cases where speech reception cannot be sufficiently aided by conventional hearing aids, due to very poor auditory discrimination in the important speech frequency regions. This is characteristic of hearing losses of sensorineural type.

Experimental testing was performed on transposing of speech to lower frequencies where deaf persons may have better hearing. Other methods of speech alteration had been previously tested, such as time-stretching and formant exaggeration. Speech discrimination performance and reception confusions are analyzed in order to characterize deficient auditory discrimination for speech.

The work reported here has measured some of the residual auditory capacities of deaf persons and studied transposition for hearing aids. Details of rationale, methods, and results are given below for each numbered section of the following outline:

A. Residual Auditory Capacities of Deaf Persons.

   A1. Temporal and frequency discrimination.
   A2. Speech pattern perception.
   A3. Phoneme boundaries in speech perception.

B. Transposition for Hearing Aids.

   B1. Tests of transposer hearing aid.
   B2. Theoretical aspects of transposition.

A. RESIDUAL AUDITORY CAPACITIES OF DEAF PERSONS

A1. Temporal and Frequency Discrimination

Background. Sensorineural hearing-impairment often results in an inability to discriminate among sounds even when they are made audible by amplification through a hearing aid. This "discrimination loss" affects the correct perception of speech sounds and severely limits speech communication for a very large number of hearing-impaired persons. There is very little information available to indicate exactly what aspects of auditory discrimination are affected by discrimination loss. Therefore, we decided to obtain some basic information about the capacity of the impaired auditory system to process auditory signals. Essentially we were asking, can information about performance in basic psychoacoustic experiments help us to understand why sensorineural hearing-impaired people show discrimination losses for speech. In addition, this information might indicate limitations on discrimination of transposed speech.

Our starting point was the observation that the auditory system, either normal or impaired, must process acoustic signals in time. Time-factors such as the durations of signals and their sequence of occurrence would give important cues to the discrimination or recognition of complex auditory patterns such as speech. Therefore we investigated the effects of temporal factors on basic auditory abilities of sensorineural hearing-impaired people.

Temporal Effects on Detection of Sound. Although recognition of sounds and discrimination between sounds is done at suprathreshold levels, we began by determining the temporal effect on auditory detection of sounds. This study seemed important because hearing-impaired people often have a limited dynamic range between the threshold of audibility and the threshold of discomfort for audible sounds. Thus any additional reduction of dynamic range due to temporal factors might have serious effects on their auditory discriminations.

This problem had already been investigated to some extent in clinical studies by Miskolczy-Fodor, 1953; Eisenberg, 1956; Harris, Haines and Myers, 1958; Simon, 1963; Sanders and Honig, 1967; Wright, 1968a, b; Wright and Cannella, 1969. These authors had found that the thresholds of both normal and hearing-impaired Ss are relatively fixed for tone durations longer than about 200 msec. However, for shorter duration, there is a systematic upward threshold-shift as duration is decreased. The intensity-time trading relationship reflects an auditory process known as temporal integration. In general, the authors cited above found that there is less upward threshold-shift in sensorineural hearing-impaired Ss than in normal-hearing Ss, especially in the high frequency range (2-4 KHz).

However, these previous clinical findings were questioned as a result of a laboratory study on temporal integration (Watson and Gengel, 1969). As seen in Figure 1, this study indicated that there is a frequency effect on the temporal integration function; both normal Ss and Ss with moderate high-frequency loss show less upward threshold-shift in sensitivity with decreasing duration for high frequencies (2-4 KHz) than for low frequencies (.25-.5 KHz). Possibly the data from the previous clinical studies required reinterpretation, because the frequency effect on temporal integration had not been taken into account.

To further investigate the effects of duration on auditory sensitivity, eight Ss with moderate to severe sensorineural hearing-impairment were tested with a method of limits. (For details on procedure see Watson and Gengel, 1969.) Test frequencies were the octave intervals between .25 and 4 KHz and test durations were 512, 64 and 32 msec. Threshold for each combination of duration and frequency was measured at least 2 times for each S. The results, shown in Table 1, indicate that some of the Ss with moderate to severe sensorineural hearing impairment show reduced temporal integration functions even when the frequency effect is taken into account.

While indicating that reduced temporal integration functions are sometimes seen in sensorineural hearing-impaired Ss this study also raised some issues regarding the clinical testing of temporal integration. In addition to considering the frequency effect on normal temporal integration functions we indicated that both normal and hearing-impaired Ss show considerable variability in re-tests of auditory sensitivity (See Figure 2), and that single estimates of thresholds could be highly unreliable. For this reason we have used the mean of a minimum of 12 measurements to define threshold.

Finally, we suggested that some psychophysical procedures might be more sensitive indicators of the frequency effect than others. Specifically we indicated that the tracking procedure was less sensitive than either a method of adjustment or a two alternative forced choice procedure.

Temporal Integration at Masked Threshold. Although the data from Gengel and Watson, 1971, seemed to indicate in a convincing way that reduced temporal integration functions were sometimes seen in Ss with moderate to severe sensorineural hearing-impairment, a possible artifact remained. Sensorineural hearing-impaired Ss, by necessity, must be tested at high sound levels. Possibly normal Ss would also show reduced temporal integration functions if tested at similarly high levels of stimulation. To check this possibility four Ss with normal hearing were tested in the presence of an 87 dB SPL noise (re 0.0002 dyne/cm^2). Test frequencies were the same as those previously used. The data from this experiment were compared with the data from Watson and Gengel, 1969. Figure 3 shows that the data obtained at high stimulation levels are very similar to the data previously obtained in quiet. Therefore reduced temporal integration functions appear to be a valid manifestation of sensorineural hearing-impairment and are not an artifact due to high stimulation levels.

Perception of Temporal Order. While the studies of temporal integration were in progress, study was initiated on the perception of temporal order, i.e., the perception of the order in which two auditory events occur. The motivation for this investigation came especially from papers by Hirsh and his co-workers dealing with the perception of temporal order in normal Ss (Hirsh, 1959; Hirsh and Sherrick, 1961; Hirsh and Fraisse, 1964) and from his emphasis on the importance of temporal pattern perception in hearing (Hirsh, 1967). Since auditory information such as speech and music is sequential in time, it seemed important to determine if perception of temporal order were normal in sensorineural hearing-impaired persons.

Six sensorineural hearing-impaired Ss and five normal hearing Ss were tested. The temporal patterns consisted of two tones (250 and 335 Hz) which were independently turned on by two electronic switches so that one tone began either 20, 40, 60, 80, 100 msec or more (150-400 msec) before the onset of the second tone. Both tones were turned off simultaneously 500 msec after the onset of the lagging tone. Ss' task was to indicate which tone (either the higher- or lower-pitched tone) began first. Ss were told whether or not they were correct after each trial. Practice effects were taken into account by collecting data from each S over eight one-hour sessions.

The results, shown in Figure 4, indicate that while both groups showed large practice effects, the performance of the hearing-impaired group is very similar to that of the normal group. Thus it appears that sensorineural hearing-impaired Ss are able to perceive normally, auditory temporal order.

However, an exception to the main results was found. Two Ss, one hearing-impaired and one normal, were unable initially, to perform as well as the other Ss during the first eight test sessions. They required 200 msec or greater onset lead times to perceive temporal order. Therefore their data were analyzed separately. It was hypothesized that these two Ss were unable to correctly perceive the temporal patterns with small onset differences not because of impairment to the auditory system, but because they had not yet learned to perceptually organize the cues that were appropriate for making the correct recognition. Indeed with further practice, including sessions where stimuli were presented repeatedly before response, the hearing-impaired S came to perform similarly to the other Ss. Research using similar procedures is still being done with the normal Ss. (This experiment was described in part at the Convention of the American Speech and Hearing Association, November 1971. A detailed manuscript has been completed and submitted for publication.)

<u>The Temporal Effect on Frequency Discrimination</u>. The last experiment in this series investigated the temporal effect on frequency discrimination and additionally the relationship between frequency discrimination and speech discrimination. It is well established that for durations of tone less than about 150 msec the difference limen for frequency (DLF) in normal Ss becomes progressively larger as duration is made progressively shorter (Turnbull, 1944; Oetinger, 1959; Chih-an and Chistovich, 1960; Cardozo, 1962). This effect seems to be due to the physical characteristics of short tones; i.e. the bandwidth of the signal increases as duration decreases. The resulting uncertainty of the frequency of the signal is manifested as an increase in the size of DLF. The purpose of this study was to determine if the temporal effect on frequency discrimination is the same in hearing-impaired as in normal Ss.

A secondard purpose was to re-examine the relationship between frequency discrimination and speech discrimination in sensorineural Ss using the measure of DLF for short tones as the data for correlation with speech discrimination. It seemed possible that the correlation might be higher than previously reported (Hayes, 1951; Harris, et al, 1955; Ross, et al, 1965) if short tones were used to measure DLF, because many speech cues are also short in duration.

Five Ss with sensorineural hearing-impairment and three Ss with normal hearing were tested with standard frequencies at 0.5, 1.5 and 3.0 KHz and with tone-durations of 500 and 50 msec. A modified adaptive procedure was used to measure DLF. Ss task was to indicate after a stimulus presentation whether the first tone was higher or lower in pitch than the second tone burst. A 250 msec silent period marked the offset of the first tone from the onset of the second. After each response S was informed whether or not he was correct. Because we anticipated large practice effects (Gengel, 1969; Pickett and Martony, 1970) Ss were given extensive practice with each combination of frequency and duration to insure performance had reached an asymptote before data collection began. However, even after training the hearing-impaired Ss showed considerable performance variability. Therefore the data from the hearing-impaired Ss were based on 10 measures of DLF for each hearing-impaired S for each combination of frequency and duration while about five estimates per condition were obtained from each normal hearing S.

Speech discrimination of the hearing-impaired Ss was measured with the vowel test described by Owens,et al, 1968, and with the consonant test described by Kreul, et al, 1968. In all, each S responded to 300 items in a four alternative forced choice test (vowels) and 400 items in a six alternative forced choice test (consonants).

The results of this experiment indicated that although the DLF for long tones tends to be larger for hearing impaired Ss (see Table 2), the temporal effect on the size of DLF is similar for both hearing-impaired and normal-hearing Ss (see Table 3). Thus, although hearing-impaired Ss generally show greater frequency uncertainty (as reflected in the absolute size of the DLF for 500 msec tones) the additional frequency uncertainty due to shortening tone-duration, is the same for hearing-impaired and normal-hearing Ss.

To examine the correlation between size of DLF and speech discrimination Spearman Rank Order Correlation coefficients (r_s) were computed separately for vowels and consonants. Figure 5 shows the relationship between the DLF for 50 msec tones and speech discrimination. The value of the correlation coefficient (r_s) range from 1.0 at 3.0 KHz to .70 at 0.5 Khz. For 500 msec tones r_s range from 1.0 at 3 KHz to 0.5 at 0.5 KHz.

These high values of correlation should be viewed cautiously since only ive Ss were used. Nevertheless, in view of the fact that 1) Ss were trained prior to data collection, 2) mean values of DLF are based on 10 or more estimates of DLF, and 3) speech discrimination scores are based on a total of 700 stimulus items, we believe that the results are highly reliable.

Implications of the Findings. The results of these studies indicate that the duration of a signal may have a differential effect on its detectability by sensorineural hearing-impaired persons compared to normal. However, temporal effects on frequency discrimination and perception of temporal order seem normal and therefore provide little help in explaining low speech-discrimination abilities. Is there then, no relationship between performance on basic psychophysical discrimination tests and speech discrimination?

The high correlation between frequency discrimination and speech discrimination suggests that these activities are related and we now propose an hypothesis to indicate how. Tables 2 and 3 indicate that although the temporal effect on frequency discrimination is similar for hearing-impaired and for normals, the absolute sizes of DLF are larger for the hearing-impaired Ss. We hypothesize that these larger DLFs reflect a fundamental signal uncertainty caused by sensorineural hearing-impairment. Subjectively, pure tones might not sound pure to a hearing-impaired person. Instead they might sound rough (Corliss, et al, 1968) or buzzing or noisy (Ward, 1955). The degree of frequency uncertainty might vary among hearing-impaired persons depending on the nature of their impairments. The effect of this type of frequency uncertainty would be reflected as DLFs that were larger-than-normal to a varying degree.

One could hypothesize that the frequency uncertainty due to sensorineural hearing-impairment, which is manifested as a reduced ability to discriminate small differences in frequency, also might reduce a person's ability to discriminate among vowels with closely-adjacent formant frequencies and among spectrally-similar consonants such as those contained within the categories of nasals, unvoiced stops, voiced stops, and unvoiced fricatives. Thus discrimination of frequency-differences and discrimination of speech might be highly correlated, not because good speech discrimination is dependent on good frequency discrimination but because both types of discrimination are affected similarly by the degree of frequency uncertainty produced by sensorineural hearing impairment.

A second hypothesis is that under the difficult listening condition imposed by sensorineural hearing-impairment, people may have learned to utilize the available auditory cues in different ways. Thus some hearing-impaired people might utilize subtle auditory cues which other hearing-impaired people might tend to ignore or to think are unimportant. The same kind of reasoning might also explain the differences found among normal-hearing Ss discriminating speech in the presence of noise (Egan, 1944) or detecting tone-pulses mixed with a masking signal (Green, 1969). However, since the range of scores obtained from hearing-impaired Ss is generally wide, a correlation between two discrimination abilities due to underlying differences in learned orientations toward listening might be more evident for hearing-impaired than for normal-hearing Ss.

To summarize, from the results of these basic psychophysical experiments we conclude that performance on discrimination tasks of simple and complex stimuli may be highly correlated but that this correlation might not indicate a cause-effect relationship. Rather, it probably reflects underlying similarities in the way, either that the auditory system processes acoustic signals or the way the listener has learned to organize the stimuli impinging on his auditory nervous system or a combination of both of these factors. Therefore, we conclude that further <u>empirical</u> studies of basic psychophysical discrimination abilities probably will not help significantly in explaining why persons with sensorineural hearing impairment cannot discriminate speech normally. Instead, these basic experiments should be designed to specifically test hypotheses such as those that were suggested above.

<u>Training Effects and Congenital Hearing Impairment</u>. The experience gained from working with congenitally and/or long-term sensorineural hearing-

impaired persons has provided important insights into their auditory discrimination ability and its measurement that could not be emphasized enough in published reports. Therefore they are described here in detail to indicate the problems involved in doing research with long-term hearing-impaired Ss and in understanding their communication problems. Although the problems described are not unique to this particular population, they seem more accentuated than, for example, in normal persons or in persons where hearing-impairment has its onset in middle life or old age.

1) Language factors: Congenital and long-term sensorineural hearing-impaired persons often show reduced language comprehension abilities. Sometimes this is because sign language rather than English is their normal first language. In other cases, while English is their first language, they have not learned very well the rules of its usage. When combined with a limited vocabulary, it becomes difficult for them to communicate effectively. For example, either written or spoken instructions which seem clear to an experimenter can prove to be incomprehensible to a subject. Or when asked to give subjective impressions or to describe a given stimulus, the S cannot adequately express his experience. Thus the verbal reports that normal Ss often freely give can be very difficult to obtain at all from these hearing-impaired Ss or they are so vague as to be of little value.

2) Unfamiliarity with attributes of sound: Allied with an inability to describe verbally the characteristics of subjective impressions of sounds there is often lack of familiarity concerning the attributes of sound. Usually only the concept of the loudness of a sound is well defined. We have seen a number of persons who initially showed no consistent ability to label the pitch of a tone as being higher or lower than another. Unless they were told which tone the experimenter labelled the higher (or lower) tone these Ss were quite arbitrary in their choice and sometimes even reversed the labels in mid-test. Thus, for example, without feedback as to the correct response, an S might make 10 correct responses in a row, and then 10 incorrect responses. In both instances he can discriminate between the two tones but labels them inconsistently.

3) Listening attitude: Under difficult listening conditions, as when the frequencies of two tones are close to each other in a frequency discrimination task, some Ss initially give random responses. When asked the basis on which they are making their judgments they might reply that one sound is longer on a given trial and louder on the next. They do not realize that, in this example, only the pitch of the tones is changing from trial to trial and that they must ignore these other subjective changes they think they experience. Thus they must be encouraged to find a consistent cue and then to hold onto that cue as long as they can. Ss learn to do this with practice, but before really consistent performance is shown, wild oscillations in performance often occur. For example, in the frequency discrimination task done with the adaptive procedure, it was not uncommon for an S to respond correctly very consistently until the frequency difference between the two tones was very small. Then S would lose his pitch cue and go into random performance until the frequency difference was made very large. Only after considerable practice could he re-find his pitch cue when the frequency increment was increased only slightly from the smaller increment where he had lost it.

4) Practice and learning effects: Because of factors such as those mentioned above we feel that valid measures of discrimination or recogni-

tion performance cannot be obtained without first giving practice and taking data only after an asymptote has been reached in the learning curve. Until asymptote is reached, performance does not indicate the capacity of an S to make a particular discrimination. Rather it reflects his present learned ability to make the discrimination. And the difference between present ability and ultimate capability can be so large that some Ss who initially show grossly abnormal performance eventually perform normally. The hearing-impaired Ss who initially showed gross abnormality in ability to perceive temporal order provide a good example.

5) Variability within and between Ss: Separate from problems concerning the validity of the data we sometimes find high variability within some Ss even after training. Figure 2 gave a vivid example in the variability around detection threshold. Similar performance was also seen in the frequency discrimination study; that is, some Ss finally reached an asymptote regarding their smallest attainable DLFs. However, interspersed with these small DLFs also were some larger ones. Therefore to obtain reliable measures of performance it is sometimes necessary to obtain repeated measures of performance even after training and learning effects have been accounted for. In a realistic situation, this means that data must be collected from the same Ss for extended periods of time; anywhere from weeks to an entire school year. Nevertheless, at present we know of no other way to obtain data that describes both validly and reliably the auditory-sensory capabilities of these hearing-impaired Ss.

When a correlation study is contemplated the problems concerning validity and reliability are doubled since training and repeated measures must be obtained with both discrimination tasks. Possibly sensorineural hearing-impairment might be so diverse across Ss that a high correlation between two abilities, as for example frequency and speech discrimination, might be found only infrequently. However, we must seriously doubt the validity of the low correlations previously reported where comparatively meager data was obtained from each S.

6) Auditory training: Because of a lack of experience about sound attributes and because of undeveloped listening attitudes hearing-impaired Ss can show large training effects. Although there is, within the field of audiology, considerable emphasis on auditory training, when we began our studies we found that there seemed to be very little data to indicate how it might best be accomplished, and if indeed congenitally hearing-impaired Ss actually showed measureable changes in performance as a result of training.

And here we must first differentiate between practice only and training. Working independently at that time (1968-1969) we found that Ss often showed very little change in discrimination performance as a result of only practice in listening. Ss generally could not reliably select the cue necessary for correct response based only on the instructions he received. His knowledge of the relevant cue for correct discrimination has to be shaped and refined. This was accomplished by giving trial-by-trial feedback (knowledge of results) after each response. By using practice accompanied by trial-by-trial feedback (training) we demonstrated that this form of auditory training could modify the discrimination performance of congenitally sensorineural hearing-impaired persons. We have now demonstrated that auditory training can improve discrimination of tones (Gengel, 1969, 1972), low-frequency vowel formants (Pickett and Martony, 1970), F2 formant-transitions (Martin, Pickett and Colten, 1972) and in the recognition of temporal patterns (Gengel, 1972). Because of the modifications in performance that we have demonstrated, we feel that assessment of auditory capabilities of hearing-impaired people could be grossly in error if Ss are not trained prior to final assessment. By extension, we question much of the clinical data on auditory capabilities of hearing-impaired people.

Indeed we have been forced to question our own data when an S performs in a seemingly grossly abnormal way. Recall the hearing-impaired S who initially could discriminate only very large differences in temporal order with the training procedure employed. By modifying the training procedure, her performance eventually became the same as the other Ss. Thus we must continuously consider the problem of adapting training procedures to meet the needs of individual persons. This aspect of our research is still in its infancy. However, we feel that the study of different training procedures is very important not only in obtaining reliable and valid data but also in obtaining these data in the most efficient way, i.e., the most efficient procedure of auditory training.

7) Stimulus cues: It is not at all facetious to say that hearing-impaired people do not have normal hearing. We do not know what a hearing-impaired person experiences subjectively in response to a given auditory stimulus. Therefore, as a subject is being trained, great care must be taken to insure he is not responding to some extraneous cue, the presence of which the experimenter might not be aware. For example, in the case of an S with a steeply sloping sensitivity curve who showed greater high than low frequency loss, two suprathreshold tones might be different in pitch but might also be different in loudness. If the lower tone, for example, is consistently louder, then he might utilize the loudness cues rather than the pitch cues. The results of such an experiment will be invalid because while the experimenter thinks the S is discriminating differences in pitch he is actually discriminating differences in loudness. To control for such a possibility great care must be taken to randomize all variables except the independent variable. In the example, the amplitude of the two tones could be randomly varied from trial to trial to break up a consistent loudness cue. In cases where randomization is not easily accomplished, control experiments should be run to insure at the data obtained in the main experiment is valid. Such procudures lengthen the time of data collection. Nevertheless we feel they are necessary in research with the hearing-impaired.

Long term experiments present another problem which must be recognized. Many of our Ss take a personal interest in our experiments and are eager to do as good a job as possible. We have found that when the order of presentation of stimuli is fixed, as on tape recordings, that Ss will attempt to memorize the order of presentation. Thus if simple stimuli such as tones are used, order of presentation must be randomized by logic circuits in the instrumentation of the experiment. If tape recordings are used, many different orders of presentations must be recorded.

8) Motivation: We have mentioned above that some of our Ss take a personal interest in our experiments and are quite willing to return for testing sessions spread over long periods of time. In fact, in our initial interviews we stress that we are only interested in hiring people who are willing to work an entire semester, for example. As might be expected,

some Ss who are initially very enthusiastic, find the task eventually becomes routine and boring to some extent. The wage we pay them is not necessarily sufficient incentive to keep them coming. Therefore, keeping motivation high is a constant problem. Since our investment in an S in terms of time as well as money can become quite high in a long term project we must try to make the work situation as pleasant and meaningful as possible. One procedure that has been helpful is to explain as fully as possible why we are doing the experiment, what we expect to gain from the experiment and what the consequences of Ss participation in the experiment will be.

Although not as desirable a procedure we have also found that we must sometimes bend our schedules to suit students' needs. Although Ss normally work only two or three hours per week, they sometimes will not want to work the day before an exam, for example. Therefore, we give them this time off even though it further lengthens the overall time for data collection.

We stress here that the longer an experiment takes the higher becomes the chance an S will drop out. Therefore, considerable thought must go into the efficiency of the design of an experiment. While we do not want to undertest an S and thereby obtain unreliable data, we also do not want to overtest either and obtain unnecessary data.

9) Equipment: Another consequence of long term testing is the need for frequent routine calibration of equipment and for preventative maintenance to keep equipment operational over the long term. Electronic equipment ages with time and as it does the characteristics of electroacoustic signals which are generated by the equipment can also change. Therefore, it is mandatory that we keep at hand sophisticated monitoring and calibrating equipment to insure our signals remain constant and to anticipate breakdowns in equipment. These procedures are time-consuming in themselves. However, it would be devastating to an experiment if near the end of a school year, equipment were to break down and subjects left for vacation before the experiment were completed; or alternatively to find for example, that a test-frequency had drafted, or an earphone had lost some of its output power. Probably these problems must be considered in any lab. Nevertheless, in a short-term experiment, a stimulus artifact or equipment breakdown means considerably less loss in time and money than in a long-term experiment.

10) Special equipment: Modern hearing aids have output sound pressure levels which exceed 130 dB and are used at these high levels by some severely hearing-impaired persons. However most clinical audiometers presently in use have maximum output levels which do not exceed 115-120 dB. It has been our experience that some severely impaired persons who show no responses with a conventional audiometer do give responses with our laboratory audiometer. This laboratory audiometer has maximum output of 135 dB SPL: that is, the same maximum output as that of the hearing-aids they use.

With its use we are able to perform discrimination tests at all output levels below an individual's discomfort threshold. With less powerful equipment some Ss could not be tested because their threshold of sensitivity is above the maximum output of conventional equipment. As a consequence one might invalidly assume such a person was incapable of making specified discrimination because he was not sensitive to such sounds.

Progress Report on Manuscripts Cited in this Section. Publishing of the manuscripts giving specific details of the experiments described in this section are in various stages of completion. Their present status is listed below.

Gengel, R. W. and Watson, C. S. Temporal integration: I. Clinical implications of a laboratory study. II. Additional data from hearing-impaired subjects. J. Speech Hear. Dis., 36, 1971, 213-224.

Gengel, R. W. Auditory temporal integration at relatively high masked-threshold levels. J. Acoust. Soc. Amer., 51, 1972, 1849-1851.

Gengel, R. W. Recognition of auditory temporal patterns by long-term hearing-impaired persons. Submitted for publication, November 1972.

Gengel, R. W. The temporal effect on frequency discrimination by hearing-impaired listeners. Submitted for publication October 1972. The manuscript has undergone editorial review, has been revised and resubmitted, and is presently awaiting final editorial review.

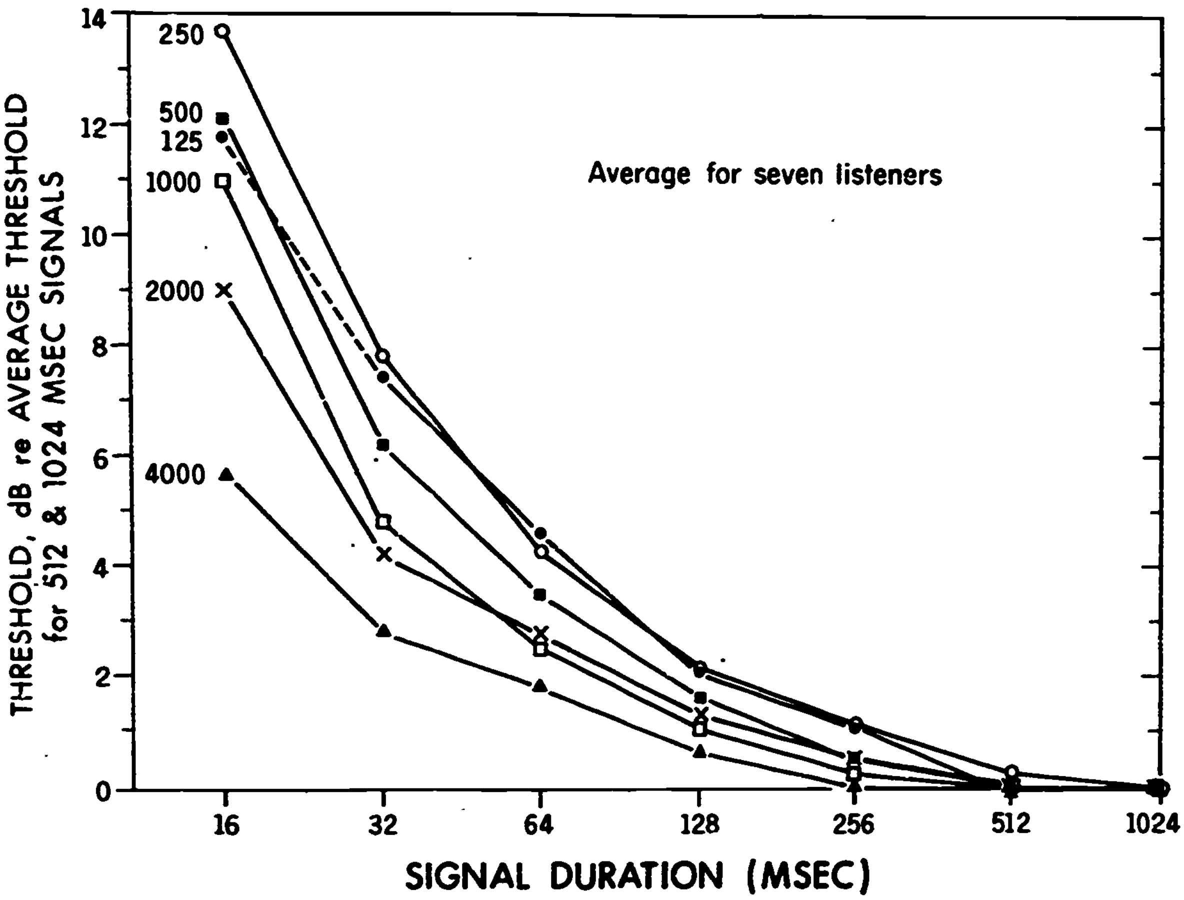

Fig. 1. Average integration functions for seven listeners. Each data point represents the average of at least 12 measurements for each listener (From Watson and Gengel, 1969).

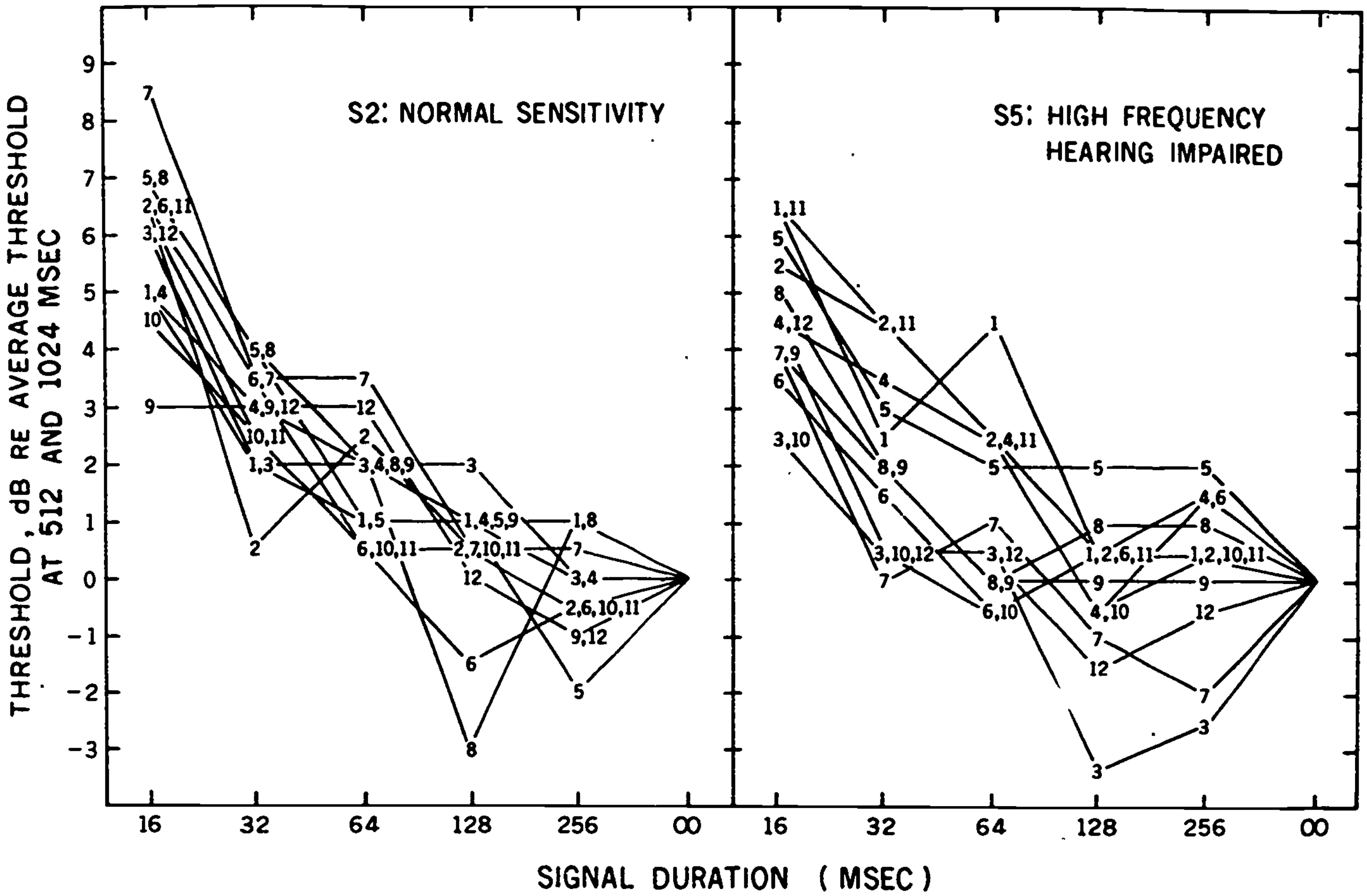

Fig. 2. Examples of the variability in slope of temporal integration functions obtained from 12 independent measurements at 4000 Hz. The numbers identify the 12 functions of a subject with normal sensitivity and a subject with high-frequency loss (From Gengel and Watson, 1971).

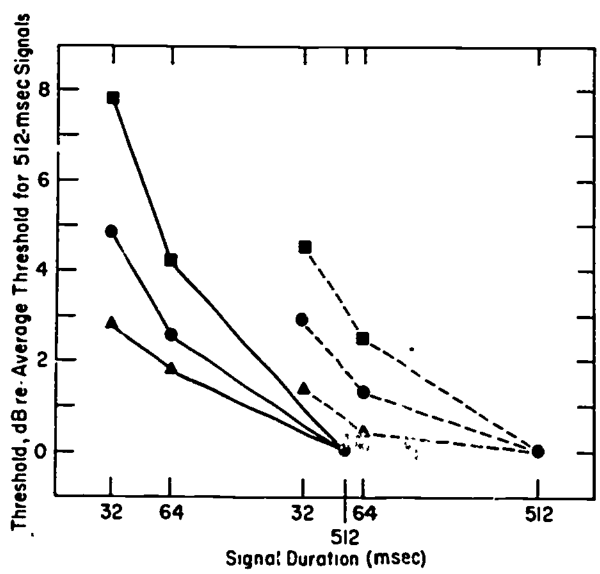

Fig. 3. Comparable temporal integration functions for two groups of Ss. The solid lines are average data for Ss with either normal sensitivity or moderate high-frequency hearing loss (adapted from Watson and Gengel, 1969). The dashed lines are average data from Ss with moderate to severe sensorineural hearing impairment at all test frequencies (adapted from Gengel and Watson, 1971). ■:0.25 kHz; ●: 1 kHz; ▲:4 kHz.

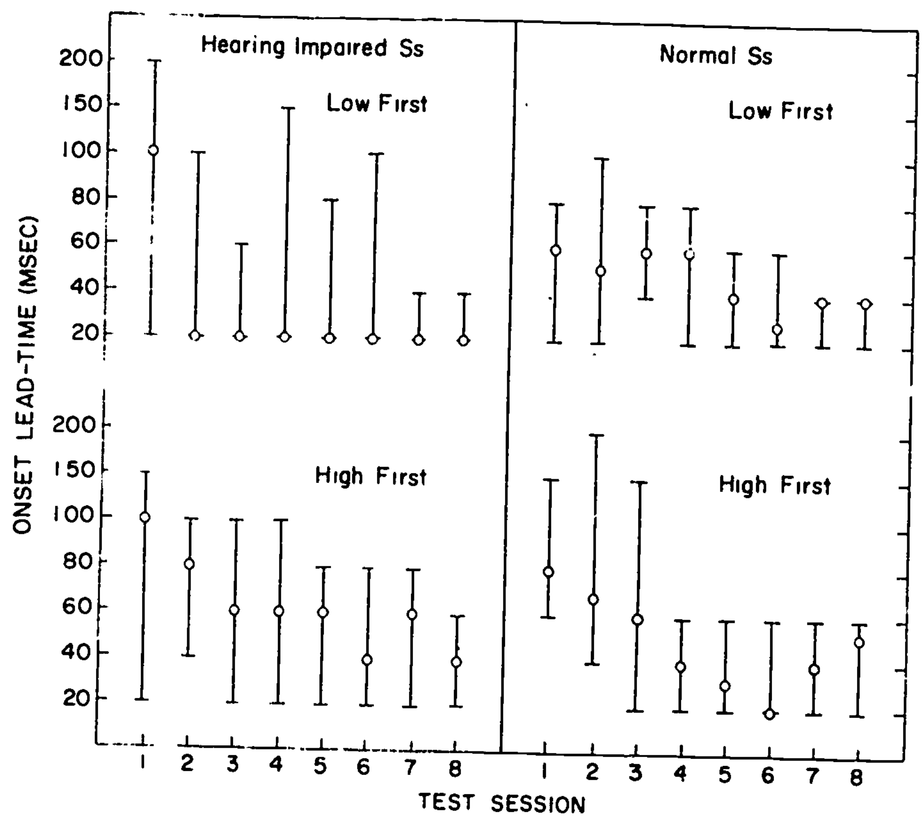

Fig. 4. Group medians (closed circles) and the range of onset lead-times required to recognize temporal order. The data are based on the smallest onset lead-time Ss could recognize with greater than 75 percent accuracy.

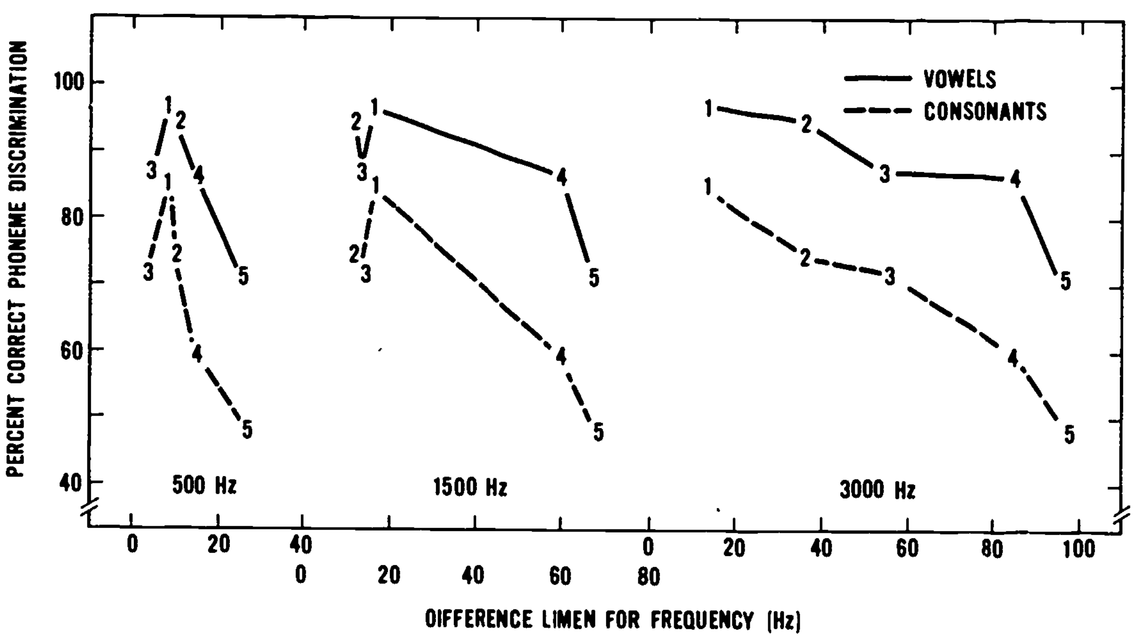

Fig. 5. The relationship between the absolute difference limen for frequency (50 msec signals) and speech discrimination scores for five subjects with sensorineural hearing impairment. The numbers identify the data points of the individual Ss. The lines identify performance seperately for vowel and consonant discrimination.

Table 1. Threshold in dB relative to threshold for 512-msec signals (From Gengel and Watson, 1971).

Frequency	Subject	Duration in msec	
		64	32
250 Hz	Range S1–S7	3.5–5.0	6.0–10.0
	S8	3.8	6.0
	S9	5.8	9.3
	S10	4.1	6.4
	S11	2.3	4.0
	S12	2.7	4.4
	S13	–0.2	1.9
	S14	2.2	4.4
	S15	2.6	4.6
500 Hz	Range S1–S7	2.2–4.5	5.0–7.5
	S8	3.1	5.2
	S9	5.9	6.8
	S10	1.9	4.1
	S11	1.1	3.6
	S12	1.4	3.2
	S13	0.1	0.9
	S14	1.5	3.3
	S15	–	–
1000 Hz	Range S1–S7	1.0–4.0	3.0–7.0
	S8	1.7	2.8
	S9	2.3	3.9
	S10	1.8	3.7
	S11	1.6	3.8
	S12	1.4	2.6
	S13	0.0	1.6
	S14	0.2	2.1
	S15	–	–
2000 Hz	Range S1–S7	0.2–4.0	2.2–6.5
	S8	0.4	1.3
	S9	–0.7	–1.3
	S10	1.1	2.3
	S11	1.6	2.2
	S12	1.5	2.2
	S13	0.0	0.8
	S14	–	–
	S15	–	–
4000 Hz	Range S1–S-7	1.2–2.2	2.0–3.7
	S8	–0.5	0.1
	S9	–	–
	S10	0.8	1.4
	S11	1.1	2.5
	S12	1.4	2.2
	S13	–0.5	.7
	S14	–	–
	S15	–	–

Table 2. Mean values of the size of the absolute difference limen for frequency (in Hz) for five hearing-impaired and for three normal-hearing listeners.

		Frequency of Standard Tone (KHz)					
		0.5		1.5		3.0	
		Stimulus Duration (msec)					
	Subject	50	500	50	500	50	500
Sensorineural Hearing-Impaired	1	7.8	5.8	16.3	13.0	13.6	11.1*
	2	10.3	4.8	12.0	6.4	35.9	19.6
	3	4.6	2.6	12.8	9.8	54.4	30.8
	4	13.9	10.5	59.4	36.2	84.0	34.8
	5	25.7	9.8	67.0	37.6	96.9	88.1
Normal-Hearing	I	4.2	1.6	6.8	1.6	13.3	5.2
	II	4.8	1.6	5.5	1.6	21.0	5.7
	III	4.0	1.5	11.5	3.2	29.6	7.6

* All values are in Hz

Table 3. The difference between the size of DLF_{50} and DLF_{500}, in Hz, for individual hearing-impaired and normal-hearing Ss.

	Subject	Frequency 0.5	1.5	3.0
Sensorineural Hearing-Impaired	1	2.0	3.3	2.5
	2	5.5	5.6	16.3
	3	2.0	4.0	16.4
	4	3.4	23.2	49.2
	5	15.9	29.4	8.8
Normal-Hearing	I	2.6	5.2	7.1
	II	3.2	3.9	15.3
	III	3.5	8.3	22.0

A2. Speech Pattern Perception

Background. Speech perception by listeners with severe hearing impairment has not been studied intensively to describe its detailed characteristics. For normal listeners we know fairly well what acoustic pattern cues are used to discriminate the main phonetic features of speech sounds. If we had similar knowledge about impaired speech perception we might be able to develop better methods of auditory training and provide a better basis for designing aids for the deaf. The impairments of most crucial concern are cases of moderate and severe sensorineural damage which typically show deficient perception of speech even under optimum conditions. In this part of our study we analyzed data on the reception of the phonetic features of consonant sounds within divisions of a group of severe sensorineural cases.

A large population of severe sensorineural cases is assessed routinely in our clinic, upon admission to Gallaudet College. A special version of the Fairbanks-House Modified Rhyme Test was constructed and administered to 99 such subjects who appeared to have residual auditory discrimination. The responses were then analyzed by examining confusions and by calculating the proportions of responses correct as to feature for the consonant features of voicing, manner, and place of articulation, for both initial and final consonants.

Methods. The Rhyme Test was constructed of 50 items, 20 testing initial consonants, 20 testing final consonants, and 10 testing vowels. Each item consisted of six one-syllable response words chosen as nearly as possible to cover the distinctions of interest. The stimulus word for each item was chosen at random from among the six response words; all were one-syllable words. The 50 stimulus words were recorded and pronounced by an experienced male talker who monitored himself closely on a VU meter.

The Rhyme Test responses of ninety-nine selected students were analyzed. The basis for selection was to use the data of all students who showed any residual discrimination for speech. The subjects' audiograms and probable causes of deafness were carefully examined with a view to grouping the response data for analysis in various ways. Correlations were run between Rhyme Test score, average hearing loss, and duration of use of a hearing aid. None of these approaches looked especially cogent or promising so we decided to group the responses of the subjects by quartiles of discrimination ability as measured by the overall Rhyme Test score.

There was no significant correlation between Rhyme Test score and duration of use of a hearing aid, or between duration of hearing aid use and average pure-tone threshold. These low correlations indicate to us that the test responses do not depend highly on amount of experience with amplified sound. Thus we believe that our results reflect effects of inherent auditory factors. The correlation between Rhyme score and average pure-tone threshold (1K, 2K, in dB SPL) was -0.66, significantly different from zero at $p<.01$.

Response Analysis. The consonant responses were analyzed to determine how well certain phonetic features were received by the listeners. The analysis was made for three features: 1) place of articulation, 2) voicing, and 3) low continuant, i.e., the occurrence of strong low-frequency energy as in nasals, liquids, and glides, as opposed to stops and fricatives.

The reception measure used was the proportion of pooled responses, that were correct as to the feature-state of the stimulus consonant as adjusted for chance. Correct proportions equal to or very near the chance proportion were adjusted to zero or nearly zero.

The analysis showed, first that the place features of both initial and final consonants are received much more poorly than the voicing feature and the low-continuant feature. For final consonants voicing was received somewhat better than the low-continuant feature but these are about equally received in initial consonants. As a whole, the features of initial consonants are received better than those of final consonants. The subjects in the top quartiles of discrimination receive initial voicing and low-continuant almost perfectly but still make errors in hearing the place of articulation for initial consonants.

Discrimination of Consonant Cues. It is well known that discrimination of place of articulation of consonants by normal listeners can be accomplished on the basis of perceiving the transitions in the frequency of the second formant of the adjacent vowel. Our results show that the place feature is poorly perceived by sensorineural listeners. In related work, measuring discrimination of vowel formant transitions by sensorineural listeners, we have found deficiencies in the second formant region compared with normal listeners, especially for brief transitions.

On the other hand, the consonant features of voicing and of presence or absence of low-continuant energy, may depend on hearing only the gross features of the low-frequency speech patterns. Voicing of consonants may be partially perceived by discriminating vowel durations. Also there may be amplitude differences in vowel-onset envelope that help to differentiate the voiced and low-continuant consonants from other classes and these differences may be perceivable with low-frequency hearing alone, or even through tactual sensation.

Conlcusions. From these studies we draw the following general conclusions:

1. Sensorineural hearing-impaired listeners have better residual reception for low-frequency speech patterns, such as voicing, nasal murmurs, and the first formant of vowels, than the the middle- and high-frequency patterns, such as the bursts of noise after unvoiced stops, the fricative consonants, and the second, and higher vowel formants.

2. The superiority of low-frequency pattern reception holds over a rather wide range of degrees and types of sensorineural impairment.

The previous studies on this problem were reviewed in detail and a complete report was published (Pickett, et al, 1972).

A3. Phoneme Boundaries in Speech Perception

A preliminary study was carried out to further explore the perceptual discrimination structure for speech patterns of persons with severe sensorineural impairment. Normal listeners discriminate between speech sound patterns in a discontinuous manner; their discrimination is "tuned" to respond very sensitively to a physical sound change which would be produced by an essential articulatory difference, i.e. a phonemic difference, but if the same amount of sound change is made in a different frequency region so that it does not correspond to a phonemic difference, then it is not discriminated by the listener. To the extent that the discrimination of a hearing-impaired listener is also "tuned" in this way to respond to the naturally occurring phonemic differences, we would expect that acoustic transposition of the differences could make them indistinguishable at least until discrimination could be re-trained. This is obviously an extremely important possibility to check.

Tests for this purpose were designed. The stimuli were synthetic CV syllables with voiced stops and two vowels, /i/ and /a/. The second formant (F2) transitions of the syllables were arranged, in a set of 17 syllables with each vowel, so as to form a continuous physical series of steps in the frequency location of the starting point of the F2 transition. When a normal listener hears the /a/ series, the first few syllables all sound like /ba/, the middle syllables all sound like /da/, and the last few sound like /ga/. Taking from the series all the pairs of syllables that are two steps apart, on the scale of F2 starting points, a discrimination test was made up containing 16 stimulus pairs. The members of a pair of syllables normally sound alike at the ends and middle of the scale of F2 starting location; that is at the low end a pair sounds like /ba/-/ba/, in the middle /da/-/da/, and at the high end /ga/-/ga/. A normal listener will judge the members of these pairs as sounding very similar. However, pairs in which the two-step difference bridges a normal phoneme boundary sound very different. If the difference is between low and middle F2 starting points the pair sounds like /ba/-/da/ and pairs bridging middle and high starting points are like /da/-/ga/. The amount of difference between F2 starting frequencies is the same for all pairs namely two physical steps, but if the difference does not correspond to a phoneme difference, it does not sound like a difference to the normal listener. Tests were begun with two deaf listeners and one normal listener. The task of the listener was to say, for each pair of sounds, whether or not he heard a difference between the pair members and to rate the certainty of his answer on a 5-point scale. The listeners did not know that a difference always existed in the pair.

In the first part of the experiment the listeners were instructed to listen for the occurrence of any difference at all between the members of a stimulus pair. Under this instruction the normal listener showed peaks of discrimination across phoneme boundaries, in other words the stimuli apparently sounded to him like the syllables intended in the synthesis series, i.e. /ba/, /da/, or /ga/ and /bi/, /di/, or /gi/. However, the deaf listeners did not show any consistent discrimination. In the second part of the experiment, the listeners were instructed that the stimuli might sound like syllables, such as those intended in the synthesis. This caused the deaf listeners to hear more differences and to demonstrate phoneme boundaries. However, the phoneme boundaries appeared only when some of the normal low-frequency sound in the stimuli was suppressed by reducing the playback level of the first formant (F1).

B. TRANSPOSITION FOR HEARING AIDS

B1. Tests of Transposer Hearing Aid

Background. Deafness often affects hearing for high-frequency sounds more than for low-frequency sounds. Thus many hearing-impaired persons cannot hear some of the high frequency features of speech. The transposer hearing aid (Johansson, 1959) is designed to make certain high-frequency sounds audible by transposing them to a lower frequency range. The aid has two channels of operation. One channel acts as a conventional hearing aid, amplifying sound in a frequency range between approximately 0.2 and 3.0 KHz. The second channel transposes sounds in the 4.0 to 6.0 KHZ range down to the frequency region below 1.5 KHz. The outputs of the two channels are then added together. Subjectively the user hears amplified speech with added low-frequency bursts of sounds. The low-frequency bursts are the transposed versions of the high-frequency sounds of speech. These occur mainly above 4 KHz and they are primary features of strong friction-like sounds such as s, ʃ(sh), f, and θ(th), and the brief noise bursts of stop consonants. Thus the transposer aid offers the possibility of providing additional speech information for persons who normally cannot hear these high-frequency sounds.

The initial evaluations of the transposer were done in Sweden (Wedenberg, 1959; Johansson and Sjogren, 1965; Risberg, 1965; Johnasson, 1966). Hearing-impaired children were used as subjects (Ss), as well as normal Ss where hearing loss was simulated by filtering the speech. The stimulus materials were Swedish monosyllabic words or consonant-vowel syllables such as /sa, ʃa, ka, ga, va/ or both types of materials. In all of these studies speech discrimination-performance was higher with the transposer than with conventional amplification alone.

However, Ling, 1968, questioned the value of the transposer aid when he found no differences in discrimination-performance from hearing-impaired children between the transposer and conventionally amplified speech. He used English disyllabic and monosyllabic words as stimuli and included a relatively long training period (18 hrs, 20 min per S).

Unfortunately Ling neglected to control a possible stimulus artifact which may have influenced his results. The transposing channel of the transposer aid is adjustable to allow different amplitude levels of the transposed sound. The level is also dependent on how the bandwidth of the high frequency input is adjusted. With the maximum adjustment, which is the one Ling used, the level and relative on-time of the sound is very high and may have been so high as to nullify any potential benefits of the transposed signal. By using a lesser amount of transposed signal, Ling might have verified the previous results.

In light of the generally favorable results described above we began pilot studies with the transposer aid. At that time we felt that our facilities provided two large advantages over other laboratories for evaluating this aid. First we could work with hearing-impaired adults (college students) and thereby by-pass some of the problems involved in testing hearing-impaired children. Second these subjects could be hired to work for extended periods of time in order to take training effects into account. All of our subjects had long-term hearing impairment of sensorineural type.

When we began our work two versions of the transposer aid were available on a limited basis; a desk model and a wearable body-model. The latter was a prototype aid, developed by the Oticon Corporation, Inc. and designated Tp 64. For technical reasons all of our evaluations were done with the body-worn Tp 64, loaned to us by Oticon Corporation. We originally also planned to evaluate a second ear level aid, the Acousis binaural aid. Unfortunately, prototypes of this aid have not yet been produced.

We first carried out a pilot evaluation of the transposer aid using as subjects three college students with severe hearing loss in the high-frequency range. Their audiograms are given in Appendix 1, Audiograms S1-S3. These Ss had residual discrimination for words that was low but appreciable. They appeared to be good candidates for the transposer.

The Ss were trained and tested in the laboratory and they also used the aids in daily routine activities. The laboratory sessions were two half-hour sessions per week using the following conditions of amplification: (1) transposer aid; (2) body-model conventional aid; and to a lesser extent, as a subcondition, S's personal aid. The training and test materials consisted of spoken monosyllabic words which were used in sets where the words differed only in the initial consonant. An example of a set of test words is shop, chop, top, sop, fop. The initial consonants of these words differ mainly in the high frequencies. These would be inaudible to our subjects under conventional amplification but with the transposer these consonants are heard in the low frequencies. These consonants also differ somewhat in their mid-frequency patterns (around 1. to 2. KHz) but these patterns are briefer and considered to be less salient.

Tests were arranged as forced-choice discrimination tests. For each spoken test word, S was provided with 2, 4, or 5 alternative response words corresponding to the set of stimulus words used by the talker. The training procedure used in this study and all subsequent ones was to give Ss immediate knowledge of the correct stimulus word after each response. Performance was scored as the percentage of correct response. In addition to the laboratory sessions the Ss used the hearing aids during their routine daily activities for a period of from two to seven weeks depending on the availability of the S.

The results of the tests were as follows:
Subject 1. Scores obtained with the transposer were 16% higher than with the body model aid and 32% higher than with the personal aid.

Subject 2. Scores with the body model aid were 12% higher than scores with the transposer and 22% higher than with the personal aid.

Subject 3. Scores with the body model were 5% higher than with the transposer and 7% higher than with the personal aid.

These results indicate that with a limited vocabulary one subject (S1) obtained significantly higher discrimination scores with the transposer while another subject (S2) obtained significantly higher scores with conventional amplification, while the third showed essentially no differences between the transposer and conventional amplification.

At that time we could only speculate as to why these three Ss performed so differently from each other. The reduced scores obtained while using

using their personal aids could have been due to the lesser amount of training that was given. However this practice effect cannot explain the differences in scores for the transposer and conventional amplification for Ss 1 and 2.

We decided that if we ourselves could listen to the transposer, we might understand better the characteristics of the cues available in transposed speech, and thereby could train Ss more effectively to use these new cues. Therefore, a small monitoring amplifier was constructed to operate on the output of the trannposer. A Y-cord was inserted into the transposer output terminal. One arm of the Y-cord fed the output to a battery operated amplifier-attenuator circuit and subsequently to an insert receiver used by the experimenter, while the other arm of the Y-cord sent the signal unmodified to the subject. With this device, the experimenter could monitor, at a comfortable and adjustable level, all stimuli sent to the subject.

This setup was used during the training and testing of three additional Ss. (See Appendix 1, S4-S6 for the Ss' audiograms). Subject 4 had normal auditory sensitivity at 250 Hz but no apparent hearing above 1500 Hz. She used the transposer for three weeks during her routine activities and during two one-hour training and test sessions per week. The other two Ss followed similar schedules during two-week (S5) and four-week (S6) periods. The transposer Tp 64 was used both as transposer and as a conventional aid. This is possible by simply flipping the switch that disconnects the transposing channel.

While listening to the transposer during the training and test sessions, it became evident that the fricative sounds /s/ and /ʃ/ were very difficult to discriminate from one another. On the other hand /s/ and /t/ were very easy to discriminate because of the difference in duration of these two sounds.

In two-alternative forced-choice discrimination tests our subjects validated these observations; i.e. /s-ʃ/ were indiscriminable while /s-t/ were easily discriminated in the transposed mode. Actually, S4, who had normal low-frequency hearing, discriminated between /s-ʃ/ by conventional amplification, possibly because she discriminated some mid-frequency cues for /ʃ/. The other two Ss could not hear any friction noise in the conventional mode and therefore could not make this discrimination.

Short sentences were also used as test materials with Ss 4-6. Subject 4 recognized these sentences equally well in both the transposer and conventional modes. However, she complained that the low frequency noise in the transposed mode was distracting and actually made listening confusing for some sounds. We therefore concluded that a person with considerable low frequency hearing might not be a good candidate for a transposer hearing aid.

Using the transposer, the other two Ss, 5 and 6, were able to discriminate between selected fricative and stop sounds; however, sentence discrimination was no better with or without transposition. As a partial explanation of her performance Subject 6 volunteered the information that the transposer was not as powerful as her own body model aid. This suggested a need to boost the power output of the transposer when working with severely hearing-impaired Ss.

To boost the maximum output of the Tp 64 from approximately 124 dB SPL to approximately 135 dB SPL the following modifications were made: the electrical output of the aid was passed through a linear power amplifier which left the signal unaltered except for increasing its power. The signal was then sent through a splitting network, essentially a type of Y-cord. Each arm of the Y had an attenuator inserted in it so that the subject and experimenter could adjust the signals individually to their comfort settings. They listened simultaneously to the signals by means of individual insert receivers.

With the arrangement described above, four additional Ss with severe hearing impairments were trained and tested one hour per week over a two-month period. These four Ss had very low speech discrimination ability as indicated by clinical evaluation.

Without transposition these subjects could not hear any of the fricative or unvoiced stop consonants. Two-alternative forced choice tests were employed. With the transposed condition, some discriminations could be made among certain fricatives. However, the discriminations were rather difficult. For example: (1) sang vs fang could be discriminated on the basis of a louder and longer turbulent sound for /s/ than for /f/; (2) fang vs hang could be discriminated on the basis of a more rapid onset of turbulence for /f/ than for /h/; (3) discrimination of keel vs heel and peel vs heel was also based on more rapid onset of /k and p/ than /h/. /s/ and /ʃ/ were indiscriminable as we had previously found. The unvoiced stops /p, t, k/ were indiscriminable from one another. Finally, even with transposition /θ/ was inaudible.

Although the above information indicates that the transposer benefitted these severely impaired Ss, discrimination, among for example, six alternative choices, was near the chance level. One of the Ss even scored near chance on a vowel discrimination test. In addition, although she used a hearing aid, she did not seem to understand the differences between voiced and voiceless stops.

Measurements with these Ss were terminated due to a malfunction in the transposer hearing aid. However, it was apparent that to obtain useable data from such severely impaired subjects, very long concentrated training program might be necessary. Furthermore it would probably be more useful in these cases, to evaluate the transposer as an aid to lipreading rather than solely as an aid to auditory communication.

The next experiment employed lipreading as well as listening. The subjects had various configurations of hearing loss. (See Appendix 1, S11-20 for audiograms). Most of the Ss had appreciable speech discrimination and did not require overly long training periods. Standard clinical tests of speech discrimination were used, namely the Modified Rhyme Test and the CID Phonetically Balanced Word Lists. These two tests contain a total of 500 words arranged into 42 different lists. Subjects were trained and tested with these materials during two or three one-hour sessions per week for approximately five weeks. Test conditions included listening only, listening and lipreading combined, and for comparative purposes, lipreading only.

Analysis of the group data indicated that, on the average, the group obtained higher overall scores with the transposer- than with conventional-amplification. This result occurred both for listening alone and for listening combined with lipreading. However, inspection of the individual data indicated that all Ss did not benefit equally from transposition. (See Appendix 2 for the individual data). The differences in scores between transposer- and conventional-amplification varied between subjects from essentially no difference to approximately 10 percent higher scores with the transposer.

Significant training effects were seen for most Ss. Improvements in discrimination scores by as much as 10 to 20 percent were common, both for transposer and for conventional amplification. Furthermore, the data indicated that, at the end of the experiment, these Ss had not reached maximum performance under all conditions and that, with more training, their scores would have shown further improvement.

In addition to the objective measures just described, we also obtained subjective evaluations of the transposer. Ss were asked to state their preference for either the transposer test condition or the conventional condition, and to describe how the signals sounded. Initially, only two of the eight Ss preferred the transposer, but at the end of testing six of the eight Ss preferred the transposer. Early comments indicated that the new cues were difficult to interpret, or that the additional low frequency information tended to confuse or mask out the rest of the stimulus. One S found that the transposer altered the vowel /i/ so that she confused it with /ɛ/. Another S said that sometimes, the transposer made it more difficult to discriminate (p/t) and (p/b). One S commented that he "didn't like the sound of his own voice with the transposer." However, as the training progressed, the comments became more favorable. Some of the Ss reported that discrimination of (k/t) in the final position was easier with the transposer. Another girl said it was "just easier to hear" with the transposer and she was "getting used to it." In response to the questions asked at the end of the project, five of the seven regular hearing aid users felt it was a little, or much better than their present hearing aid.[1]

Conclusions and Discussion. Our results have verified the positive results obtained by other experimenters that, on the average, speech discrimination-performance is higher for transposer amplification than for conventional amplification. Our final experiment was the first to employ the transposer with lipreading and it appears that the transposed information is complementary to lipreading information. However, there are individual differences which indicate that not all Ss will benefit equally from the transposer. At best we have found approximately 10% additional benefit for transposer amplification compared to conventional amplification while at worst, there have been no differences in performance. In the latter case, some of the Ss indicated that listening was more difficult with the transposer and therefore our tests might not have been sensitive enough to indicate real differences favoring conventional amplification.

Nevertheless, our data indicate that a person will perform either about the same with the transposer as with conventional amplification or will perform slightly better with transposer amplification. Group data will not indicate which specific Ss will receive the additional benefit of the transposer and therefore future evaluations of the transposer should deal primarily with evaluation of individual performance with transposer and conventional amplification.

1. The results of this experiment will be reported at the Third International Oticongress, Copenhagen, sponsored by the Oticon Corporation.

Our experiments indicate further that subjective, as well as objective responses need to be considered when evaluating the transposer. Initially we found considerable resistance to the transposer. A number of Ss at first found that the new sounds were confusing or unpleasant to listen to and only with training were these negative reactions overcome. Possibly, the trial-by-trial feedback helped convince the Ss that useful information could be obtained from the transposed speech signals and possibly this knowledge helped change their opinions about the transposer.

Two very important questions remain to be answered in future evaluations of the transposer. The first question is: given that transposer amplification can give greater benefit than conventional amplification for isolated syllables and words, will these benefits hold also for running speech? Conceivably the transposed consonant sounds could act to obliterate syllable or word boundaries and as a result make running speech less discriminable.

The second question is: how will environmental noise affect discrimination with the transposer? We do not know how clothing noise, competing speech and other environmental sounds will degrade transposed speech discrimination.

Before these two questions are answered, evaluation of the transposer aid should not be considered to be complete. Nevertheless at least one model, the Oticon Tp 72 just recently was made available commercially with advertising suggesting its use with severely hearing-impaired children.

We propose a further series of experiments to measure the effects of the transposer in listening to fluent speech and in noisy situations. Detailed plans are given in the attached proposal.

B2. Theoretical Aspects of Transposition

Our past thinking about a transposing aid for hearing-impaired persons has put a high weight on electronic feasibility for a wearable aid. This has led us to employ the heterodyne method for frequency-shifting; this method produces transposed sounds that have an "unnatural" structure in relation to the original sounds. The heterodyne method is used in the transposer hearing aid and in our laboratory transposer system.*

Our studies of speech acoustic patterns in relation to speech perception (Pickett, et al, 1972) show that deaf persons rely on perceiving the same speech patterns as do normal listeners. Therefore we should consider the strong possibility that, for the best transposing scheme, the normal speech pattern relations should not be so radically altered as they are when transposed by the heterodyne method. Also, even if it were found that hearing-impaired listeners, especially deaf children, could acquire speech communication abilities through a radically re-structured auditory code, these persons might be totally at a loss when their re-coding aid is out of order because they would not be able to use conventional amplification (hearing aid, classroom amplifier, or speech at the ear).

There is a type of speech transposition that occurs naturally and retains the relational aspects of all the speech sounds; it is the translation of speech frequency patterns that occurs when the same word or phrase is spoken by a small child, then by a woman, and then by a man. The frequency translation occurs because the speech articulations are virtually the same for child, woman, and man but the resulting frequency patterns depend on the size of the spaces in the vocal tract. These spatial dimensions increase by a factor of two or more going from children to women to men, and there is a corresponding shift downward in the speech frequency patterns.

There is some evidence suggesting that this natural downward translation of speech frequency patterns makes them more intelligible to hearing-impaired persons. First, audiological patients often report that it is easier to understand men than women and easier to understand women than children. Second, in a British study of hearing aids the male speakers were more intelligible to deaf listeners than the female speakers (Medical Research Council, 1947); the intelligibility of the males was 30 percentage points higher! Finally, a study by Bennett and Byers (1967) showed that hearing-impaired listeners obtained 16% higher speech reception scores by means of a 10% downward frequency translation obtained by slow tape playback.

Current technology has made it easy to process speech so as to shift all the frequency patterns. Computer demonstrations of frequency translation indicate that speech is reasonably intelligible when translated downward by as much as a factor of 2 to 1; the effect is that of listening to a speaker whose vocal dimensions are larger than those of the original speaker. A woman's speech thus translated sounds like that of a very deep-voiced man; a small child's voice would sound like that of an average man. A man's voice

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*In the transposer aid the frequency spectra of the original fricative sounds are inverted, folded at the carrier frequency, and re-scaled with the carrier frequency as zero. A similar procedure is used in our laboratory transposing system where it results in a frequency inversion of the vowel formant relations.

still sounds fairly intelligible when translated downward by a factor of 2 to 1. Computer techniques are available that will produce an adjustable frequency translation of any desired amount with negligible time lag.

Would this type of "natural" transposition result in a speech signal that is more intelligible to deaf persons? We think it is now time to carefully test this possibility.

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Appendix 1. Audiograms (Hearing Level re: ISO, 1964) for the test ears of subjects used for the evaluation of the Tp-64 transposer hearing aid.

	Frequency (in KHz)					
Subject	.25	.5	1.0	2.0	4.0	8.0
1	50	60	90	NR	NR	NR
2	70	65	85	85	NR	NR
3	60	70	80	NR	NR	NR
4	15	25	80	NR	NR	NR
5	90	85	100	100	100	NR
6	80	85	95	NR	NR	NR
7	75	90	110	NR	NR	NR
8	80	95	110	NR	NR	NR
9	75	85	100	NR	NR	NR
10	85	85	100	NR	NR	NR
11	65	80	110	110	100	NR
12	80	75	85	110	105	NR
13	105	105	110	105	95	NR
14	95	95	100	110	NR	NR
15	55	85	100	95	90	NR
16	75	80	85	70	65	NR
17	90	100	110	105	80	NR
18	40	70	95	105	110	NR
19	65	75	90	110	NR	NR
20	65	75	90	110	NR	NR