PERCEPTION OF AMPLITUDE COMPRESSED SPEECH BY PERSONS EXHIBITING LOUDNESS RECRUITMENT

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This is to certify that the

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ABSTRACT

PERCEPTION OF AMPLITUDE COMPRESSED SPEECH BY PERSONS EXHIBITING LOUDNESS RECRUITMENT

by

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Speech discrimination performance of thirty-six subjects was compared for conditions of amplitude compression and for no compression. These conditions were achieved with a prototype amplitude compressor. The instrument had input-to-output amplification ratios of two-to-one and three-to-one and it also functioned as a linear amplifier which was called one-to-one amplification.

The thirty-six subjects, all of whom had unilateral sensorineural hearing loss, were partitioned into partial or complete loudness recruitment groups on the basis of their response to a speech noise alternate binaural loudness balanace (ABLB) test. Classification of subjects was carried out according to two procedures. The "classical" procedure involved a comparison of the magnitude of the sensation levels above threshold necessary to make the test signals equally loud. The second system was based on intra-aural comparison of the loudness growth function.

Samuel Britton Burchfield

Speech discrimination tests employing monosyllabic CNC words were presented at 24 dB sensation level at the affected ear under each compression condition. Broad band masking noise was routinely applied at the contralateral ear.

Statistical analyses of the data, partitioned by either method for defining recruitment, yielded similar results. Speech discrimination scores were significantly higher for the two-to-one and the three-to-one compression than for the one-to-one and the benefit was of the same order of magnitude for both recruitment groups.

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By

Samuel Britton Burchfield

A THESIS

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For my wife Burch,

who gave us Christy

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CHAPTER I

INTRODUCTION

The idea that amplitude compression can aid persons with loudness recruitment in their perception of speech is neither novel nor new. Huizing (1948, 1952) and Huizing and Reyntjes (1952) implied that speech discrimination was impaired by loudness recruitment because of increased sensitivity for differences in intensity and thereby normal loudness relationships among speech sounds are altered. Caraway (1964) and Caraway and Carhart (1967) conjectured that persons with recruitment, therefore, may not need as large a dynamic range as do normal listeners in order to take full advantage of speech signals. They hypothesized that speech with reduced dynamic range (i.e. amplitude compressed speech) would improve speech discrimination in subjects exhibiting loudness recruitment. Their hypothesis was tested by comparing the discrimination scores for compressed speech in four groups of subjects whom they assumed to differ in their magnitude of loudness recruitment. The groups demonstrated only slight improvement for the compressed speech, and it was concluded that the technique offered no important advantage over linear amplification.

The present study extends Caraway and Carhart's research by first operationally defining loudness recruitment and then testing their original hypothesis within this constraint.

A necessary requirement for conducting the experiment was employment of a method for quantifying loudness recruitment. An alternate binaural loudness balancing technique, employing speech noise signals, was devised for this quantification.

Specification of the performance characteristics of the amplitude compression system was also of primary importance.

Purpose of the Study

This study sought basic information concerning the relationship between loudness recruitment and the discrimination of amplitude compressed speech. The purpose was to compare speech discrimination performance of two groups that were heterogeneous with respect to degree of loudness recruitment. Speech signals were presented at two levels of amplitude compression and also with no compression. The following questions were formulated to delimit the research:

1. Does amplitude compression improve speech discrimination in persons who exhibit loudness recruitment?

2. Is the amount of improvement in speech discrimination related to the amount of the loudness recruitment?
3. Is the amount of improvement in speech discrimination related to the degree of the amplitude compression?

Importance of the Study

Design specifications of hearing aids involve numerous compromises necessitated by the interaction of distortion produced by the aid and by the response characteristics of the pathological ear. Appropriate hearing aid design depends, or should depend, on an understanding of these interactions.

In reference to the relationship between the characteristics of amplitude limiting systems and hypoacusic speech discrimination, Lynn (1962) commented that the "scanty" evidence is contradictory and indicates the need for additional study. Furthermore, Caraway's research, which was conducted in 1964, is the first and only systematic, empirical investigation employing amplitude compression (as distinguished from amplitude limiting).

The idea that amplitude compression can offer recruiting ears special enhancement in their discrimination of speech signals has, therefore, received recognition but only very limited study. In this context, recruitment has never been quantified and many basic questions remain unanswered.

Information obtained from the study is viewed as having possible application in increasing the hypoacusic's potential success in utilizing amplification.

CHAPTER II

BACKGROUND INFORMATION AND LITERATURE REVIEW

This chapter describes the performance characteristics of amplitude controlling devices and summarizes their effects on speech discrimination. Amplitude control as a solution for loudness recruitment is also discussed.

Performance Characteristics of Amplitude Controlling Devices

Three important features of amplitude controlling devices are input-output relationships, time constants, and problems associated with the control.

Input-Output Relationships. In linear amplifiers input-to-output intensity ratios remain essentially constant. For example, the output sound pressure will increase 10 dB if the input signal is increased 10 dB. Moreover, this linear ratio is maintained over most of the operational range of the instrument, except at very high input levels. Input above this level is usually accompanied by marked distortion of the waveform of the output signal.

Electrical engineers have sought linearity in amplifiers for many applications. There are, however, specific situations which necessitate nonlinear amplifiers or amplitude controlling devices (Appendix A). These devices restrict either the dynamic range or the peak output of amplified signals via nonlinear input-to-output pressure ratios. They are used routinely in the recording, transmission, and reception of audio signals, and recently they have been incorporated in hearing aids.

Two types of amplitude controlling devices are amplitude limiters and amplitude compressors (Langford-Smith, 1952). Limiting amplifiers are linear for low-input signals; however, gain is reduced when the input exceeds a set value. All inputs above this critical level show a fairly constant output. Compressors, operating on a somewhat different principle, are amplifiers with input-output ratios such that output pressure is inversely proportional with input signal strength. Input-output functions for limiters, compressors, and linear amplifiers are shown in Figure 1.

In linear amplification (curve A-B-C), gain is constant over the entire input range. For each increment in the input signal, an equal increment is observed in the output signal. This relationship yields a linear slope at an angle of 45 degrees.

On the other hand, amplitude controlling systems do not have constant input-output ratios. Curves A-B-F and A-B-G illustrate the output of two limiters. Both curves are linear below a critical level (point B), but increments

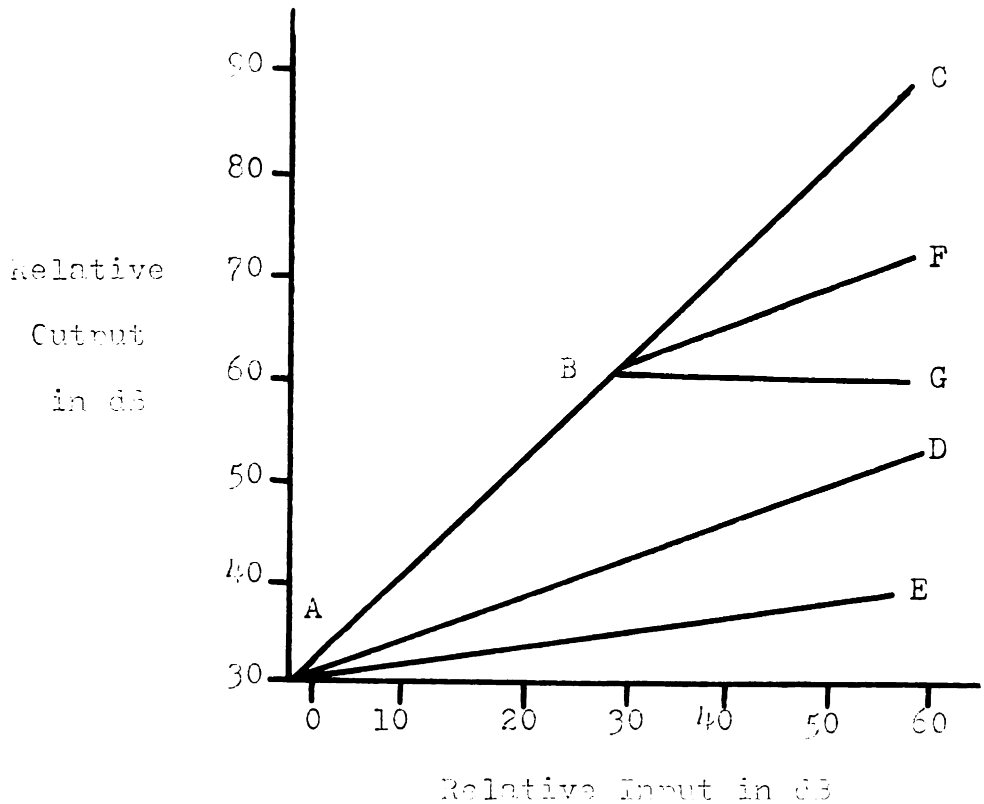

Figure 1. Gain characteristics of limiter and compressors. (A-B-C) linear amplifier 1:1 ratio, (A-D) compressor 2:1 ratio, (A-E) compressor 3:1 ratio, (A-B-F) limiter 3:1 ratio, (A-B-G) limiter 1:0 ratio (from Caraway and Carhart, 1967, p. 1425).

in the input signal above this point produce relatively smaller increments in the output signal. Curve A-B-G is actually an idealized limiter with output gain reduced by the amount that the input exceeds point B. Curve A-B-F shows the limiter function usually found in clinical application. These functions have fixed maximum output which tends to eliminate the distortion that accompanies linear amplification at very high input levels.

Curves A-D and A-E are compressor functions with two-to-one and three-to-one dB of input-output gain respectively. In amplitude compression, the shape of the waveform remains relatively intact while amplitude relationships are modified according to the input-output ratio.

The net effect of amplitude compression is dynamic range reduction. The amount of the reduction is determined by the input-output ratio of the amplifier. Reduction produced by one-to-one, two-to-one, and three-to-one compression ratios for speech signals having a 30 dB dynamic range are shown in Figure 2. The peak components of the speech signals, in this example, are equated at 30 dB sensation level. Dynamic range reduction under the two-to-one ratio is 15 dB, under three-to-one the reduction is 20 dB. This means that the peak components are held constant for each ratio, whereas the

Figure 2. Dynamic range reduction produced by one-to-one, two-to-one, and three-to-one amplitude compression for speech with a 30 dB dynamic range.

fainter components are amplified relatively more. The term "compression", therefore, refers to dynamic range reduction and should not be confused or equated with presentation level per se.

Time Constants. Amplitude control can be thought of as auto-regulation of gain based on input signal strength. Generally, the control action results from negative voltage feedback. For example, increments in input signal strength cause relatively more negative voltage to be applied to the amplifier, resulting in less gain. Decrements in the input signal strength result in less negative feedback, producing relatively more amplification.

The time needed to accomplish gain increments or decrements are called "time constants". The lapse before gain reduction is called "attack time", and the lapse before gain is restored is called either "release" or "recovery time". These concepts are applicable both to circuits which use control voltage to vary the gain of a linear amplifier and to circuits that operate on nonlinear components, as does the Weiss unit.

There is no standard for specifying the time constants of amplitude controlling devices. The percentage change in gain upon which these intervals are based are usually not specified in literature reports. The specifications utilized in this study, as well as the previous study by Caraway (1964), were suggested in 1949 by Grimwood. He proposed computing the constants upon ninety percent completion of gain change because the value provided a realistic estimate of the function and because it was manageable from the standpoint of accuracy of measurement.

The only systematic investigation of the influence of time constants on speech discrimination was conducted by Lynn (1962). Results, published by Lynn and Carhart in 1963, indicate that the time constants influence both the audibility and intelligibility of speech.

Problems Associated With Amplitude Control

Appropriate selection of the time constants can minimize the undesirable products of amplitude control. This section is devoted to a discussion of these problems and their amelioration.

Thump. Audible pulses which result from fast operating time are called "thump" (Maxwell, 1947; Grimwood, 1949; Singer, 1950; and Ancona, 1956). This is a d.c. pulse which results from the sudden change in gain. Fortunately, the pulse is usually low frequency and can be eliminated by low frequency filtering (Marcus and Marcus, 1965).

Program Gaps and Pumping. Program gaps are caused by slow release times on occasions when a faint sound follows a loud sound. The loud signal triggers an amplitude control response which can obscure a weak signal when it is in effect. Until the amplifier "recovers", its performance is analagous to the refractory phase in neural stimulation. "Gaps" in the program can be eliminated by using faster release times; however, "pumping" may result when this time is too fast. Pumping is excessive attack and release and occurs as a result of the rapid fluctuations in running speech (Maxwell, 1947; Grimwood, 1949; and Poliakoff, 1950).

Excessive Noise Level. Excessive noise is created by ambient noise being amplified at higher than normal relative levels. This noise is analogous to the fainter speech components in that it is amplified proportionately more than the stronger components. Several writers have commented about this undesirable concomitant feature of amplitude control (Davis et. al., 1947; Parker, 1953; Poliakoff, 1950; Rutherford, 1957; and Caraway, 1964).

Effects of Amplitude Control On Speech Discrimination

The effects of three methods of amplitude control, namely, peak clipping, amplitude limitation, and amplitude compression, will be considered in this section.

In peak clipping the amplitude of the sound wave is eliminated above a certain value. The degree of clipping can be specified by the fraction of maximum amplitude that is passed. Several writers have reported on methods of peak clipping and the effects produced by this method of control (Licklider and Pollack, 1948; Tolhurst, 1959; Velichkin, 1962; Gustavsson, 1963; and Pyron and Williamson, 1964).

Normal hearing subjects are able to understand speech which is dramatically clipped. Evidence of this ability is provided by Licklider and Pollack's statement that

> the so-called dynamic characteristics of speech are not of vital importance for intelligibility. It is apparently just as well to reproduce all the fundamental speech sounds (or what is left of them after infinite clipping) at the same intensity as it is to preserve their natural intensities (1948, p. 49).

This implies that intensity variations are probably not the basic cues in speech discrimination. Their statement, however, should not be interpreted as implying that intensity distributions of normal speech have no role in recognition.

Davis et.al. (1947), as a part of the Army and Navy aural rehabilitation programs, reported on a master hearing aid with both peak clipping and limiter action. The superiority of limiter action over peak clipping was shown in a series of speech discrimination tests using Harvard PB-50 stimulus material in three normal-hearing subjects. Similar results were observed in six hard-of-hearing subjects.

Hudgins et. al. (1948) built a wearable hearing aid with limiter action. This instrument was compared, via articulation tests with six hard-of-hearing subjects, with the master hearing aid just discussed and with two commercial hearing aids. The subjects were trained listeners who had utilized amplification for at least one year. Comparisons were based upon percent correct discrimination of Harvard PB-50 word lists (presented via monitored live voice) for successive input levels.

Results were summarized by the following statement:

> These results indicate clearly both the feasibility and the desirability of limiting the output of hearing aids by means of compression amplification. Furthermore, it is demonstrated that limiting the power output by means of compression amplification not only protects the ear but at the same time reduces distortion to a minimum, thus maintaining in most cases the maximum level of performance over a wide range of speech-input levels (1948, p. 253).

Several researchers have reported dramatic improvements in speech discrimination for hearing aids with amplitude limitation when compared with conventional hearing aids (Fournier, 1951; Pestalozza, 1953; Portmann and Portmann, 1961; Rice and Flemming, 1968, Bizaguet, 1968; and Flemming and Rice, 1969). Fournier (1951) and the Portmanns (1961) showed articulation functions for patients who demonstrated superior understanding for limited speech as compared with linear amplification. Pestalozza (1953) compared hearing aids with peak clipping, with volume limiting and with linear response. Superior scores were obtained under the volume limiting.

Edgardh (1951) observed that dynamic equalization was not obtained between the vowels and consonant sounds unless amplitude control functioned over the entire operative range. Working with extreme limitation, he found that speech was as intelligible as untreated speech, although the subjects observed quality differences.

The effects of peak clipping and amplitude limitation in the presence of white noise were studied by Kretsinger and Young (1960). These investigators compared the effects of two degrees of control, achieved by either method, on the discrimination of thirty normal-hearing subjects. The subjects exhibited superior scores

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for the limited PB-50 word lists (C.I.D. Auditory Test W-22) than for either no control or peak clipping.

It has been asserted that the amount of amplitude control preferred and needed by persons with different types of hearing loss varies considerably (Silverman and Harrison, 1951; Poliakoff, 1950; and Rice and Flemming, 1968). Parker's (1953) findings support this assertion. He investigated the effect of amplitude limitation in ten persons with various amounts of sensorineural hearing loss by constructing articulation functions for Harvard PB words at sensation levels of 6, 16, 26, and 36 dB. Results indicated considerable individual subject variability in the benefit afforded by limitation. Of the ten subjects, nine did obtain higher intelligibility with amplitude limitation at one of the sensation levels. Three had superior discrimination at all levels; six had superior discrimination at some levels and poorer scores at other levels; only one failed to benefit at all test levels. Notably, improvements ranged from 2 percent to 50 percent and the maximum help seemed to be at the lower sensation levels.

Lynn (1962) systematically investigated time constants of limited speech in groups of subjects with otosclerosis, labyrinthine hydrops, and presbycusis. The limiting was achieved with an instrument built from hearing aid components. Time constants were found to influence speech perception of Harvard PB word lists. Labyrinthine hydrops subjects performed optimally with shorter release times, and otosclerotics performed as well when no limitation was used. Lynn believed that time constants could be selected which yield optimum intelligibility and that these values do not appear to remain constant for all types of hearing loss.

It is important to note that the reports involving limiting demonstrate advantages for this type of amplitude control when compared to abrupt peak clipping and no advantages over speech without amplitude control.

As previously mentioned, the only systematic investigation of hypoacusic speech perception using amplitude compression per se was conducted by Caraway (1964). She investigated the effect of two degrees of compression compared to no compression using twelve subjects in each of the following catagories: labyrinthine hydrops, labyrinthine otosclerosis, presbycusis, and normal hearing.

Amplitude compression was achieved with the same compressor that was used in the present study. The instrument had compression ratios of two-to-one and three-to-one and it also functioned as a linear amplifier, called one-to-one compression amplification. Performance specifications of the instrument include a flat frequency response from 250 to 5000 Hz and time constants for all amplification conditions of 1.5 msec rise and 1 msec decay.

Caraway determined speech reception thresholds for spondees under each compression condition. She also constructed articulation functions for CNC words (Northwestern University Auditory Test No. 4) under each condition at sensation levels of 0, 8, 16, and 24 dB. Performance in speech discrimination improved only minimally for the compressed speech in all her subjects. Also, no important differences were found among the three degrees of compression when comparisons were made at a given sensation level.

Amplitude Control as a Solution for Loudness Recruitment

Persons with recruitment exhibit a reduction in the range of comfortable loudness for speech signals. This means that the decibel difference between the faintest audible sound and the strongest tolerable sound, i.e. the dynamic range of hearing, is reduced. At the same time, intensity variations encountered in the daily acoustic environment are great enough to tax even the normal ear's wide range of comfortable loudness. Moderate reduction in the comfort range may lead to problems in hearing faint sounds or annoyance from loud sounds.

Conventional linear amplification may not be ideal for persons with recruitment or a tolerance problem because it must be operated at high gain in order to make the faint sounds audible. When these sounds are amplified to an audible level, the loud sounds may become intolerable. With this mode of transmission, the only solution is gain reduction, thus sacrificing intelligibility of the fainter sounds.

Several people have expressed a special need in hearing aids for people with recruitment or for similar problems associated with tolerance (Groen, 1951; Neuberger, 1954; and Portmann and Portmann, 1961). Davis and Silverman (1970) contended that persons with loudness recruitment encounter difficulty in linear amplification because of the abrupt transition from hearing little or nothing to hearing very loud sounds. In other words, recruitment both disrupts normal loudness relationships and sharpens differential sensitivity (Huizing and Reyntjes, 1952; and Caraway and Carhart, 1967).

Pestalozza (1953) compared speech reception thresholds and speech discrimination measures for peak clipping and amplitude limitation. He found that limiting was the method of choice for controlling the maximum power of hearing aids and that linear amplification increased distortion and reduced discrimination when marked recruitment was present.

A specific type of articulation function, "regression", which appears in sensorineural hearing loss when recruitment is present, has been reported by several writers (Dix, Hallpike and Hood, 1948; Eby and Williams, 1951; Huizing and Reyntjes, 1952; and Schultz and Streepy, 1967). This function has increments in discrimination for increments in sensation level up to a point, but the discrimination decreases fairly rapidly for higher sensation levels. It has been suggested that optimum amplification would be provided by output limitation corresponding to a person's optimum range of intelligibility (Shutts, 1950; and Huizing and Reyntjes, 1952).

Design characteristics and an excellent rationale for using compression in amplification for recruiting ears were reported by Aspinall (1951) and by Rice and Flemming (1968). However, experimental results are not presented in either report. Other writers have specifically suggested compression for persons with a narrow range between the thresholds of intelligibility and tolerance limits (Ashton, 1951; Poliakoff, 1950; and Menzel, 1966). Again, however, experimental evidence is scanty and the effects of recruitment on the perception of amplitude controlled speech is not known.

Summary

Amplitude controlling devices, limiters and compressors, can be specified by their input-to-output dB ratios. Their performance as well as their effects on signals they transmit is markedly different. Amplitude compression acts to reduce the dynamic range of speech signals, whereas amplitude limitation tends to limit the maximum levels of the signals.

Although the time constants of limiters were found to influence audibility and intelligibility, there has been no systematic study of these constants in compressors. There appear to be concomitant problems associated with amplitude control. Fortunately, most of these difficulties can be minimized or eliminated by appropriate selection of the time constants.

Only one study (Caraway and Carhart, 1967) which investigated the effect on speech discrimination of using amplitude compression is reported in the literature. Several studies using amplitude limitation have been reported. These indicate that limitation appears to be preferable as a means of limiting the maximum output of hearing aids when compared with abrupt peak clipping. Extreme limitation does not seem to effect adversely speech understanding in normal hearing persons. However, when clipped and limited speech are immersed in noise, normal hearing subjects understand the limited speech better. Other studies have shown that sensorineural subjects vary greatly in the amount of benefit they achieve through limitation and that time constants influence discrimination.

The only study involving compression failed to demonstrate any important advantage for the amplitude controlled speech over speech with no amplitude control. It is important to note that the reports involving limitation demonstrate advantages for the control when compared to abrupt peak clipping and no advantages over speech without control.

Finally, the question remains regarding the differential effect on speech discrimination as a function of the degree of loudness recruitment.

CHAPTER III

EXPERIMENTAL PROCEDURES

This study investigated the ability of persons with different amounts of loudness recruitment to discriminate amplitude compressed speech. An alternate binaural loudness balance technique provided a criterion for placing subjects into either a partial or a complete recruitment group. Subjects were then tested under two degrees of compression and a condition of no compression. Two discrimination scores for CNC monosyllabic words were obtained for each subject under the three compression conditions.

Amplitude compression was accomplished with a prototype instrument built by Mr. Erwin Weiss and supplied by the Beltone Electronics Company. This compressor had input-to-output amplification ratios of two-to-one and three-to-one. It also functioned as a linear amplifier; this condition was called one-to-one amplification.

The test battery contained both preliminary audiometric evaluation and speech discrimination measurement. This included pure tone air and bone conduction thresholds, speech reception thresholds, speech noise alternate binaural loudness-balance test (ABLB), and speech discrimination tests under each of the three compression ratios.

For speech discrimination testing three permutations of Northwestern University Auditory Test No. 6 (lists II and III) served as stimulus material. The two scores at a given compression ratio were based on one arrangement of List II and one of List III. Each list was recorded at the three compression ratios in such a way that the average peak levels of the output signal were equivalent. That is, the speech signals for each condition were equated at their peak levels, and long term dynamic ranges below these levels differed from one ratio to another. For example, the uncompressed dynamic range of the speech stimulus material was approximately 24 dB. Under two-to-one compression this range was reduced to 12 dB and under three-to-one it was reduced to 8 dB.

A pre-test CNC list was presented at the outset and again as a post-test to investigate practice effects and time dependent influences.

Subjects

Thirty-six subjects, constituting two groups of eighteen each, were selected for the study. Their age and sex distributions are shown in Table I.

TABLE I

Age and sex distributions for the two groups

Recruitment Group	Age in Years			Sex Distribution	
	Mean	Median	Range	Male	Female
Partial	49.0	50.1	31.2-68.2	5	13
Complete	52.7	54.7	21.5-68.3	11	7

Preliminary selection of subjects was based on the results of audiograms available at the offices of Dr. Sanford C. Snyderman, Dr. E. H. Bergendahl, Dr. Charles S. Giffin, Dr. John Thomas, and Mr. Patrick Carter in Fort Wayne, Indiana.

Each met the following criteria for inclusion into the study:

1. All subjects were medically diagnosed as having unilateral, sensorineural hearing loss.
2. Better ear within normal limits (air and bone conduction thresholds no greater than 25 dB re ISO-1964 Norm) for 500, 1000, and 2000 Hz.
3. Intraaural speech reception threshold differential of 25 dB or greater.
4. No air-bone gap or no response by bone conduction at the maximum limits of the equipment.
5. Sufficient residual hearing in the speech frequencies of the test ear to allow speech discrimination assessment of 24 dB sensation level.
6. Eighth grade or higher education.
7. Hearing loss acquired after the development of English language.

The restrictions of a normal better ear and a 25 dB intraaural speech threshold differential were necessary for administering and obtaining meaningful results with the speech noise ABLB test. The eighth grade minimum education level increased homogeneity with respect to test vocabulary. Possible contamination due to faulty language and due to foreignism was controlled by requiring all subjects to have acquired hearing loss after the development of English language.

Median pure tone thresholds of the two groups are shown in Figure 3. For clarity, bone conduction responses are omitted. The air and bone conduction results for both groups were interweaving, excepting some subjects whose bone conduction responses were beyond maximum limits of the audiometer.

As anticipated, the groups exhibited similar audiometric configurations bilaterally. Median nontest, better ear results are remarkably alike. Despite differences in the low frequency region, both groups show unilateral hearing loss with gradually downward sloping configuration in the test ear.

A comprehensive summary of the subjects responses to preliminary tests is presented in Appendix B. Pure tone thresholds, pure tone average thresholds, and speech reception thresholds are shown.

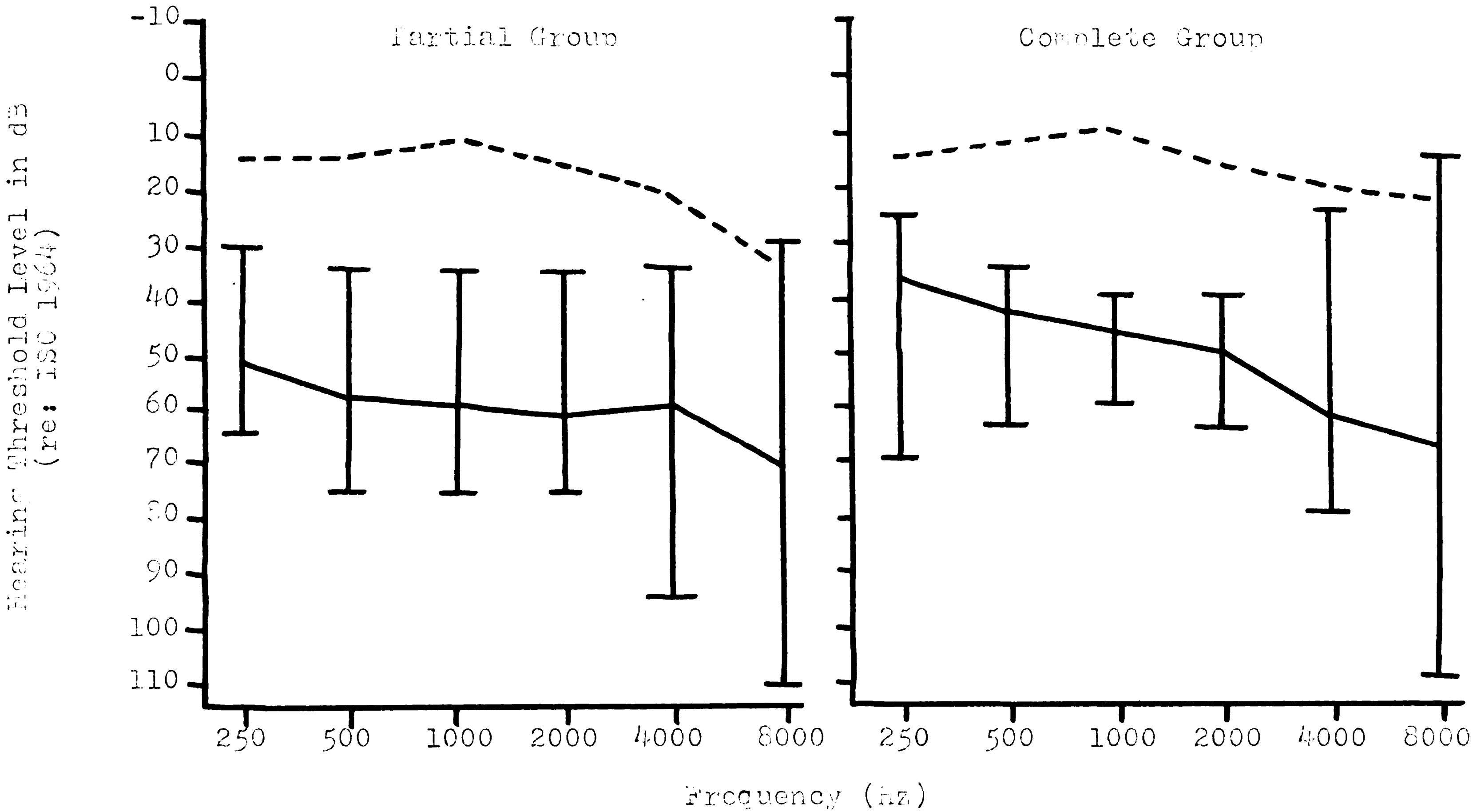

Figure 3. Median pure-tone thresholds for the test ear (solid line) and the nontest ear (dashed line) for both recruitment groups. For clarity, only the air-conduction thresholds are shown. The ranges of thresholds are shown for the test ear.

Recruitment Quantification

A necessary requirement for conducting the experiment was the development of a method for quantifying loudness recruitment. Although Jerger and Harford (1960) and Jerger (1962) contended that the pure tone ABLB test is the most valid existing measure of loudness recruitment, results of this test are somewhat unwieldy. Attempts to relate recruitment to other variables have suffered because of the difficulty in quantifying recruitment by this pure tone procedure, e.g. Clemis and Carver (1967). An alternative procedure using speech stimuli may offer some advantages.

Harris et. al. (1952) stated that "The practical significance of recruitment is largely in speech reception" (p. 108). In an investigation of recruitment for speech, this group of investigators found their subjects could readily make loudness matches for speech in two ears of unequal ability and that the matches were as easy and precise as those for pure tones. It was also found that "recruitment for speech followed a course parallel to that for pure tones and roughly intermediate among the curves of recruitment for pure tones in the speech range" (1952, p. 132).

Studying the effects of noise exposure on loudness-balance and intelligibility, O'Neill (1954) used speech material for pre- and post-exposure loudness-balances. Mean values of the matches indicated that his normal hearing subjects were able to make accurate judgments with connected discourse serving as the stimulus. O'Neill concluded that,"Apparently speech (connected discourse) can serve as adequate stimulus material in loudness-balance matches" and that "there was little intra- or inter-individual variability in such judgments" (1954, p. 6).

Specific rationale for employing speech noise for the ABLB test stimulus include the following: (1) literature reports that subjects can adequately balance speech-type stimuli; (2) the close relationship between speech noise and the dependent variable; and (3) because the speech-type signals are capable of demonstrating growth of the loudness function over a relatively broad auditory area.

<u>Speech Noise ABLB Test</u>. Stimulus parameters and test procedures are similar to those suggested for the pure tone ABLB by Jerger (1962). Identical signals are presented to both ears alternately. The signal was fixed at levels of 20, 40, and 60 dB above the good ear's speech reception threshold and the subject adjusted the intensity at the poor ear for each presentation level until the signals were judged equally loud in both ears.

The procedure for administering the test described here calls for fixed sensation levels in the good ear and variable intensity in the poor ear until the balance is achieved for each respective presentation level. Jerger and Harford (1960) and Jerger (1962) recommended fixing the signal at sensation levels of 20 and 40 dB above the poor ear's threshold and varying the intensity at the good ear; however, they reported that either system yields the same results. Their rationale for these recommendations include standardization and clinical utility. With respect to the presentation levels, they suggested that "the 20 dB level gets at the question of recruitment near threshold and the 40 dB level is usually high enough to tell you whether recruitment is complete" and that "it is very seldom that you can go much higher than 40 dB above threshold on the bad ear anyway" (1962, p. 142).

The decision to fix the three sensation levels at the good ear was governed by the desire to obtain information about the loudness function over a broad span of sensation levels. Because the magnitude of loudness recruitment is relative and varies as a function of stimulus presentation level, a procedure based on the good ear's threshold level may lead to somewhat different absolute results than those obtained by classical procedures.

Specific signal parameters and procedures included the following:

1. Signals alternated automatically.
2. Signal duration was 500 msec.
3. Signal rise and decay time was 50 msec.
4. The intensity was always fixed at the good ear and varied at the poor ear.
5. Each subject controlled the intensity at his poor ear by a hand-held switch.
6. The intensity was fixed at sensation levels of 20, 40, and 60 dB at the good ear.

An Allison 22B clinical audiometer was used to administer the test. In order to obtain a speech noise signal and the capability of alternating signals to a subject's two ears, the test signals were recorded on magnetic tape and played-back on the audiometer's "stereo" magnetic tape recorder.

The array of equipment shown in Figure 4 was utilized for recording the test stimuli.

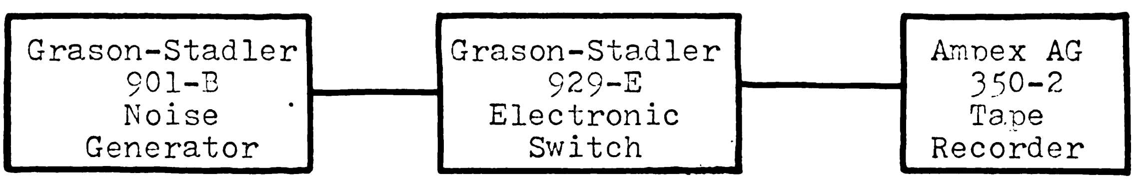

Figure 4. Schematic diagram of the Speech-Noise Alternate Binaural Loudness Balance recording equipment.

The noise generator (Grason-Stadler 901-B) produced speech noise which was transmitted to the electronic switch. The switch was adjusted at a 50% duty cycle, 50 msec rise and decay time, and a 1000 msec period. These adjustments resulted in brief bursts of the speech noise being transmitted (switched) alternately to the two separate channels of the Ampex Tape Recorder (AG 350-2). When the two channels of this recording procedure are transmitted separately to the left and right ears, the signals are perceived as alternating. Signal parameters were monitored with a Tektronics (564 B) Storage Oscilloscope.

Two minute continuous segments of speech noise were recorded at the beginning of each channel for calibration. Spectral analyses of these signals are shown in Figure 5. The curves show that the frequency spectrum of the recorded signals conforms to the long-term average spectrum of speech signals (Denes and Pinson, 1966; also see Appendix A).

Interpretation of Speech Noise ABLB Test. Three possible outcomes of pure-tone ABLB tests are "no recruitment", "partial recruitment", and "complete recruitment". Figure 6 illustrates these hypothetical outcomes. The test signal is initially fixed at a level of 20 dB above the good ear's threshold (O_1) and the alternating signal is turned on. Because the good ear is

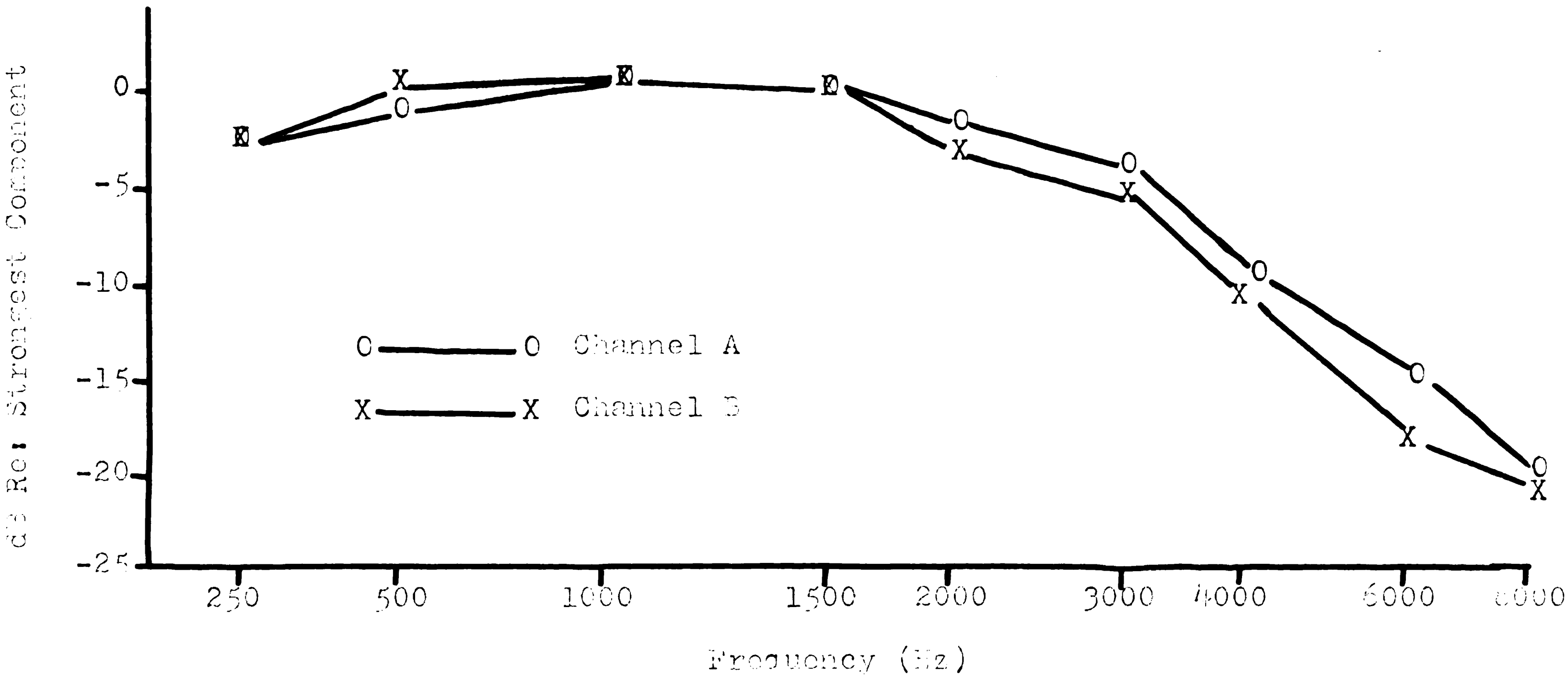

Figure 5. Frequency spectrum of the speech noise ABIB test signals.

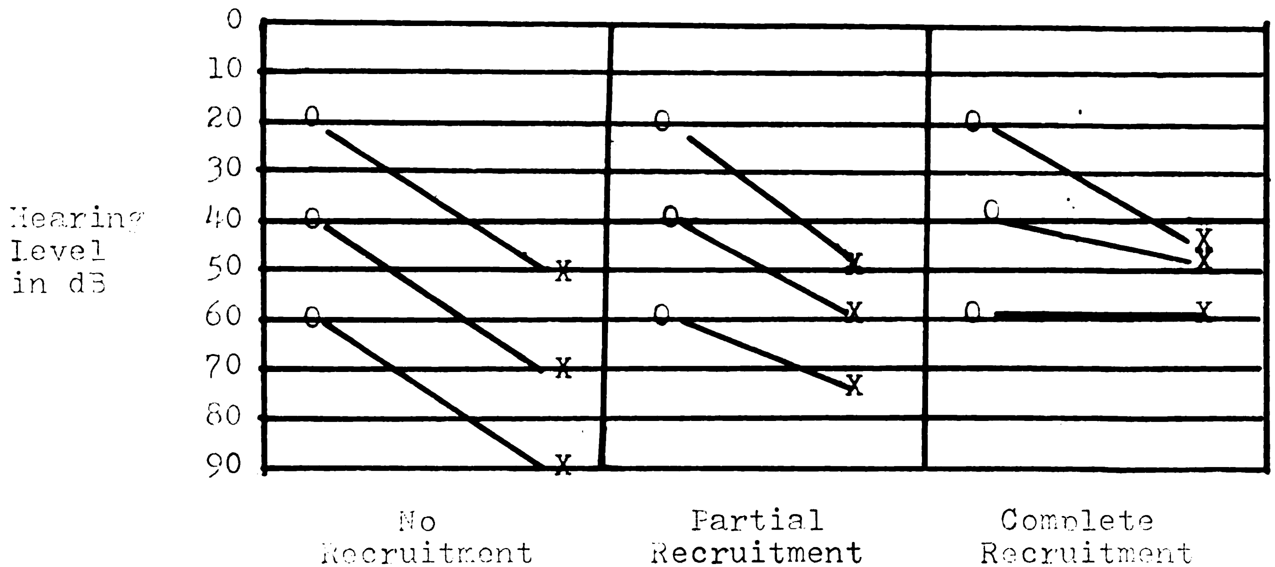

Figure 6. Hypothetical examples illustrating the traditional method for intrepreting results of the alternate binaural loudness balance test. (O: good ear; X: poor ear).

normal in the illustration, sensation level and hearing level are the same; however, it should be noted that sensation level is in reference to the individual's hearing status (See Appendix A Re: Hearing Level and Sensation Level). The subject adjusts the signal at his poor ear until he judges the signals were equally loud (X_1). Next, the subject repeats the balancing in his poor ear for signals presented at 40 dB and then at 60 dB.

If the subject perceives signals presented at equivalent sensation levels in each ear as equally loud, he is not exhibiting recruitment. This means that an increment of say 20 dB in the good ear is accompanied by a 20 dB increment in the poor ear to effect a loudness balance. On the other hand, partial or complete recruitment occurs when a smaller increment is needed for the balance. In fact, if, at the 60 dB sensation level, the subject adjusts the intensity at the poor ear equal to the intensity at the good ear (in equal hearing levels), his performance is labeled as "complete recruitment". Balances which occur between the "complete" and "no" recruitment responses are labeled "partial" recruitment. Jerger (1962) reports a 10 dB "margin of error" for interpreting pure tone ABLB data. Presumably this error is related to dispersion of the loudness balances. Preliminary results in this experiment, with speech signals, indicated that subjects were able to balance the signals within a much smaller range. Accordingly, the margin for interpreting the balance data of this study was reduced to 5 dB.

The two groups of subjects used in this study conformed to the above specifications for partial and complete recruitment. That is, when the mean of balances was rounded to the nearest 5 dB, eighteen subjects exhibited partial recruitment and eighteen exhibited complete recruitment for the speech noise signals (loudness recruitment is defined in Appendix A).

Speech Materials

Three speech tests were required by the experiment: (1) determination of sensation levels for presentation of the compressed speech; (2) measurements of discrimination performance under compressed speech; and (3) pre-test and post-test to assess base level performance and time dependent influences.

Speech reception thresholds, based on spondee words, were used in determining the presentation levels for the compressed speech. Magnetic tape recordings of the CID Auditory Test W-1 (Hirsh et. al., 1952) were recorded by a male speaker (Dr. William F. Rintelmann) with General American dialect. The speaker monitored the level of the two syllable peaks of each word at 0 dB VU meter deflection (± 2 dB). List A, one of four lists used in routine clinical testing at Michigan State University, was arbitrarily chosen as the stimulus material for the preliminary speech test.

Northwestern University Auditory Test No. 6 (Tillman and Carhart, 1966) was used to assess speech discrimination under the three compression ratios. This test has four lists of 50 monosyllabic, CNC words derived from lists developed and revised by Lehiste and Peterson (1959 and 1962). The lists used in this study were recorded on magnetic tape by the same male speaker who recorded the spondee material. Each word is preceded by the carrier phrase, "You will say . . .". In recording the words, the last word of the carrier phrase was monitored at 0 dB VU meter level and the test item was then said naturally.

Because each subject was tested twice at each of the three compression ratios, a minimum of six different test lists was needed. Previous investigations with the N. U. Test No. 6 revealed that lists II and III yield equivalent scores (Rintelmann and Jetty, 1968). Therefore, these two lists were selected. Four additional lists needed for the experimental conditions were constructed by permuting the two original lists; two permutations of list II A provided lists II B and II C and two permutations of list III A gave list III B and list III C.

Speech discrimination was measured at the beginning and again at the end of the experiment by a pre- and post-test. The pre-test acquainted the subjects with test conditions and provided a base level for assessing initial group differences. A comparison of pre- and post-test scores indicated the magnitude of practice and other time dependent effects. List I A of N. U. No. 6 was arbitrarily selected for these measures. Of the fifty CNC words that constitute this test, the first ten were recorded at one-to-one compression, the next fifteen words at two-to-one, and the remaining twenty-five words at three-to-one.

The Weiss Amplitude Compressor

Compression of the speech test material was achieved with an instrument developed by Mr. Erwin Weiss of the Beltone Electronics Corporation of Chicago, Illinois. Operating characteristics and calibrating information were supplied by Mr. Richard Brander (1970). The compressor functions to:

1. Divide input signals into three bands: 400 Hz to 1000 Hz, 1000 Hz to 2000Hz, and 2000 Hz to 4000 Hz.
2. Provide symmetrical, nonlinear amplitude compression in each channel.

3. Provide independent control of the degree of compression in each channel.

A schematic diagram of the compressor is shown in Figure 7.

Input-Output Calibration. The instrument was calibrated to the three compression ratios by adjusting the specified amount of compression for each channel while maintaining equivalent gain in each channel. The capability of adjusting both the amount of compression and the amount of gain made available a wide array of conditions that could be achieved with the instrument. The controls of adjacent channels are not entirely independent, however. This is particularly true when there is high gain combined with a compression level and the filters do not cut off abruptly. In this situation attenuated signals are allowed to enter the wrong channel. Specific procedures used in adjusting the controls of the compressor to the three levels were as follows:

1. A Hewlett-Packard oscillator (4204-A) applied a 1 V (RMS), 1500 Hz sine wave to the input terminals of the compressor. A Beckman (6148) Electronic Timer assured correctness of the frequency output ($\overline{X}$ percentage error of 0.05%) before and after the experiment. The internal

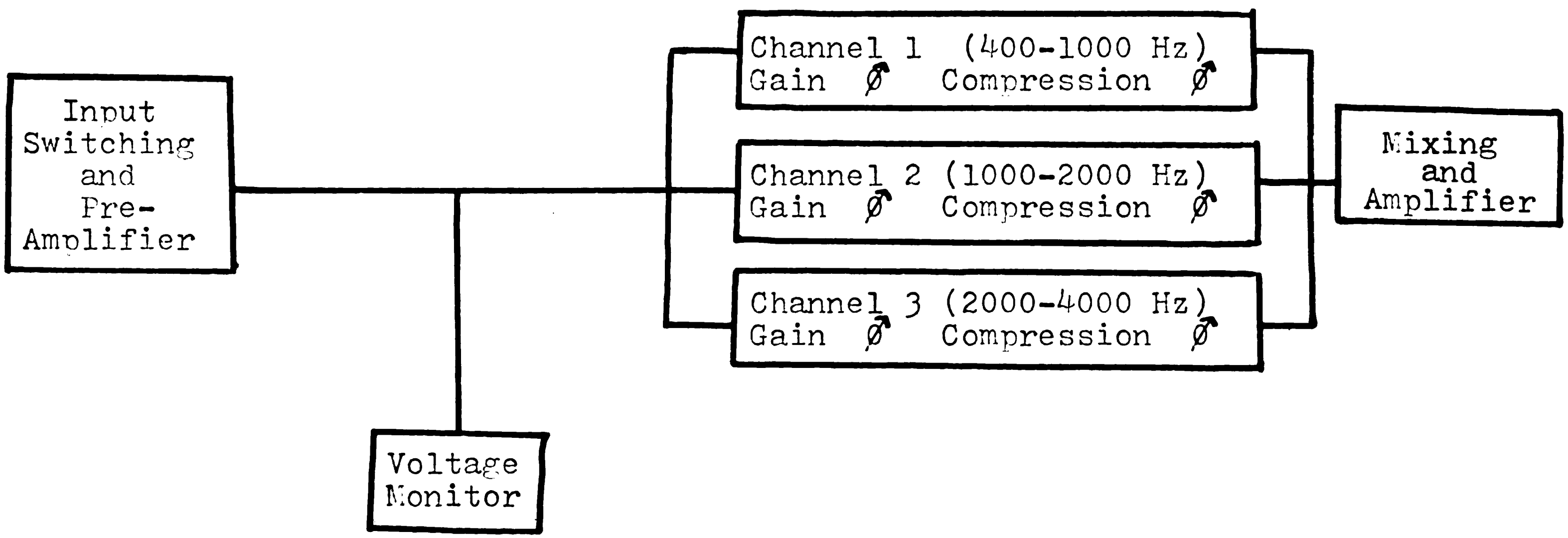

Figure 7. Schematic diagram of the Weiss amplitude compressor.

volume control of the compressor was adjusted to produce 1 V (RMS).

2. With all compression controls at zero, and with the 1500 Hz 1 V (RMS) input, the mid-channel (1000 Hz to 2000 Hz) was adjusted to produce 1 V (RMS) at the output terminals. With 700 Hz input (1 V RMS) the low-channel (400 Hz to 1000 Hz) gain was adjusted for output voltage of 1 V (RMS). Similarly, with 3000 Hz input 1 V (RMS) the high channel (2000 Hz to 4000 Hz) gain was adjusted for 1 V (RMS) output.
3. With a 1500 Hz input signal, the mid-channel compression was adjusted until a 10 dB change in output level was produced by changing the input from 0 dB Re: 1 V (V) to -30 dB V. This was for the three-to-one compression ratio. For the two-to-one ratio the compression control was adjusted to give 15 dB output change for an input change from 0 dB V to -30 dB V. Obviously, during the one-to-one condition a 30 dB reduction in output resulted from an input change from 0 dB V to -30 dB V.
4. For each respective condition (i.e., one-to-one, two-to-one, and three-to-one) step three above

was repeated with a 3000 Hz input signal with appropriate high-channel compression adjustment.

6. With 0 dB input, low channel (using a 700 Hz signal) and high channel (using a 3000 Hz signal) gain were adjusted until they were equivalent in overall gain with the mid-channel (i.e., the 1500 Hz signal) gain.
7. Steps number three to six above were repeated for each respective compression condition (i.e., one-to-one, two-to-one, and three-to-one) until the three were equivalent in gain and compression.

Input-output relationships and the frequency response of the compressor were monitored by the above calibration procedures immediately before and after compressing the stimulus word lists. Additionally a calibration tape, consisting of two sections of recorded pure tones, was constructed to determine performance of the compressor during the actual processing of the words.

Section one of the calibration tape was used to determine input-output relationships. It consisted of three tones near the center of the bands passed by the compressor channels (i.e., 700 Hz for the 400 to 1000 Hz channel, 1500 Hz for the 1000 Hz to 2000 Hz channel, and 3000 Hz for the 2000 Hz to 4000 Hz channel). In constructing this part of the tape, a 1 V (RMS), 700 Hz tone which produced 0 dB VU meter deflection was recorded for fifteen seconds. Next, the level of the input signal was reduced 10 dB. A signal of fifteen seconds was again recorded. In this manner, the input level of the signal was reduced in decrements of 10 dB until a 30 dB span was covered. Similarly, 1500 Hz and 3000 Hz tones were recorded at 1 dB V and at decrements of 10 dB (i.e., -10, -20, and -30 dB V).

Eleven pure tones (i.e., 200 Hz, 250 Hz, 500 Hz, 700 Hz, 1000 Hz, 2000 Hz, 3000 Hz, 4000 Hz, 6000 Hz, and 8000 Hz) constituted the second section of this tape. These tones were recorded at constant voltage 1 V (RMS) and were used to determine the frequency response of the compressor when the speech stimuli were actually compressed.

Rise-Decay Transients. Amplitude controlling devices usually need intervals of time to achieve and escape their control. These intervals are called attack and release times or constants. Typically, these constants are applied to circuits which use a control voltage to vary the gain of a linear amplifier. Since the Weiss Compressor operated on non-linear components, its reaction times are best referred to as rise-decay transients (Caraway, 1964).

Transients of the compressor were determined by observing its response to instantaneously initiated sinusoids. A tone burst generator (General Radio 1319) initiated the signals applied to the compressor and externally triggered an oscilloscope (Tektronics, 561) which allowed observation of the compressor's performance. Specifications reported by Caraway (1964) were adopted:

> The rise time was defined as the time required for a 90 percentage completion of gain change from the instantaneous application of a signal to the compressed equilibrium value. The decay time was the time required for the same percentage of gain change in the return of the compressed gain to its former value upon the instantaneous cessation of the input signal.

The compressor had a rise time of 5.4 msec and a decay time of 2.5 msec. These values did not vary as a function of frequency or of the compression ratios.

<u>Harmonic Distortion</u>. Energy measured in the first two overtones was utilized to estimate harmonic distortion (Caraway, 1964). For this measurement, 1 V sinusoids with calibrated frequency were applied to the compressor at each ratio. The compressor was connected to a Bruel and Kjaer 2107 Frequency Analyzer which enabled measurement of the fundamental (h_1), the second harmonic (h_2) and the third harmonic (h_3). Percent distortion was calculated at each frequency by the formula:

$$\text{Percent Distortion} = \frac{\sqrt{h_2^2 + h_3^2}}{h_1} \times 100$$

Table II shows the distortion percentages.

Table 2. Percentage distortion of the second and third harmonics of the Weiss Compressor for one-to-one, two-to-one, and three-to-one compression.

Frequency (Hz)	one-to-one	two-to-one	three-to-one
250	3.31	3.06	5.63
500	2.78	6.39	1.50
1000	2.78	9.79	6.03
2000	1.95	4.77	7.96
3000	3.32	2.50	2.74
4000	2.46	1.81	1.61
Mean Distortion	2.77	4.72	4.25

The distortion, although somewhat greater for the two-to-one and the three-to-one compression ratios, was not excessive.

Noise Level. In order to obtain resting internal noise levels, the input of the compressor was terminated with a 600 ohm resistor and the output was terminated with a Bruel and Kjaer Voltmeter. Resting voltages were read under each compression ratio. Results of these measurements were -57.5 dB for the one-to-one ratio, -44.0 dB for the two-to-one ratio, and -33.25 dB for the three-to-one ratio.

Preparation of the CNC Test Stimuli

A diagram of the equipment used in compressing the stimulus words is shown in Figure 8.

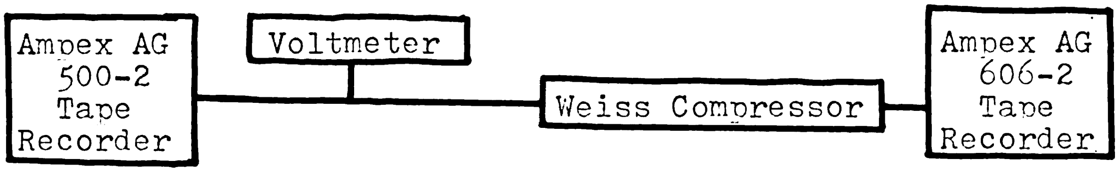

Figure 8. Schematic diagram of the CNC test stimuli recording apparatus.

After gain and compression were adjusted, both the recorded calibration tape and the word lists were reproduced by an Ampex AG 500-2 magnetic tape recorder. Output voltage of the recorder was monitored by the voltmeter circuit of a Bruel and Kjaer 2603 Microphone Amplifier. The previously recorded speech stimuli were then transmitted through the Weiss Compressor. The output of the compressor was connected to the input of a second tape recorder, an Ampex AG 606-2, which was used to capture the calibration tones and the actual stimulus materials for the study.

Performance of the compressor during the processing and recording of the speech was determined by the calibration tape. Input-output relationships of the instrument were determined at each ratio by recording the first series of tones after they had passed through the equipment array. Input-output functions of the mid-channel (1500 Hz), for each ratio, are shown in Figure 9. These curves are very compatible with the values for both the

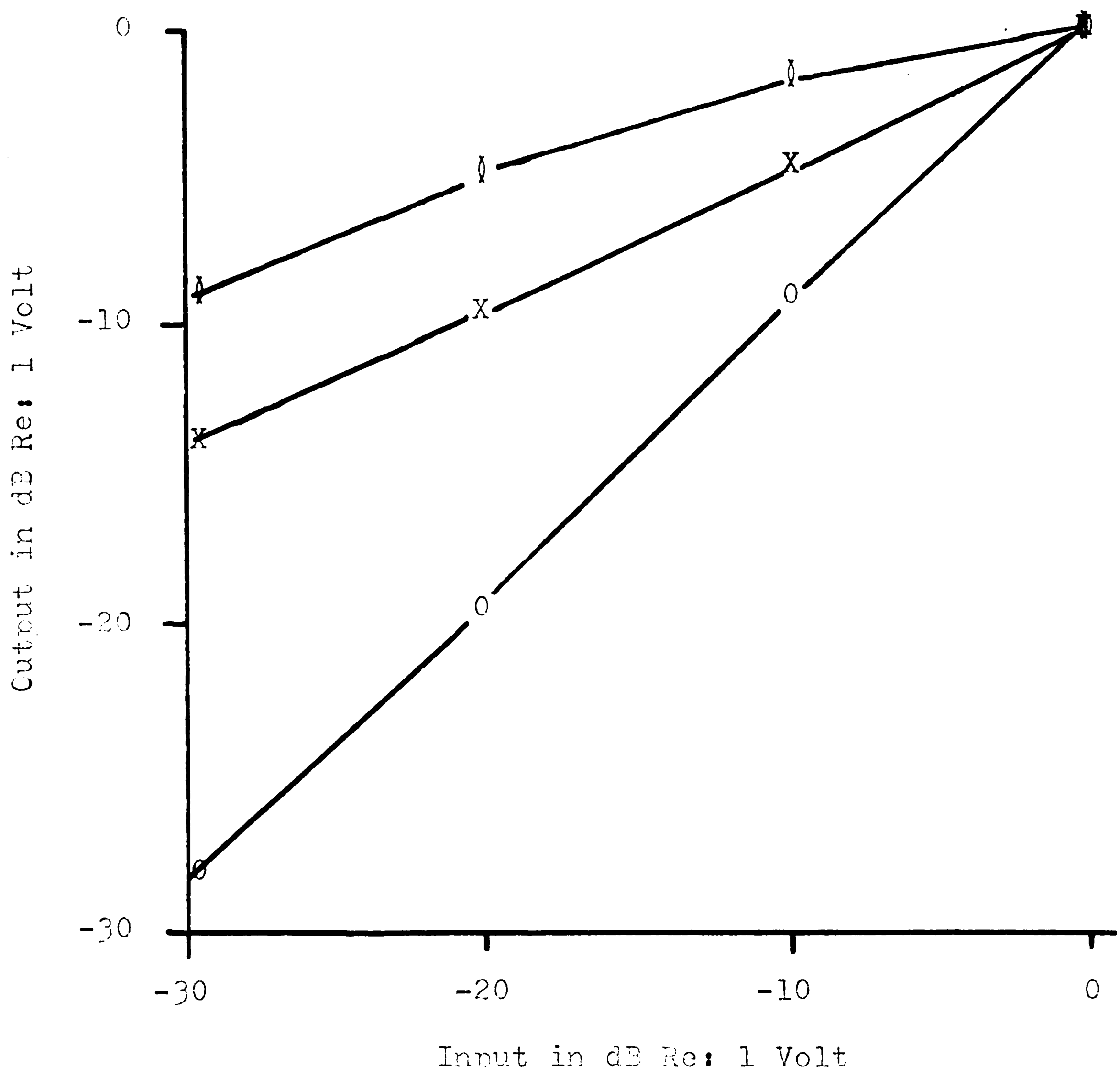

Figure 9. Input-output functions of the mid-channel (for a 1500 Hz signal) for each compression ratio when the CMC words were compressed under one-to-one compression (0), two-to-one (X), and three-to-one (Ø).

low- and high-channels (i.e., 700 Hz and 3000 Hz) which are presented in Appendix C.

The second part of the calibration tape was also transmitted through the recording equipment under each ratio. Recall that this section consisted of eleven constant voltage (1 V, RMS) pure tones. The purpose of these tones was to determine the frequency response of the processing and recording system under each ratio. Voltage levels of these tones, after being converted to relative dB values, are shown in Figure 10. These functions indicated that the frequency response was essentially flat from 400 to 4000 Hz for all three compression ratios.

The research design specified a comparative analysis of the perception of speech with three degrees of dynamic range reduction achieved by one-to-one, two-to-one, and three-to-one compression. Specific procedures used in obtaining these conditions included the following:

1. Appropriate gain and compression controls of the compressor were adjusted to achieve the ratio to be recorded.
2. The 1500 Hz segment of the calibration tape was produced by the Ampex AG 500-2 Recorder. This signal was monitored at 1 V (RMS), passed through the compressor for the ratio being recorded, and transmitted to the Ampex AG 606-2

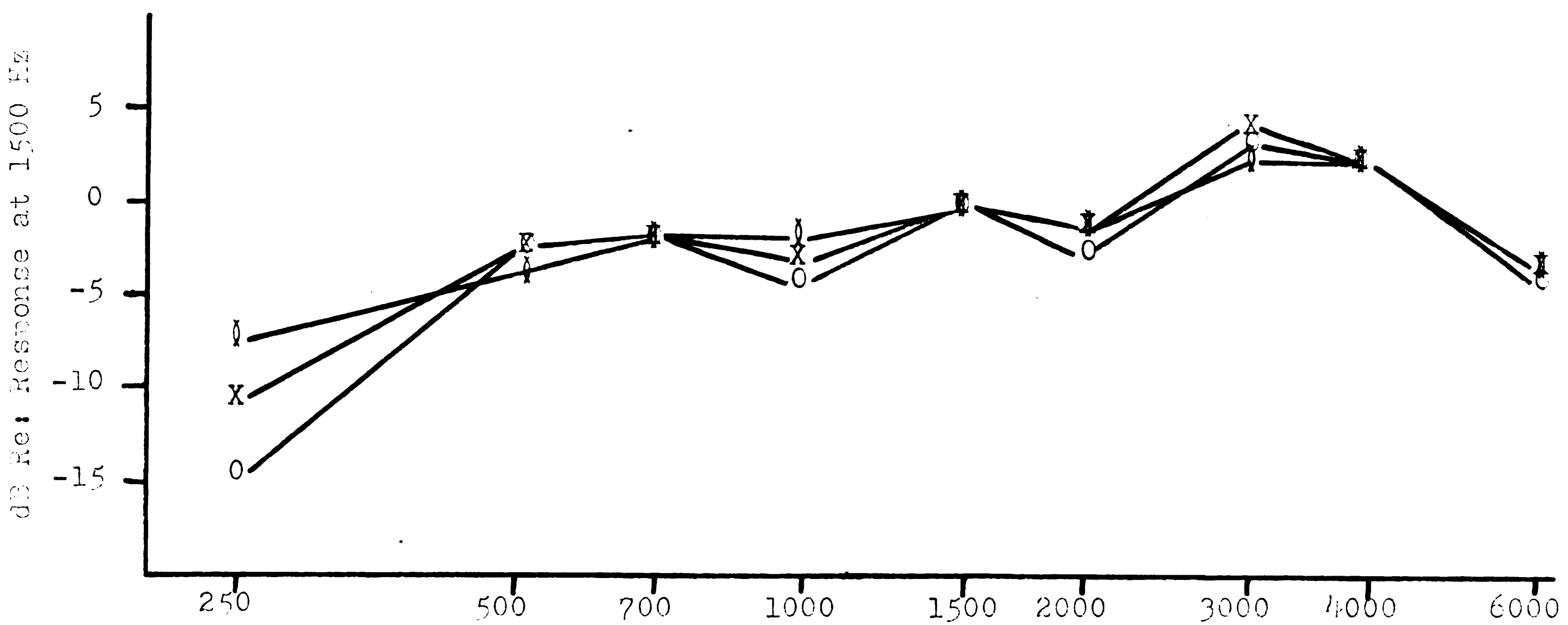

Figure 10. Frequency response of the recording and processing system when the CNC words were compressed under one-to-one compression (O), two-to-one (X), and three-to-one (Ø).

recorder used to capture the actual stimulus items. At this point the signal was used in adjusting the input record level at 0 VU meter deflection.

3. The entire calibration tape was then produced by the AG 500-2 recorder, transmitted through the compressor, and recorded by the AG 606-2 recorder under each compression ratio.
4. Next, magnetic tape recordings of the N. U. No. 6 lists were produced by the Ampex AG 500-2 recorder. The 1000 Hz calibration tone at the beginning of each tape was adjusted to 1 V (RMS) and applied to the compressor under the ratio being recorded. The compressor output was, in turn, used to adjust the record level of the AG 606-2 recorder to 0 dB VU meter deflection. Following these adjustments, all test lists were copied under each compression ratio.
5. The final recording procedure involved copying list IA (N. U. No. 6) for use in the pre- and post-test. Following procedures outlined above, word one through ten of this list were copied with one-to-one compression. Words eleven through twenty-five with two-to-one

compression, and words twenty-six through fifty were copied with three-to-one compression.

Experimental Procedures

During a single test session, lasting approximately two hours, each subject undertook the following tests in the order given:

1. Bilateral pure-tone air- and bone-conduction threshold tests.
2. Bilateral speech reception threshold tests.
3. Speech-noise ABLB test.
4. Speech discrimination experimental pre-test.
5. Speech discrimination experimental test lists.
6. Speech discrimination experimental post-test.

The subjects sat in a single walled IAC booth having an ambient noise level of 54 dB (C scale) as measured with a 2203 Bruel and Kjaer sound level meter and an associated 4132 condenser microphone. All test materials were presented to the subjects via an Allison clinical audiometer (22 B) and associated TDH-39-10Z earphones mounted in MX-41/AR cushions.

Pure-Tone Threshold Tests. Air-conduction pure-tone thresholds were measured by the Revised Hughson-Westlake Ascending Technique described by Carhart and

Jerger (1959). Test frequencies were 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz, and 8000 Hz.

Bone-conduction thresholds were determined at octave intervals from 250-4000 Hz by the Hood Technique (1960) employing narrow band masking. The masking agent was produced by the Allison 22-B audiometer and its accompanying narrow-band masking generator (Model 26). Analysis of this system indicated appropriate critical band widths. By applying the critical band data of Fletcher (1940) in the manner described by Sanders and Rintelmann (1964), the effective masking for a zero dB hearing level was determined at each band.

Performance of the pure-tone air-conduction system was checked on all days that subjects were tested. A Bruel and Kjaer sound level meter (2304) and an artificial ear (4152) were used for monitoring this system. A Beltone Artificial Mastoid (M5A) and voltmeter contained as an integral part of the Bruel and Kjaer 2107 Frequency Analyzer were used to check performance of the bone-conduction system. The calibration of these systems remained stable throughout the time the study was being conducted.

Speech Reception Threshold Tests. Reception thresholds for speech were measured with recorded spondee words. The subjects listened to the recorded test list at a

24 dB SL to become familiar with the individual words (Tillman and Jerger, 1959). After this the following instructions were read:

> You will now hear the same words again. At the beginning they will be loud, however, eventually they will become very faint. Your task is to repeat as many of the words as you possibly can. Even though the word may be faint if you think you hear it, repeat it. Do you have any questions?

Thresholds were measured by the method described by Tillman and Carhart (1966). Specific procedures used in obtaining these thresholds included the following:

1. Two test words were presented at a level approximately 30 dB above the suspected SRT.
2. The intensity was decreased in 10 dB steps with two words per level until no response was obtained for either word.
3. Next, the intensity was increased 10 dB and pairs of words were presented in descending steps of 2 dB.
4. This process was repeated until the subject either failed to respond or he responded incorrectly to at least five out of six consecutive test words.
5. Speech threshold was that point where the subject last correctly identified both of the

words at a level minus 1 dB for each correct response below this point.

Broad-band thermal masking was used during all speech testing at the impaired ear. Effective levels were computed and routinely applied to the good ear to shift the non-test ear to a hearing level 20 dB lower than the hearing level of the speech signal of the impaired ear. This assured that the test speech signal did not cross-over to the non-test ear.

The speech circuitry of the Allison audiometer was used to amplify and attenuate the electrical output of the audiometer's tape deck (Viking, Model 87) used to present all of the recorded speech materials. This circuitry was calibrated so that zero hearing level was 22 dB above 0.0002 dyne/cm^2. Speech noise was used for monitoring this system according to procedures outlined by Tillman, Johnson, and Olsen (1966). Monitoring procedures for the TDH-39 earphone include these steps:

1. The phone is coupled to the condenser microphone (Bruel and Kjaer, Type 4144) of the precision sound level meter (Bruel and Kjaer, 2304) by means of a standard 6-cc artificial ear (Bruel and Kjaer, 4152).
2. The level of the speech noise at a given attenuator setting is adjusted until it produces

a deflection to zero on the VU meter with the sound level meter set on the linear scale.

3. The resulting output of the system was measured and the value is accepted as the intensity of the spondee words at the same attenuator setting under the condition in which the peaks of the words also produced a deflection to zero on the VU meter of the audiometer. For example, with the attenuator set at 60 dB hearing level, the output of the artificial ear would be 82 dB SPL.

Speech Noise ABLB Test. The speech noise ABLB test was administered next. The intensity of the speech noise was fixed at sensation levels of 20 dB, 40 dB, and 60 dB at the good ear. At each sensation level the subjects balanced the intensity of the speech noise at their impaired ears by a hand-held switch. This switch controlled gain and attenuation at rates of 2 dB per second. Five loudness-balances, with alternating ascending and descending presentations, were obtained at each sensation level.

Instructions given for the speech noise ABLB test were as follows:

> In this test you will hear noise alternating between your ears. The loudness of the noise will be fixed at your good ear and your task is to adjust the loudness

> of the noise in your impaired ear so that it is equally loud with the noise in your good ear. To make the noise in your impaired ear softer press the button marked 'softer' and to make it louder press the button marked 'louder'. The loudness of the noise will not change unless you press one of the buttons. Allow some time for the noise to become louder or softer. Remember that you are to make the noises equally loud. Take all the time you need for this balancing and make them as precise as possible. Do you have any questions?

For practice, the subjects were required to make ascending and descending balances before the actual testing was initiated.

Experimental Battery. This array consisted of eight speech discrimination tests. These included two tests at each compression ratio and a pre- and post-experimental test. All tests were presented at the subject's impaired ear at 24 dB sensation level. Two aspects of the speech material should be recalled. First, each compression ratio was represented in the pre- and post-experimental test. Second, for the three compression ratios, the stimulus words were equated at their peak powers and the long-term dynamic ranges below these levels differed. The dynamic range of the uncompressed speech, about 24 dB, was reduced to approximately 12 dB under two-to-one compression and 8 dB under three-to-one.

Each subject was assigned a sequence of the three compression ratios. The six possible orders of presentation of the three compression ratios was used equally often. Next, two different test lists were randomly assigned to each of the compression ratios. A complete schedule was constructed by first counter-ordering the ratios, and then two test lists were assigned to each level. The following conditions were imposed on this assignment: (1) that one list from lists IIA-IIC and one list from IIIA-IIIC be used with each compression ratio; and (2) that the lists be used only once per subject. The eighteen subjects in each recruitment group were assigned to each of these predetermined programs.

Immediately before the pre-experimental test was presented to the subjects, the following instructions were given:

> In this test you hear words preceded by the phrase "say the word . . .". The words will be sufficiently loud for you to hear them. Please repeat only the last word of the phrase. If you think you hear a word, but you are not sure, go ahead and repeat what you think it might be. Do you have any questions?

Next, the subjects listened to the six lists under the three compression conditions after which they heard the post-experimental test. The stimulus words were repeated orally and the experimenter recorded their responses on an answer sheet. Each word counted two percentage points. Accordingly, the percentage of the fifty words correctly repeated was the discrimination score for that list. The two scores for each compression ratio were averaged, thus providing the dependent variables of the study.

Summary

Speech discrimination performance was assessed in thirty-six subjects for CNC words with two degrees of amplitude compression compared with no compression.

Speech reception thresholds for CID W-1 spondee words were used in determining the presentation levels for the compressed speech. Northwestern University Auditory Test No. 6 lists were used to assess speech discrimination under the three compression conditions. Speech discrimination was also measured before and after the experiment by a pre- and post-experimental test.

The subjects had unilateral sensorineural hearing loss with concomitant loudness recruitment in their affected, i.e. test, ear. Recruitment was quantified as either partial or complete by an ABLB technique that employed speech noise signals. Speech noise signals were used because the literature indicates that subjects can adequately balance these signals, because of their consanguinity with the dependent variable, and because of their electical nature in showing the loudness growth function over a relatively broad auditory area.

Amplitude compression was obtained with an instrument with input-output ratios of two-to-one and three-to-one. The system used also amplified linearly, a condition which was called one-to-one amplitude compression. The compressor had 5.4 and 2.5 millisecond rise and decay transients. Average percent distortion for the second and third harmonics was 2.77, 4.72, and 4.25 for the one-, two-, and three-to-one ratios respectively.

The test battery included pure-tone air-and bone-conduction threshold tests, speech reception threshold tests, speech noise ABLB test, six experimental CNC discrimination lists, and pre- and post-experimental CNC discrimination tests. In the research battery, two test lists were presented under each compression ratio with the peak components equated at 24 dB sensation level for each condition. Pre- and post-experimental tests acquainted the subjects with the test conditions and provided a base level for assessing initial group differences.

Responses of the subjects to the CNC words under the three compression conditions provided the dependent variables of the study. These were analyzed statistically to answer the experimental questions. The results, together with appropriate discussion, constitute the following chapter.

CHAPTER IV

RESULTS AND DISCUSSION

The purpose of this study was to examine the relationship between loudness recruitment and the perception of amplitude compressed speech. Thirty-six subjects with unilateral sensorineural hearing loss were divided into two equal groups of "partial" and "complete" recruitment on the basis of their performance on a speech noise ABLB test. They were given (1) a pre-experimental test that included CNC words at three compression levels; (2) discrimination tests under conditions of compression and no compression; and (3) a post-experimental test which was a repeat of the pre-test. Results of the pre- and post-experimental tests were analyzed to determine practice and time dependent influences.

The speech discrimination test scores for the three compression ratios were analyzed to answer the questions of interest which were as follows:

1. Does amplitude compression improve speech discrimination in persons who exhibit loudness recruitment?
2. Is the amount of improvement in speech discrimination related to the amount of the loudness recruitment?

3. Is the amount of improvement in speech discrimination related to the degree of compression?

<u>Analysis of Practice Effects</u>. Pre- and post-experimental scores were compared to determine whether performance changed during the experiment. Analysis of difference scores (post-test minus the pre-test) revealed that the subjects in each group had significantly higher post-experimental scores than pre-experimental scores (see Table 3).

The mean pre- and post-experimental test scores are shown in Table 3.

Table 3. Mean percent correct discrimination scores for the pre-experimental and the post-experimental tests for the partial and the complete recruitment groups.

Recruitment Group	Pre-Test	Post-Test	Difference	t
Partial	57.78	62.11	4.33	3.25**
Complete	71.44	75.11	3.66	2.77*

* p 0.05   ** p 0.01

Although discrimination performance improved, the absolute magnitude of the gain was rather small. The fact that both the partial and the complete groups had similar improvement is supported by the mean gain values shown for each group.

The question of change in performance during the experimental test session, due to familiarity with the response set, was also studied. Recall that list II and list III of N. U. No. 6 were each permuted twice to provide the test lists. Although the order of words was changed, the same word sets were repeated for each compression ratio. The mean discrimination scores for each successive order (i.e., the first, second, and third presentations) were averaged over all subjects. These averages are shown in Table 4.

Table 4. Mean percent correct discrimination scores for the thirty-six subjects for the first, second, and third presentation orders for the one-, two-, and three-to-one compression conditions.

Compression Ratios	Presentation Orders First	Second	Third
One-to-one	58.00	65.25	65.75
Two-to-one	73.83	71.17	76.17
Three-to-one	72.42	78.67	75.42
Combined	68.08	71.69	72.44

In obtaining the values shown in Table 4, each compression ratio was represented equally often in each position. For example, the ratios one-, two-, and three-to-one were each presented first to twelve subjects in each recruitment group. The difference between the first and third presentation averaged 4.1 percent for the entire experimental population. There was no systematic trend in performance within the three compression ratios from the first to the second to the third presentation orders; however mean performance was consistantly better for the third presentation than for the first.

Analysis of Effects of Amplitude Compression. Figure 11 shows the mean discrimination scores of the two experimental groups for the three compression ratios as well as the pre- and post-test scores. Both groups appear to benefit from the compression. The largest increase in performance occurs between the one-to-one and the two-to-one compression ratios. Oddly enough, the complete recruitment groups performance was superior throughout.

Experimental group differences were significant at both the pre-experimental test (t of 2.29, 17 df) and the post-experimental test (t of 2.57, 17 df). Obviously, any comparison between the groups performance would be biased by the difference observed at the pre-test. Specifically, statistical tests of group differences must account for the influence in prior ability.

A method is available for testing the significance among means which have been influenced by such confounding variables. This procedure, analysis of covariance, adjusts the means for the effect of the confounding variable

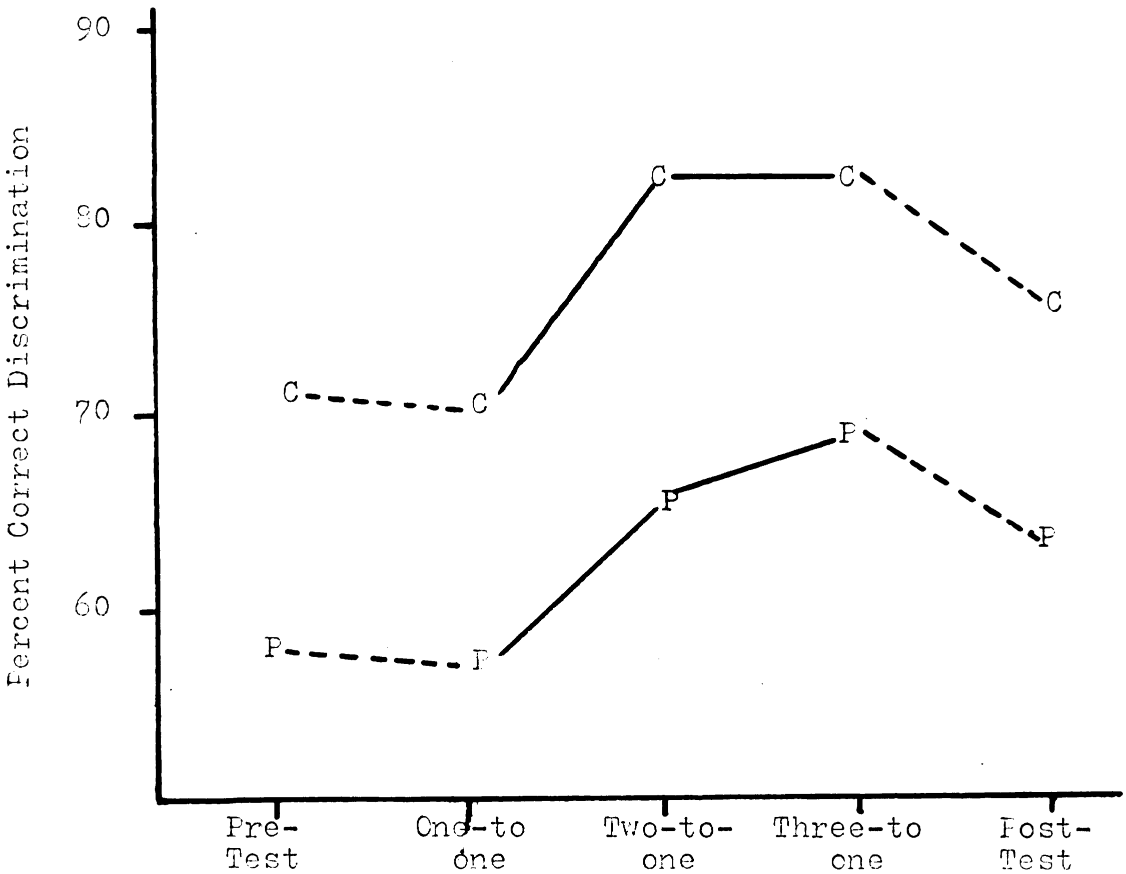

Figure 11. Mean speech discrimination scores of the "Partial" group (P's) and the "Complete" group (C's) for the experimental compression ratios as well as the pre- and post-experimental tests.

(prior ability) and makes the necessary modifications in sampling error. The corrected sampling error is then used to test for the differences in the adjusted means (Downie and Heath, p. 186). The covariance analysis was used to determine whether there was (1) a main effect due to the two recruitment groups; (2) a main effect due to the three compression ratios; and (3) interaction between the compression ratios and the recruitment groups.

In addition to the pre-experimental test differences observed for the recruitment groups, the covariance analysis also was indicated by the pre-experimental test being correlated highly with the three compression ratios (r values of 0.86, 0.88, and 0.84 for one-, two-, and three-to-one compression ratios respectively). The design fits a 2 x 3 fixed model, with repeated measures on the compression variable. Factor R represents the two recruitment groups and factor C represents the three compression ratios. The covariate measure (the pre-experimental test score) for all criterion measures for factor C is constant for each subject. Accordingly, no adjustment is required for the main effect because of the compression factor (Winer, p. 614).

Results of the analysis of covariance are summarized in Table 5.

Table 5. Summary of analysis of covariance comparing performance of the two recruitment groups for one-, two-, and three-to-one amplitude compression.

Source of Variance	df	MS	F ratio
R (adjusted)	1	228.76	1.44
Subj. W. R (adjusted)	33	159.27	
C	2	1584.45	37.80**
RC	2	28.12	0.67
Residual	68	41.91	

** p 0.01

There is no significant effect for recruitment, nor is there any evidence for an interaction between recruitment and the compression ratios. The analysis indicated that there is a significant main effect due to the compression ratios. The omnibus covariant analysis does not, however, provide specific information relative to the differences between the individual means. Rather, it only indicates whether or not a significant difference exists or does not exist for a particular factor. Therefore, in order to further evaluate the significance of the compression conditions the data were subjected to multiple comparisons using Duncan's New Multiple Range Test (Edwards, p. 136-157). These results are shown in Table 6.

This analysis reveals the following: (1) the two-to-one mean was significantly different from the one-to-one mean; (2) the three-to-one mean was significantly different

Table 6. Duncan's new multiple range test applied to the differences between the three compression ratios. (N=36).

	Compression Ratios		
Means	one-to-one 63.14	two-to-one 73.72	three-to-one 75.36
one-to-one	———	10.58**	12.22**
two-to-one	———	———	1.64
three-to-one	———	———	———

**p 0.01

from the one-to-one mean; and (3) the two-to-one and the three-to-one means do not differ significantly.

Supplemental Analysis of the Effects of Amplitude Compression

Careful inspection of the speech noise balance data, which was used in grouping the subjects, revealed that the adopted system may not be the most suitable one for quantifying loudness recruitment. Specifically, it was observed that subjects who appeared to have comparable growth in their loudness functions were classified not on the basis of their recruitment but on the basis of the magnitude of the interaural difference in their hearing levels. This is illustrated by the two balances shown in Figure 12.

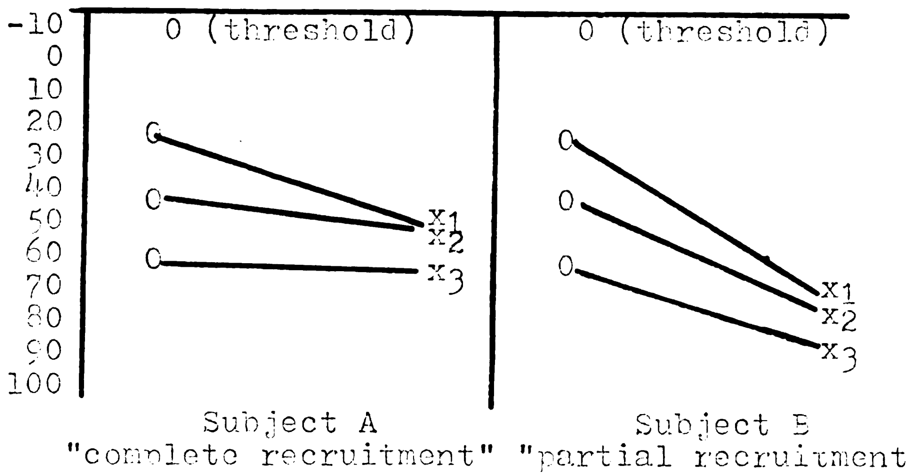

Figure 12. Speech-noise ABLB balance data of two experimental subjects.

Recall that the points (Figure 12) for the good ear (i.e., the 0's) are at 20 dB intervals in sensation level and the points for the poor ear (X's) are plotted as a mean of five equal loudness balances. As shown by the figure, the subjects exhibit similar relative increments in judged loudness (X_1, X_2, and X_3) corresponding to the 20 dB, 40 dB, and 60 dB sensation levels presented in their good ears. For example, the change in the poor ear from X_1 to X_2 is 5 dB in both cases as the sensation level changes from 20 to 40 dB sensation level in the good ear. Furthermore, both poor ear balances covered a range of 15 dB (X_1 to X_3). This indicates that the growth of these subjects' loudness functions is very similar. Despite this fact, the originally adopted classification schema placed them into different groups. This suggested that an alternate system for categorizing the subjects' loudness balance data might uncover some relationships between recruitment and compression that were obscured by the earlier classification system.

The traditional system for classifying loudness recruitment is contaminated, in some cases, by the magnitude of interaural difference in hearing level. In order to circumvent this contamination, an index of recruitment (I_r) was developed that estimated the growth of the function in the impaired ear. To obtain the subject's I_r, the growth of loudness in the impaired ear (i.e., X_3-X_1) is subtracted from the total range of sensation level presented at the good ear (i.e., 40 dB). For the sensation levels of this experiment, the I_r formula can be stated:

$$I_r = 40 - (X_3 - X_1)$$

I_r scores can vary from a score of 0 for subjects who show no interaural difference in their loudness function growth to a score of 40 for those subjects who balance all the sensation levels presented at the good ear with a single level in their poor ear. In other words, subjects who show no recruitment receive a score of 0, while those who show more recruitment receive higher scores. Figure 12 provides convenient data for illustrating scoring procedures. Both subjects show loudness growth ranges of 15 dB in their impaired ear. These values subtracted from the 40 dB constant yield I_r scores of 25 for each subject. Similarly, I_r scores were computed for all thirty-six subjects. The frequency distribution of these scores is shown in Figure 13.

The histogram (Figure 13) shows that the subjects distribute themselves throughout the range of possible scores with approximately half above (n of 16) and half below (n of 20) an I_r score of 20. Accordingly, the subjects were regrouped into two new recruitment groups according to their I_r score for the speech noise ABLB test. Subjects with I_r scores of 20 or less were assigned to Class I recruitment. Class II recruitment consisted of subjects who have I_r scores greater than 20. In other words, the two classes of recruitment fall on a continuum of 40 dB (re: growth in loudness) whereby Class I represents less recruitment than does Class II.

The pre- and post-experimental tests and the experimental speech discrimination data of the two new recruitment groups were again compared to further investigate the relationship between recruitment and amplitude compression. Mean speech scores of the two groups are plotted in Figure 14.

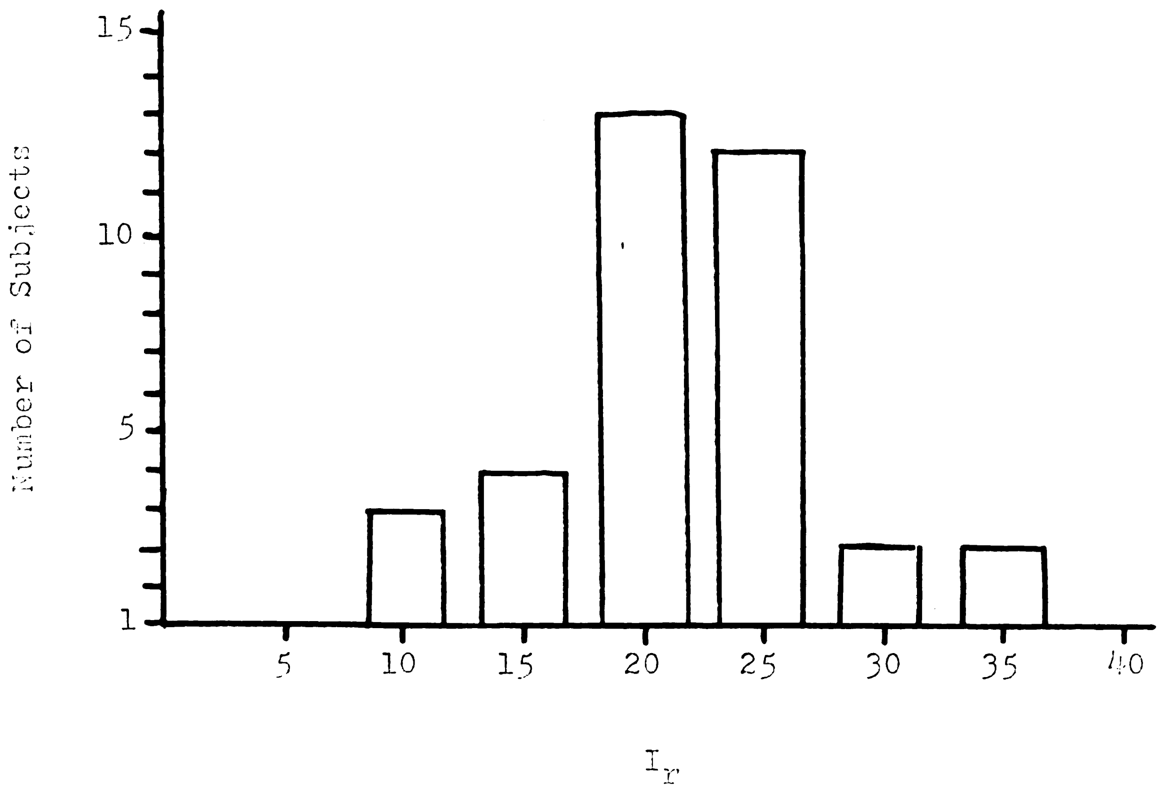

Figure 13. Histogram showing the speech noise index of recruitment (I_r) scores for the thirty-six experimental subjects.

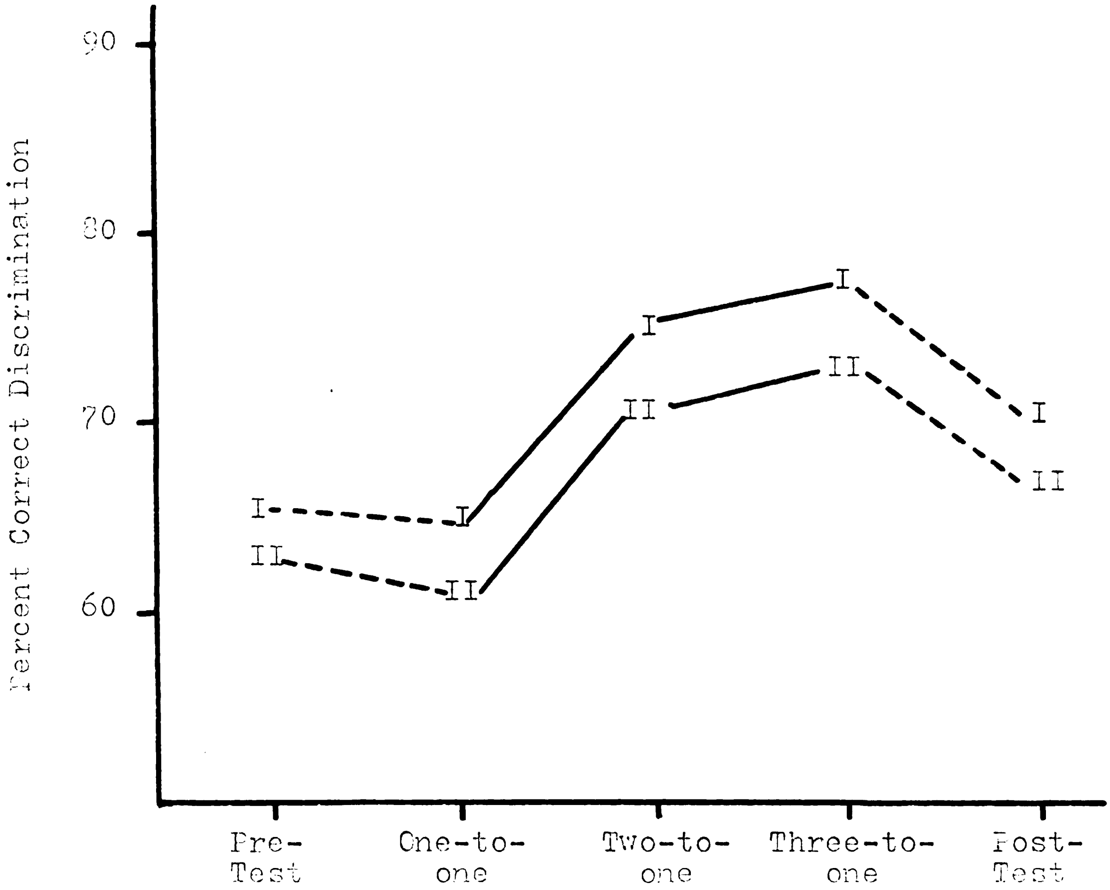

Figure 14. Mean speech discrimination scores of the twenty Class I (I's) and the sixteen Class II (II's) subjects for the experimental compression ratios as well as the pre- and post-experimental tests. (Class I represents less recruitment than Class II).

When classified by the I_r, both groups again appear to benefit from the amplitude compression. The largest gain in performance also occurred between the one-to-one and the two-to-one ratio. The groups did not differ at the pre-experimental test (t of 0.44, 17 df) or at the post-experimental test (t of 0.43, 17 df).

In contrast to the original analysis the Class I group performance was slightly superior throughout. This is clearly evident when one compares Figures 11 and 14. This finding demonstrates the necessity for additional research concerning methods for quantifying the "amount" of loudness recruitment.

An unweighted-means analysis of variance was utilized to determine if statistically significant differences existed: (1) between Class I and Class II recruitment; (2) between the three compression ratios; or (3) among the classes and the compression ratios. A 2 X 3 fixed model, with repeated measures on the compression factor was utilized. Factor R represents the two recruitment groups or classes. Factor C represents the three compression ratios.

Results of the unweighted-means analysis are summarized in Table 7. Differences between the recruitment groups classified by their I_r were not significant at the 0.05 level (F of 0.43). Differences among the compression

Table 7. Summary of unweighted-means analysis of variance comparing performance of Class I and Class II recruitment for the one-, two-, and three-to-one compression ratios.

Source of Variation	SS	df	MS	F
R	409.94	1	409.94	0.43
Subj. w. R.	32520.80	34	956.49	______
C	3122.90	2	1561.45	31.44**
RC	1.25	2	0.63	0.01
Residual	3379.84	68	49.70	______

**p 0.01

ratios were found to be statistically significant at the 0.01 level (F of 31.44).

The significant main effect for the compression ratios was further evaluated by multiple comparisons using Duncan's New Multiple Range Test (Edwards, pp. 136-157). This analysis yielded identical results with those presented in Table 6. Recall that the former analysis indicated that (1) the mean of the two-to-one compression was different from the one-to-one compression, (2) the three-to-one mean was significantly different from the one-to-one mean, and (3) the three-to-one mean was not significantly different from the two-to-one mean.

Gain in speech discrimination between the three ratios is shown in Table 8.

Table 8. Means, ranges and standard deviations of percent gain in speech discrimination scores from the one-to-one ratio to the two-to-one ratio, and from the one-to-one ratio to the three-to-one ratio (N=36).

Gain Comparison	Mean	Standard Deviation	Range
One-to-one to Two-to-one ratio	10.58	9.55	-3 to 32
One-to-one to Three-to-one ratio	12.22	11.86	-13 to 38

Discrimination improved significantly between the one-to-one and the two-to-one conditions and was also significantly better for the three-to-one condition when compared with the one-to-one condition.

Summary of the Results

An experimental battery consisting of (1) a speech discrimination pre-test, (2) discrimination tests under conditions of compression and no compression, and (3) a post-experimental discrimination test was administered to thirty-six subjects who exhibited loudness recruitment for a speech noise ABLB test. Two classification systems, based upon estimation of the magnitude of the loudness recruitment, were utilized for placing the subjects into experimental groups. The first system involved a comparison of the magnitude of the sensation levels above threshold necessary to make the test signals equally loud. This is the conventional method of quantifying recruitment according to Jerger (1962). The second system, an index of recruitment (I_r), was based on intra-aural comparison of the loudness function growth.

The data were analyzed independently for both systems of classification. Results of these analyses were strikingly similar in that both indicated (1) no significant main effect for the recruitment factor, (2) a significant main effect for the compression ratios, and (3) no significant interaction between recruitment and the three compression ratios.

Additional evaluation of the significant main effect for the compression ratios indicated that the two-to-one and the three-to-one ratios were significantly different from the one-to-one ratio but not significantly different from each other.

Discussion of the Results

Data concerning the discrimination of amplitude compressed speech by persons with loudness recruitment were provided by this study. Analysis of these data provided the basis for this section which will address, individually, the three experimental questions.

1. Does amplitude compression improve speech discrimination in recruiting ears?

The evidence clearly indicated superior speech discrimination for the two-to-one and the three-to-one compression conditions when compared with the one-to-one condition. Average performance of all subjects was 63.14 for the one-to-one condition, whereas it improved to 73.72 and 75.36 for the two-to-one and three-to-one conditions, respectively. These findings supported the experimental hypothesis that persons with loudness recruitment would be afforded special benefit in their understanding of speech signals by amplitude compression.

The observed gain in speech discrimination might lead to the arguement that it is the dynamic range rather than the sensation levels of the strong components which had the greater influence on the sensorineurals' speech perception. Cr, stated differently, when the peak powers of amplitude compressed speech are equated, the individual components assume new relationships and these changes appear important for perception. This is a very attractive hypothesis, but only partially confirmed by the results of the present study. A definitive answer must await further evidence based on other approaches. For example, it should be known whether comparable results would ensue by equating the peak components of the speech signals at other presentation levels.

The improved speech discrimination in this study has not been observed previously. Parker (1953), Lynn (1962), and Caraway (1964) have investigated hypoacusic perception of amplitude controlled speech. Contrary to the findings of this study, these three reported no systematic beneficial effects with amplitude controlled speech. The conflicting outcomes can perhaps be best explained by careful attention to differences in method of amplitude control and in the fidelity of the equipment.

Parker (1953) and Lynn (1962) utilized a method of amplitude limitation for controlling their speech signals. The discrepancy between their results and those of this study might well be due to differences in the dynamic functioning of compressors and limiters. Caraway's (1964) research, however, involved amplitude compression using the same compressor that was utilized in this study.

It is imperative, then, to determine a reasonable basis for the discrepancy between the results of this experiment and those obtained by Caraway. The most reasonable explanation can be found in the performance variation of the Weiss compressor during stimuli processing and recording during the two separate experiments. The compressor has been modified since it was used by Caraway. This modification provided more rapid roll-off of the frequency response below 400 Hz and above 4000 Hz.

Although restricting the frequency response, these changes reduced noise and harmonic distortion. Performance differences are evident when one compares the percent harmonic distortion before and after the modifications. The averages of Caraway's percentage distortion measurements of the second and third harmonics were 4.93, 10.09, and 22.98 for the one-, two-, and three-to-one conditions respectively. Corresponding measures, after the modifications, were only 2.77, 4.72 and 4.25. An analysis of the compressor's performance by Caraway indicated severe harmonic distortion in the low frequencies with systematic decrements in the distortion in subsequently higher frequencies. Apparently, most of this distortion was eliminated by the modifications consisting in rapid low-frequency rejection.

The commonly held opinion that speech discrimination suffers in the presence of harmonic distortion is documented by several research reports. Harris et. al., (1961); Jerger, (1967); and Kasten et. al., (1967) found positive relationships between speech understanding and harmonic distortion; specifically, all observed optimum discrimination under conditions of minimal distortion. Thus, explaining differences between the results of this study and Caraway's results on the basis of harmonic distortion differences appear warranted.

Rise-decay transients measured after the instrument modifications are slightly longer than the values measured by Caraway. She measured rise and decay transients of 1.5 and 1.0 msec. respectively. Corresponding values, after the modifications in the present study were 5.4 and 2.5 msec. These findings should be interpreted with considerable caution because they may have resulted as an artifact of measurement. Also in the event that they are real differences, their rather small magnitude would tend to limit any systematic effect on discrimination (Lynn, 1964).

2. Is the amount of improvement in speech discrimination related to the amount of the loudness recruitment?

This question asks whether increase in the intelligibility of compressed speech is related to the amount of loudness recruitment and does not concern absolute discrimination performance.

The thirty-six subjects involved in the study gave evidence of loudness recruitment for a speech noise ABLB test. Data relative to their perception of three degrees of amplitude compressed speech were partitioned into two groups according to their amount of loudness recruitment. Actually, two systems were utilized for this partitioning. The first involved comparing sensation levels necessary to make the speech noise signals equally loud. The second system compared, intra-aurally, the loudness function growth.

Neither of these methods for defining recruitment offered evidence that amplitude compression has a differential effect on the two recruitment groups. Both the partial and complete groups showed similar amounts of gain.

The subjects who exhibited the most recruitment and the most gain (benefit) for the compression were studied in detail. I_r scores for the nine subjects who experienced the largest and the smallest gain in speech discrimination are shown in Figure 15. The distribution of these scores, for both low- and high-gain subjects, covered a wide range and provide little evidence of a relationship between the amount of recruitment and gain from compression. A similar treatment of gain was obtained from subjects with clearly high and low I_r scores for the speech noise ABLB test at the 40 dB sensation level. I_r scores computed for all subjects at this presentation level revealed seven subjects with distinctly low I_r scores and ten with distinctly high I_r scores. The seven subjects with low I_r scores demonstrated average gain scores of 24.71 percent, whereas the ten high I_r subjects demonstrated compatible average gain of 20.30 percent. Again, the results definitely do not support the experimental

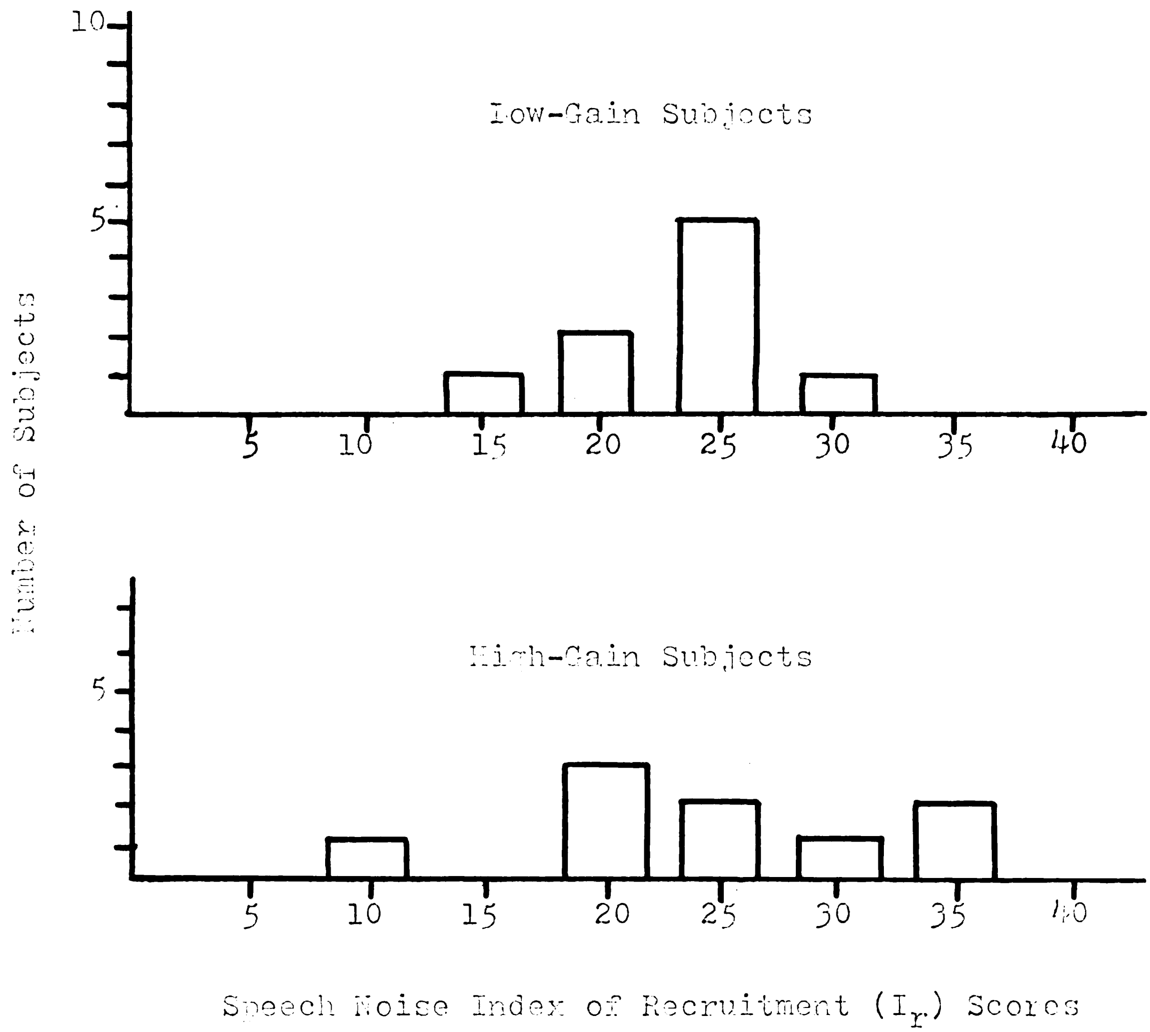

Figure 15. Histograms of the speech noise index of recruitment response (I_r) scores for the nine subjects that were benefitted the greatest (high-gain) and the smallest (low-gain) by the amplitude compression.

hypothesis that compression would have a differential effect on the two recruitment groups.

3. <u>Is the amount of improvement in speech discrimination related to the degree of the compression?</u>

This question asks whether there is a systematic effect produced by the amount of amplitude compression. The subjects responded to speech discrimination tests delivered under three compression conditions. These were rather widely spaced discrete points along a continuum of conditions which can be specified by their input-to-output ratios (in dB). Linear amplification bounds the lower limit of the continuum and, as such, is specified by one-to-one compression. A two-to-one ratio represents moderate compression, whereas three-to-one is rather extreme compression.

Data relative to the influence of the compression ratios indicated a significant main effect for the compression conditions. Subsequent analyses indicated that average performance for the two-to-one and the three-to-one ratios were significantly better than the one-to-one ratio but not different from each other. These findings do not support the experimental question stating that the amount of improvement in speech understanding would be related to the amount of compression.

The evidence does not suggest that compression did not enhance the subject's speech discrimination. Rather, it simply implies that no linear or systematic relationship was found between the amount of discrimination enhancement and the degree of compression. This relationship is evident by the amount of gain in discrimination realized from each compression condition. Average gain for all subjects between the one-to-one and the two-to-one ratios was 10.58 percent. However, the average improvement between the two-to-one and the three-to-one ratio was only 1.64 percent. In other words, the evidence indicates that the subjects were benefited about equally for the two- and three-to-one ratios.

Range and standard deviation values of the gain scores (see Table 6, p. 67) indicate very large subject variability. Only three subjects failed to benefit from the two-to-one condition and only four failed to benefit from the three-to-one condition.

Summary and Clinical Implications

Summary. Within the confines of the study, three tentative conclusions can be advanced. First, amplitude compression appears to enhance speech perception in persons with loudness recruitment. Second, the amount of enhancement does not appear to be related to the degree of the recruitment; and third, neither does it seem to be related to the amount of compression. These findings have obvious implications; however, certain other secondary findings emerged which may have important implications regarding our clinical management of hypoacusis.

Recruitment and the speech noise ABLB test. More than sixty persons with unilateral sensorineural hearing loss were examined in order to obtain the specified experimental sample. Failure in meeting the pure tone preliminary specifications was the predominant attrition factor. Most of the subjects could adequately perform the loudness balances; however, many needed repeated instructions and encouragement. Two people were encountered who simply could not perform this task.

Only two subjects failed to exhibit loudness recruitment for the speech noise signals. To check this finding, ABLB data for pure tone signals (i.e., 500 Hz, 1000 Hz, and 2000 Hz) were obtained for all subjects. The speech noise and the pure tone signals yielded compatible results. Recruitment was indicated by the speech noise in every case where it was indicated for a single pure tone or for any combination of the pure tones. The average I_r for the three tones and the I_r for the speech noise correlated at 0.44. Finally, the two signals used for ABLB (pure tone and speech noise) yielded compatible results in a small control sample (N of 6) of persons with conductive hearing loss.

These findings have two important clinical implications. First, if the experimental sample is representative, one can expect some degree of loudness recruitment in practically all subjects with unilateral sensorineural hearing loss. Second, speech noise appears to be a good ABLB test signal.

External Validity of the Results. Several factors prohibit generalizing the findings of this study to wearable amplification (i.e., hearing aids) utilizing amplitude compression. The CNC signals were used because they enabled quantification of the speech perception. Obviously, the dynamic range of these signals was not representative of everyday speech and the subjects listened in an artificially quiet environment. Moreover, the Weiss compression amplifier is an AC operated desk-type instrument and, as such, cannot be worn on the body.

Clinical Implementation of Amplitude Compression. People with sensorineural hearing loss generally exhibit loudness recruitment, and they discriminate speech better when it's amplitude dimension is compressed. Some few do not experience this benefit, whereas others exhibit dramatic improvement. Although the benefit of the compression cannot be predicted by the recruitment, simple clinical procedures could identify these people who potentially will be helped and could estimate the magnitude of the help.

Since there is no relationship between the amount of benefit and the amount of compression, this identification could involve a simple comparison between discrimination for compressed and uncompressed speech signals. People who are substantially helped should have great potential for success in utilizing amplification employing amplitude compression.

CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

Speech discrimination performance of thirty-six subjects was compared for conditions of amplitude compression and for no compression. These conditions were achieved with a prototype amplitude compressor built by Mr. Erwin Weiss and supplied by the Beltone Electronics Company. The instrument had input-to-output amplification ratios of two-to-one and three-to-one, and it also functioned as a linear amplifier which was called one-to-one amplification.

The thirty-six subjects, all of whom had unilateral sensorineural hearing loss, were partitioned into partial or complete loudness recruitment groups on the basis of their response to a speech noise ABLB test. Classification of subjects was carried out according to two procedures. The "classical" procedure involved a comparison of the magnitude of the sensation levels above threshold necessary to make the test signals equally loud. The second system was based on intra-aural comparison of the loudness function growth.

CNC test material, under each compression condition, was presented at 24 dB sensation level at the effected ear. Broad band masking noise was routinely applied at the contralateral ear. Statistical analyses of the data, partitioned by either method for defining recruitment, yielded similar results, namely: (1) no significant main effect for the recruitment factor; (2) a significant main effect for the compression ratios; and (3) no significant interaction between level of recruitment and three compression ratios. Additional evaluation of the significant main effect for the compression ratios indicated that discrimination scores for the two-to-one and the three-to-one ratios were significantly higher than the one-to-one ratio but not significantly different from each other.

Conclusions

Within the limitations of the experimental design of this study and the instrumentation employed, the following conclusions are warranted:

1. Amplitude compression enhances speech discrimination in persons who have unilateral sensorineural hearing loss with concomitant loudness recruitment.

2. The amount of discrimination enhancement is not related to the magnitude of the loudness recruitment.
3. There is no relationship between the discrimination enhancement and the magnitude of the amplitude compression (two-to-one versus three-to-one ratios).
4. Speech noise signals can serve as adequate ABLB test stimuli.
5. Loudness recruitment is exhibited by most persons with unilateral sensorineural hearing loss.
6. The omnibus aural rehabilitation process should include assessment of discrimination enhancement provided the hypoacusic by compression amplification.
7. Persons who demonstrate superior performance for controlled speech signals with compression amplification may have great potential success in utilizing individual amplification with compression.

Recommendations

Although this study found that hypoacusics are benefitted substantially by amplitude compression, many questions remain to be answered. Much work needs to be done regarding discrimination of amplitude compressed speech in persons with cochlear problems.

Since no attempt was made to classify and systematically study the etiology of the hearing loss, such an investigation should be undertaken. Discrimination of compressed speech, like discrimination for distorted speech per se, may be quite sensitive to the type of end-organ lesion.

The effects of noise masking on understanding of compressed speech in sensorineural subjects should be studied. Differential effects of various types of cochlear lesions in identifying noise masked compressed speech should be researched.

Multifactor studies should be designed to systematically investigate enhancement of speech perception in end-organ lesions. Such research should include specification of the pathological ear's performance with respect to time and frequency parameters. Such research also should study psychological variables such as preference for compressed speech versus enhancement in speech understanding.

The present study should be replicated using a variety of speech signals presented at numerous sensation levels. For reliability, a replication using N. U. No. 6

is needed. This should be followed by investigations with a variety of stimulus materials such as The Fairbanks' Modified Rhyme Test or a sentence intelligibility test.

Finally, much work remains to be done relative to our clinical implementation of amplitude controlling devices. Data about the performance characteristics of hearing aids currently available with some form of amplitude control should be obtained. The Weiss instrument should be compared with a hearing aid that is capable of achieving compatible control. Objective and subjective data concerning the effects of this form of amplification in a wide variety of applications is needed.

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APPENDICES

APPENDIX A

GLOSSARY OF TERMS

GLOSSARY OF TERMS

Amplitude control involves restricting the long-term dynamic range and the peak components of amplified signals. Two devices for achieving this control, amplitude compressors and amplitude limiters, are specified by the net effect they exert on speech signals.

<u>Amplitude Compression</u>: When the amplitude dimension of speech is compressed, the dynamic range between the stronger amplitudes and the weaker amplitudes is reduced regardless of the level of the input signal. Compressors, then, have variable output gain which is inversely related to input signal amplitude. They also reduce maximum power output, but this is of secondary importance to their prime function of dynamic range reduction.

<u>Amplitude Limiting</u>: Relationships between the stronger and the weaker amplitudes are unchanged during low-input levels when speech is reproduced by a limiter. However, these instruments perform similarly to compressors for high-input signals. In other words, amplitude limiters simply restrict the maximum output of amplified signals.

<u>Hearing Level</u>:

This is the ratio, expressed in decibels, of the threshold of an ear at a specified frequency to a standard reference zero level for pure-tone audiometers. Practically it is the reading in decibels, on a standard audiometer, that corresponds to the listener's hearing threshold (Davis and Silverman, 1970, p. 498).

Loudness Recruitment:

Auditory recruitment, which was given its name in 1926 by Dr. Edmund Fowler, Sr., is basically defined as an abnormally rapid increase in sensitivity to loudness as the intensity of a sound is raised above threshold (O'Neill and Oyer, 1966, p. 132).

Recruitment Classification: Two classification systems were used for placing the subjects into experimental recruitment groups. The first system placed the subjects into the traditional "partial" and "complete" recruitment catagories by comparing the magnitude of the sensation level above threshold necessary to make test signals equally loud. The second system, an index of recruitment (I_r), placed the subjects into analogous Class I and Class II groups by intra-aural comparison of the loudness function growth.

Sensation Level: Sensation level is "the pressure level of the sound in decibels above (or below) its threshold of audibility for the individual observer or for a specified group of individuals" (Newby, p. 12).

Speech Noise: Speech noise is noise which conforms to the long-time average speech spectrum. This spectrum is derived by analyzing segments of running speech in which every sound occurs many times. Energy levels in each part of the spectrum are measured and summed, separately, for the entire sequence. Finally, the summed energy for each part of the spectrum is plotted (Denes and Pinson, 1963).

APPENDIX B

RESPONSES OF THE GROUPS TO PRELIMINARY TESTING

Mean, Median, and Range of the Air Conduction Pure-Tone Hearing Levels (in dB)
Re: ISO 1964 Norm for the two Recruitment Groups

	PARTIAL GROUP						COMPLETE GROUP					
	Test Ear			Nontest Ear			Test Ear			Nontest Ear		
Hz	Mean	Mdn	Range	Mean	Mdn	Range	Mean	Mdn	Range	Mean	Mdn	Range
250	51.11	52.50	30-65	15.55	14.65	5-25	42.20	37.50	25-70	14.16	14.38	0-25
500	56.39	58.75	35-70	13.61	14.17	5-20	45.00	42.50	35-65	11.94	12.50	5-20
1000	56.66	58.75	35-70	10.83	10.83	5-15	48.05	46.25	40-60	10.00	10.00	0-20
2000	57.22	56.25	35-75	15.83	16.50	5-25	52.22	50.83	40-65	13.88	14.50	0-25
4000	64.44	68.75	35-95	24.16	22.50	5-70	58.61	63.75	25-80	26.11	20.00	0-55
8000	*	72.50	30-110	29.16	34.17	-10-60	*	69.16	15-110	23.33	22.50	-10-45

*Mean not computed because some responses were beyond the maximum limits of the audiometer.

Means and Ranges of Pure-Tone Average Thresholds (i.e. 500 Hz., 1000 Hz., and 2000 Hz.) and of Speech Reception Thresholds for the Test ear for each of the Two Recruitment Groups.

	PARTIAL GROUP	COMPLETE GROUP
Pure tone average thresholds (500, 1000, and 2000 Hz) in dB re: ISO Norm (1964)		
Mean	55.61	47.94
Range	37-68	40-58
Speech reception thresholds in dB re: 22 dB SPL		
Mean	54.22	44.94
Range	32-70	32-60

APPENDIX C

COMPRESSOR INPUT-OUTPUT FUNCTIONS

Input-output Functions (in dB) of the Three Compressor Channels when the CVC Words were Compressed under One-to-one, Two-to-one, and Three-to-one Ratios.

Level (in dB)	Frequencies (Hz) 700	1500	3000
One-to-one Compression Ratio			
0	0	0	0
-10	-9.6	-9.4	-9.0
-20	-19.4	-19.3	-18.7
-30	-28.6	-28.7	-28.3
Two-to-one Compression Ratio			
0	0	0	0
-10	-5.0	-4.8	-5.6
-20	-9.4	-9.4	-10.3
-30	-13.5	-14.0	-14.8
Three-to-one Compression Ratio			
0	0	0	0
-10	-2.4	-2.3	-3.4
-20	-5.0	-5.4	-6.1
-30	-8.5	-9.4	-9.4

APPENDIX D

PRESENTATION ORDER FOR THE CNC TEST LISTS

Presentation order for the pre-test, the compression conditions, the test lists, and the post-test for the eighteen subjects in each of the two recruitment groups.

Subjects	Pre-Test	Ratio	Lists	Ratio	Lists	Ratio	Lists	Post-Test
1	IA	1:1	IIA IIIB	2:1	IIIC IIC	3:1	IIIA IIB	IA
2	IA	1:1	IIIB IIB	3:1	IIC IIIA	2:1	IIIC IIA	IA
3	IA	2:1	IIB IIIB	1:1	IIA IIIA	3:1	IIC IIIC	IA
4	IA	2:1	IIIB IIA	3:1	IIIC IIB	1:1	IIC IIIA	IA
5	IA	3:1	IIC IIIA	1:1	IIA IIIB	2:1	IIB IIIC	IA
6	IA	3:1	IIB IIIA	2:1	IIIB IIC	1:1	IIIC IIA	IA
7	IA	1:1	IIC IIIB	2:1	IIIA IIB	3:1	IIA IIIC	IA
8	IA	1:1	IIIA IIC	3:1	IIIB IIB	2:1	IIA IIIC	IA
9	IA	2:1	IIIA IIB	1:1	IIA IIIC	3:1	IIIB IIC	IA
10	IA	2:1	IIA IIIA	3:1	IIC IIIB	1:1	IIIC IIB	IA
11	IA	3:1	IIIC IIC	1:1	IIB IIIA	2:1	IIIB IIA	IA
12	IA	3:1	IIC IIIB	2:1	IIIC IIB	1:1	IIIA IIA	IA
13	IA	1:1	IIA IIIB	2:1	IIIC IIC	3:1	IIIA IIB	IA
14	IA	1:1	IIIB IIB	3:1	IIC IIIA	2:1	IIIC IIA	IA
15	IA	2:1	IIB IIIB	1:1	IIA IIIA	3:1	IIC IIIC	IA
16	IA	2:1	IIIB IIA	3:1	IIIC IIB	1:1	IIC IIIA	IA
17	IA	3:1	IIC IIIA	1:1	IIA IIIB	2:1	IIB IIIC	IA
18	IA	3:1	IIC IIIB	2:1	IIIC IIB	1:1	IIIA IIA	IA

APPENDIX E

IDENTIFYING INFORMATION, PRELIMINARY RESPONSES, AND DISCRIMINATION SCORES OF THE THIRTY-SIX SUBJECTS FOR CNC WORDS FOR THE THREE RATIOS

PARTIAL RECRUITMENT GROUP

Identifying Information, Preliminary Responses, and Discrimination Scores of the Thirty-Six Experimental Subjects for the CNC Words Under the Three Compression Ratios

Ss	Age	Sex	Test-Ear	SRT	ITA	Raw API3 Data (Ir's) 500	1000	2000	Spch Noise	Speech Discrimination Raw Score Pre-Test	Post-Test	1:1 1	1:1 2	2:1 1	2:1 2	3:1 1	3:1 3
1	68	M	R	60	63	30	25	25	35	30	30	23	22	31	31	41	36
2	59	F	R	50	50	15	25	20	15	44	43	36	40	41	43	41	43
3	50	M	R	60	65	30	25	20	35	31	36	30	36	36	41	36	41
4	51	F	R	56	60	30	20	20	25	38	37	36	41	40	41	43	39
5	39	F	L	36	37	5	5	10	10	41	43	42	43	48	46	47	47
6	38	M	L	58	58	20	25	25	20	29	32	27	24	36	37	38	40
7	42	M	L	38	38	5	0	30	10	32	38	26	30	35	30	32	30
8	59	F	R	60	60	15	15	15	20	18	18	13	16	18	20	22	22
9	44	F	L	54	54	10	10	15	20	28	28	26	30	31	26	37	30
10	37	F	L	52	50	10	15	10	20	41	45	48	50	47	48	45	47
11	65	F	R	56	58	15	20	20	25	20	23	22	20	24	25	27	28
12	41	F	L	60	68	25	25	20	25	13	14	19	17	18	17	11	12
13	56	M	L	70	68	30	30	30	25	17	21	18	18	30	25	28	32
14	31	F	L	32	42	15	25	20	25	48	49	44	48	49	50	50	49
15	60	F	L	58	58	15	15	20	20	25	26	24	27	36	31	33	36
16	61	F	R	58	52	15	20	15	30	22	29	20	24	36	26	38	38
17	48	F	L	58	56	10	20	20	15	17	19	18	21	22	23	21	27
18	53	F	L	60	64	20	20	15	25	26	28	17	19	19	22	24	26

COMPLETE RECRUITMENT GROUP

Identifying Information, Preliminary Responses, and Discrimination Scores of the Thirty-Six Experimental Subjects for the CNC Words Under the Three Compression Ratios

						Raw AB13 Data (Ir's)				Speech Discrimination Raw Score									
												1:1		2:1		3:1			
Ss	Age	Sex	Test-Ear	SRT	PTA	500	1000	2000	Spch Noise	Pre-Test	Post-Test	1	2	1	2	1	2		
1	44	M	L	45	50	20	20	30	20	41	42	26	24	41	41	43	45		
2	57	F	L	45	45	25	15	10	20	43	45	44	42	46	47	49	48		
3	42	M	R	60	58	25	25	15	30	31	35	27	31	27	33	24	31		
4	22	F	L	56	55	25	25	30	20	19	22	26	22	25	25	27	26		
5	63	F	L	48	45	5	10	20	15	38	38	37	37	42	41	43	43		
6	60	M	L	54	50	15	20	25	20	39	41	40	41	42	42	46	43		
7	55	M	R	32	42	15	15	20	25	42	41	30	31	45	48	50	49		
8	38	F	L	52	50	25	25	15	25	27	32	24	28	37	39	37	35		
9	55	M	L	36	42	10	10	10	25	44	45	48	47	48	49	49	47		
10	68	F	R	44	48	20	15	10	25	35	36	39	40	40	37	44	42		
11	41	M	L	38	40	10	10	25	20	32	38	41	39	46	43	45	45		
12	61	M	R	38	52	20	20	30	20	28	33	30	37	40	44	47	44		
13	67	F	L	36	45	20	20	20	20	40	41	34	33	45	44	43	41		
14	53	F	R	44	45	25	15	30	10	23	31	22	24	38	39	37	31		
15	55	M	R	48	48	20	15	15	15	37	35	36	35	39	34	34	32		
16	57	M	R	38	45	25	20	25	20	44	43	41	44	45	45	45	46		
17	66	M	L	49	48	20	15	25	25	39	38	37	34	42	45	37	35		
18	43	M	L	46	55	20	25	30	25	41	40	44	43	45	46	45	48		