AN AUDITORY LOUDNESS RECRUITMENT TEST BATTERY:

ANALYSIS AND COMPARISON OF SUB TESTS

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ABSTRACT

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A survey of the literature indicates that recruitment tests can be sub-divided into tests of loudness balance, difference limen, and speech sound discrimination. The purpose of the present investigation was to establish, by means of more rigorous statistical analyses than have hitherto been employed, the capability of a series of tests to distinguish between normal hearing individuals and individuals whose auditory perception is characterized by recruitment in the loudness function. The following tests were subjected to such statistical analyses; l) Range of Comfortable Loudness test: 2) Difference Limen test; and 3) Speech Sound Discrimination test.

The procedure employed consisted of the following basic steps:

1. Administration of the three tests to five control (normal hearing) and four experimental (recruiting) subjects;
2. Statistical treatment of the data collected by the analysis of variance technique.

Test results revealed that the experimental and control groups performed differently on all three tests, that the effects of frequency and sensation level were significant within the Range of Comfortable Loudness and Difference Limen tests and that there were significant interactions among the main effects. A comparison of the test results from the experimental group with data previously reported for recruiting ears provided some instances of agreement and some of disagreement. The difference limen results were almost identical with limens reported by previous

investigators. However, the range of comfortable loudness for the experimental group was wider than previously reported, and the speech sound discrimination was superior to that reported in an earlier investigation.

within the limitations of the present investigation, the following conclusions appear to be justified:

1. Normal hearing individuals are distinguishable from individuals with impaired hearing demonstrating recruitment on the basis of the following test performances:

a) Range of Comfortable Loudness: A restricted RCL is characteristic of the auditory perception of individuals exhibiting the recruitment phenomenon.

b) Difference Limen: A smaller difference limen is characteristic of the auditory perception of individuals exhibiting the recruitment phenomenon.

c) Speech Sound Discrimination: A higher number of correct responses in a restricted range immediately above the threshold of detectability is characteristic of the auditory perception of individuals exhibiting the recruitment phenomenon.

2. The extent of the range of comfortable loudness and of the difference limen depends upon the frequency of the stimulus tone.

3. In general, the extent of the DL is inversely proportional to the sensation level of the stimulus tone, while the number of correct speech sound discriminations is directly proportional to the sensation

leavl.

AN AUDITORY LOUDNESS RECRUITMENT TEST BATTERY:
ANALYSIS AND COMPARISON OF SUB TESTS

INTRODUCTION

The importance of a more tnorough Knowledge of the auditory phenomenon of loudness recraitment has been widely recognized in the climcal setting. During world war II, speech and hearing clinics over the country were becoming more and more aware of the nature of recruitment when the returning veterans began seeking aid for problems involving tnis phenomenon. As the need arose for a more thorough insight into this problem, it became apparent that tests should be developed to insure a complete prognosis for the individuals affected. The position of the clinician in this uncharted area was accurately described by Tumarkin (39):

> Sound, as physical phenomenon, is the legitimate domain of the physicist; as a concept, it comes within the province of the psychologist. Many cliniclans would gladly surrender all claims to these territories but for the fact that modern otology and audiology have brought us right up to the frontiers into a "No Man's land" where all is vague and ill-defined. The phenomenon of loudness recruitment lies in that "No Man's Land" and it is a remarkable fact that although this phenomenon has been universally recognized as of prime diagnostic significance, no clear explanation of its mechanism has so far been proffered.

Recruitment, it is seen, is an acknowledged, recognizable clinical entity. It is only when the attempt is made to explain the etiology and basic effects upon the individual that vagueness and uncertaincy enter. Hence, determination of the significance of recruitment within the framework of auditory theory today is claiming the attention of a large number of laboratories and clinics. Data relating to the manifestations of the recruiting individual are being analyzed. Tests are being devised to indicate the presence or absence of recruitment in the individual with impaired hearing. As evidence of the spreading concern with the phenomenon, it is to be noted that manufacturers of audiometric instruments in this country and abroad now are offering equipment specifically designed for the purpose of testing recruitment.

Psychophysical research in audition since 1900 has added considerably to the growing body of knowledge in the behavioral sciences. At the turn of the century investigators were interested in basic stimulus-response aspects of human hearing. Normative data with respect to just noticeable differences were sougnt. Then, as population norms became established, the investigation of abnormalities of audition become a fruitful area for research. One of the aspects of hearing noteworthy for individual differences, both with respect to its presence or absence, and with respect to certain quantitative characteristics, was loudness recruitment. From investigations of this phenomenon, operational.definitions of loudness recruitment have been provided. According to Harris (19), E. P. Fowler is believed to have made first use of the term "recruitment" in the auditory context. Fowler (14) states:

> If one ear has normal hearing and the opposite ear is deafened by a neural or so-called "nerve" deafness, the difference between the two ears at threshold will disappear as the sound is increased over threshold, until at nigh intensities the sound appears just as loud (and sometimes louderj to the deafened ear as it does to the normal ear. This, pathological or pathophyslological increase in the increment of loudness is called "recruitment of loudness" or "recruitment".

Hallowell Davis (4) describes recruitment as follows:

> It is a curious fact that although the nerve-deaf may not be able to hear hign tones at all when the tones are faint, they are able to hear the really powerful high tones just as loudly as anyone else. The transition from hearing little or nothing to rearing

> very well is abnormally abrupt. with nerve deafness the range of comfortable hearing between the inaudible and the too loud - the zone In which we like to listen - is greatly narrowed. This effect of abnormally rapid Increase In loudness is known as "recruitment", and is very annoying, "Recruitment" is the condition where faint or moderate sounds cannot be heard, while at the same time there is little or no loss In the sense of loudness of loud sound. It explains why old people, whose deafness is usually a gradual high-tone nerve deafness, complain one moment that tney cannot near a speaker and the next moment, when he raisses his voice, that he is shouting too loudly at them.

Watson ana Tolan (42) also describe recruitment in terms of the rapid approach to normal loudness perception once the stimulus has passed the threshold of the impaired ear. They state that, "In spite of an impairment at threshold, the individual hear loud sounds with a sensation of loudness equal or more nearly comparable to the loudnoss with which a normal ear would perceive them. Loud sounds are not reduced by the degree of the impairment in decibels at threshuld."

One of the more recent operational definitions is that of Hirsh (22), who writes, "Evidence for recruitment, is obtained when it can be shown that the loudness of a given tone Increases more rapidly than normal as the sensation Level of the tone is increased in equal decibel steps."

Finally the summary statement by Bangs and Mullins(1) is considered to be representative of the many other definitions of the phenomenon to be found in clinical and experimental pubiications. "Recruitment of loudness," they wrote, "is a phenomenon involving a foresnortening of the usable range uf hearing." A graphic representation of this "foreshortened range" contrasted with a normal range is pruesented in Figure 1. Apparent in this figure is the convergence of loudness sensation at supra-threshold levels described by the authorities cited above.

While the previous definitions have been concerned with recruitment as a general case, today it is generally agreed that recruitment may be

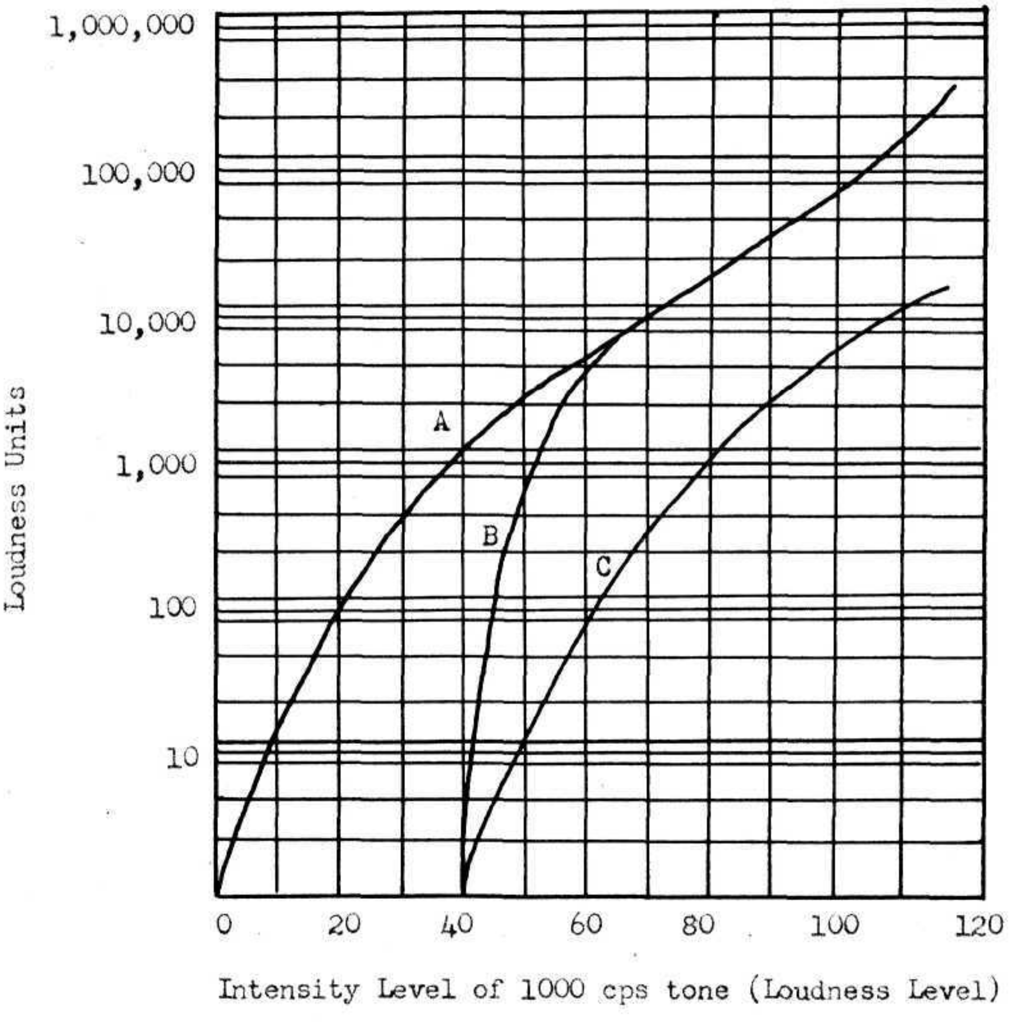


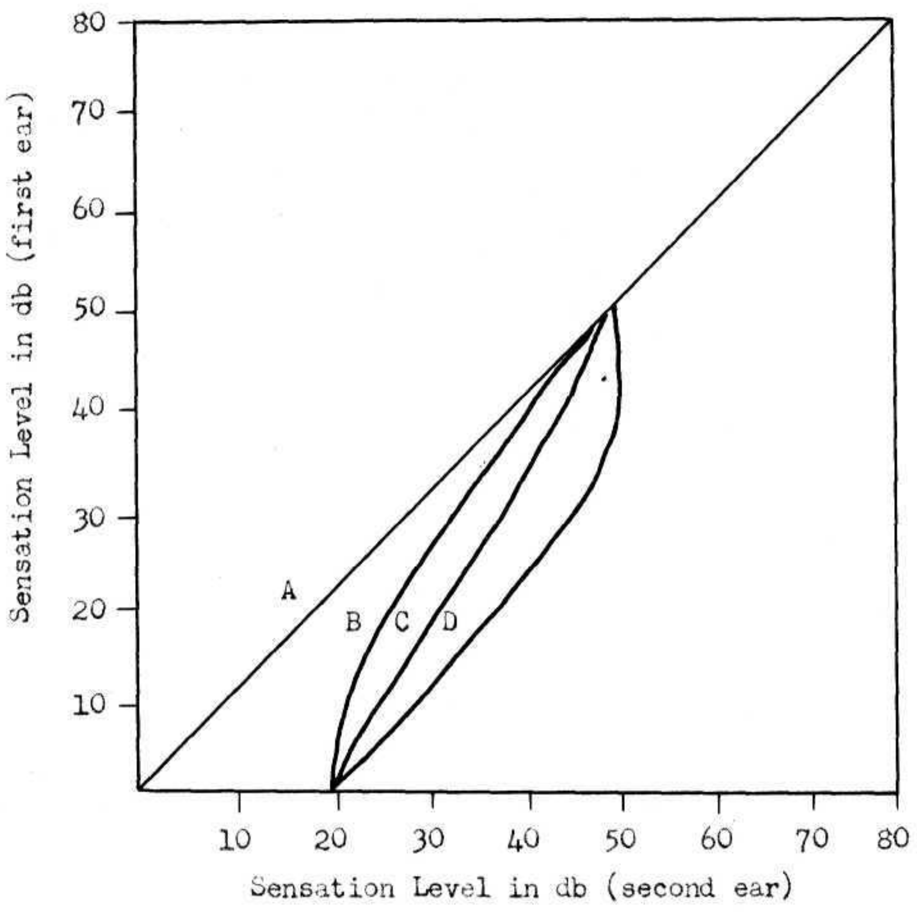
Fig. 1 Theoretical Functions Relating Loudness to Intensity Level for three cases: (A) normal hearing; (B) 40 db Hearing Loss of the Variable Type with Recruitment; and (C) 40 db Hearing Loss of constant type with no Recruitment (after Hirsh).

manifested in one or more of several ways. In addition to what may be termed "classical recruitment", there have been two other types of recruitment found and described. These are the delayed and asymptotic types. As shown in Figures 2 and 3, the delayed and asymptotic types differ from the classical case in the point at which the pnenomenon occura and the rate of loudness increment per unit of physical increment. An tne stimulus intensity is raised, delayed recruitment is Characterized by an increase in the db increment perceived as compared to regular recruitment. Asymptotic recruitment is charecarized by an increase in the db increment perceived as compared to regular recruitment in a manner that approaches the normal ratio of loudness matching asymptotically. with the isolation of the two variant in recraitment type, it has been observed that present testing procedures are inadcquate. The need for revised or expanded procedures will be enlarged upon in a later section.

Recruitment atheories

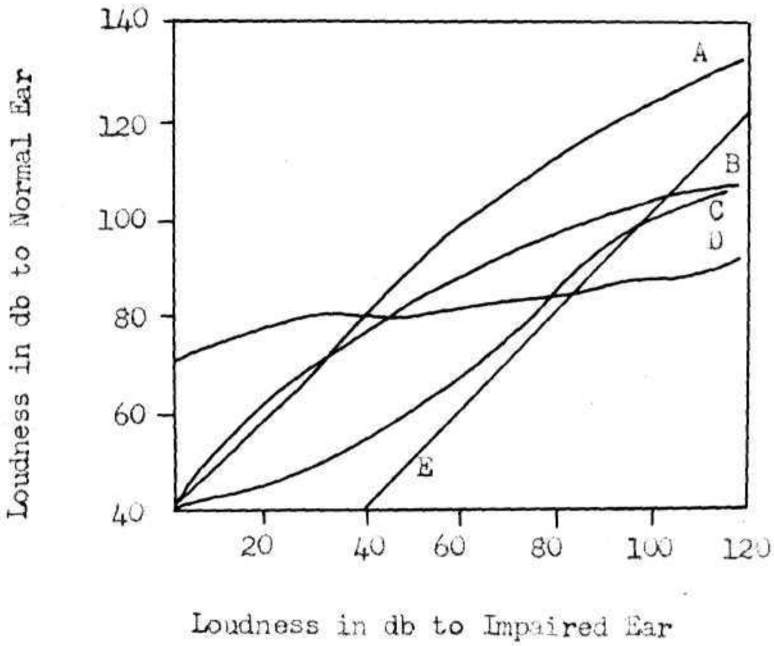
In the previous section, operational definitions of recruitment by medical and psychological authorisies were presented. A. conisideration of the neurological and psychologica1 implication of the phenomenon is desirable for background to the present study, since authorities have not agreed upon the psycho-neurological mechanism of recruitment. However, certain theories hava been advanced which have found considerable acceptanca. Among these are the hypotneses by Steinburg, Fowler, Stainberg and Gardner, Lurie, and Tumarkin. Brief summeries of their theories are presented below.

Steinberg (36) offered a fiber-loss theory in which he stated that, "If a few nerve fibers wore defective, this would have a smaller effect



A - Normal hearing
B - Asymptotic Recruitment
C - "Classical" Recruitment
D - delayed Recruitment

Fig. 2 Recruitment Increment Curves, Showing Different Types of Loudness Acceleration (after Bangs and Mullins).



A - Loudness perception curve of conductive deafened ear
B - Delayed type of recruitment
C - Asymptotic recruitment
D - "Classical" recruitment
E - Normal ratio of increased intensity to increased loudness

Fig. 3 Schematic Representation of Varying Rates of Recruitment (after Watson and Tolan).

as the stimulus intensity increased." In this statmant is the assumption that loudness is some function of the number of auditory nerve fibers actively conducting impulses. At threshold, the presence of defective nerve fibers would not rcsult in perceptual attenuation, but at levels progressively higher than threshold, the lack of sufficient fibers to carry the stimulus would become progressively more apparent. The failure of tne theory to account for delayed recruitment is obvious.

Fowler's <u>occlusion thuory</u> has been given a very detailed presentation by Lorenta de No (19), who wrote:

> If a number of hair cells in the ear or a number of fibers in the cochlear nerve is missing, the tones will appear to be weaker in intensity whon near-threshold stimuli are used; but if the intensity of the tone is increased, the wore strongly activated hair cells or cochlear fibers will be sufficient to saturate, i.e., to excite tue limiting intencity of the cochlear fibers or cells of tha cochlear nuclei, so that the cerebral cortex will receive the Same number of impulses per second for both ears and will perceive the tone delivered to the diseased ear as strongly as the one delivered to the normal or less affected ear.

Writing in collaboration, Steinberg and Gardner (36) attempted an explanation of recruitment in the frame of reference of experimental psychology of perception:

> Suppose an ear to be 20 db deaf for a certain frequency. A tone at threshold for this particular ear amounts to a loudness of about 100 loudness units for the normal ear. But suppose the tone were increased 20 db over the deafened threshold. A tone of this intensity amounts to about l000 loudness units for the normal ear. A further increase of 20 db intensity produce 4,500 loudness units; and so on. It is easily seen that because of tue nature of the relationuaip between sensation level and loudness, an ear with a type of deafness resulting, in a constant loudness loss would tend to overcome this handicap at high intensities, where the <u>percent</u> loudness loss could be unnoticeabit (in Lhe above illustration, at 40 db sensation level pcrcent loudness is only about 2.0).

This <u>constant loudness loss theory</u> has received favorable critical comment and is one more step toward a more complete explanation of the cause of recruitment.

Lurie (30) explaining recruitment in terms of the difference in sensitivity of the outer and inner hair cells, wrote, "If the more sensitive outer hair cells are defeclive, then the threshold would be raised; but if the sound intensity were raised sufficiently to stimulate the inner hair cells, these would ruspond normally and a rather sudden increase of loudness might result." This explanation makes the implicit assumption, however, that in the normal ear the outer hair cells no longer contribute significantly to loudness at intensities which stimulate the inner hair cells. Crities of Luria's theory are skeptical of the either—or principle involving the outer and inner hair function. Lurie's explanation of recruitment has been named the duplicity theory. In this theory, it is to be noted the first attempt is made to explain recruitment in terms of the hair colic rather than auditory fibers. The recent tendency has been to discount previous theories which relate recruitment to a disruption of the nerve fibers in the cochlea. As clinical and experimental evidence mounts, variations of Lurie's duplicity theory appear in the literature.

Tumarkin (39) proposed that:

> If only the more sensitive hair cells are damaged, then at some higher intensity the inner hair cells will begin to function, and to these unity the brain assigns a certain loudness. This "memory function" is then amplified. It is assumed that a sound, which has a certain psychological loudness to the normal ear, has a characteristic geometrical pattern of activity on the basilar membrane. Now if some hair cells in that ear are damaged, the resultant pattern for that sound will be affected - but the missing features will be "filled-in" by the "memory" and the psychological contribution to loudness will over-ride the physical deficiency.

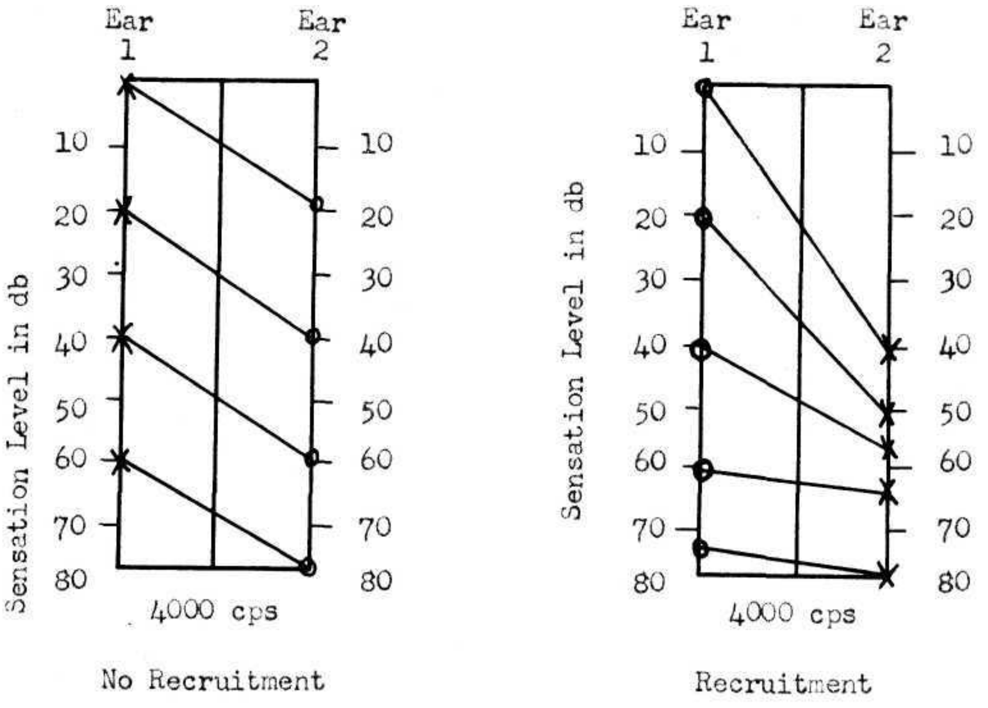
This idea has been called the gaometric theory.

The preceding brief summary of recruitment theory was intended as an over-view, rather than an attempt to arrive at a final theoretical position. It is believed that the present status is such that no final position can be taken. whether the eventual explanation should be in neural terms and the fiber-loss theory, the constant theory, the geometric theory, or some other, cannot be said at the project time. what can be said, however, is that each successive theoretical formulation and controlled investigation provides a further step toward final understanding of this interesting and significant disorder of the auditory mechanism.

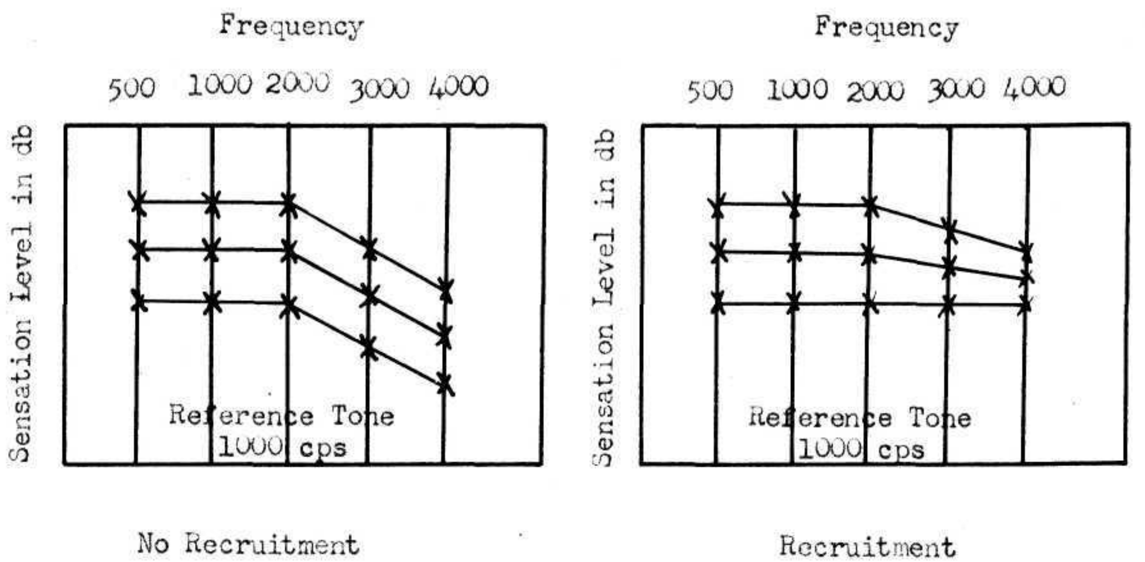
Recruitmeut Tests

Probably because of the relatively recent heightened interest in auditore recraitment, there are currently in use a rather largre number of different techniques for discovering its preseace in an indivial's ear or ears. The techniques may be roughly divided into three groups: 1) Loudness Balance (LB) testing, 2) Difference Limen (DL) teasting and 3) Rang of Comfortable Loudness (RCL)testing.

Loudness balance testing employe the direct approach in that time acceleration of loudness in the affected ear, or at an affected frequence is compared directly with that in a normal ear or at a frequency taken as normal. In this tochnique measurments are obtained of the intensities of two tones of differnt frequence when the listener reports that they sound equally loud. Comparisons of the curves obtained from grapnic plots, such as those in Figure 4, are utilized to dutermine the range and extent of recruitment present. Recruitment is said to be present when two reported intensities are far apart at low levels out approach equality at the higher levels. The two major methods used in loudness balaced testing are those of the Fowler Binaural method and the Reger Monaural method, The binaural method utilizes both ears of the subject but does not require the subject to have one normal ear. Rather, it requires only that there be a substantial difference in hearing loss between the two ears at a given frequency.



Fowler Binaural Loudness Balance Technique (Parameter: Equal Loudness Contour)



Roger Monaural Loudness Balance (Parameter: Equal Loudness Contour)

Fig. 4 Graphic Representation of the Fowler Monaural and Reger Monaural Loudness Balance Tests.

The monaural method utilizes different frequencies in the same ear and requires that there be a substantial differace in nearing loss on the same ear for the two test frequencies.

The use of difference limen testing is basically a psychophysical approach. The term "difference limen" is synonomous wilh a "juut noticeable difference." To establish a DL for loudness, two tones identical in frequency are varied with respect to intensity. The smallest, difference between the two presentations which can be discriminated is referred to as the DL. The basic assumption underlying difference limen testing witn regard to recruitment is that the just noticeable difference above threshold is smaller for the recruiting than for the normal ear. This differece in DL's for normal and recruiting ears is illustrated in Figure 5.

In range of comfortable loudness testing the listener is required to identify points of comfort and discomfort as the intensity of the stimulus tone is voried. At certain frequencies, a smaller than normal RCL is said to be characteristic of the recruiting ear. Contrasting RCL's across a wide band of frequencies for normal and recruiting ears are illustrated in Figure 6.

within the three major categories of recraitment tests are, as has been stated, many individual techniques. The variations to be found within these categories are sufficiently striking as to warrant individual attention and description. The individual tests to be cousidered are the following:

1. Loudness Balance testing
    a. Fowler Binaural Method
    b. Reger Monaural Mothod
    c. De Bruinc-Altcs masking Method

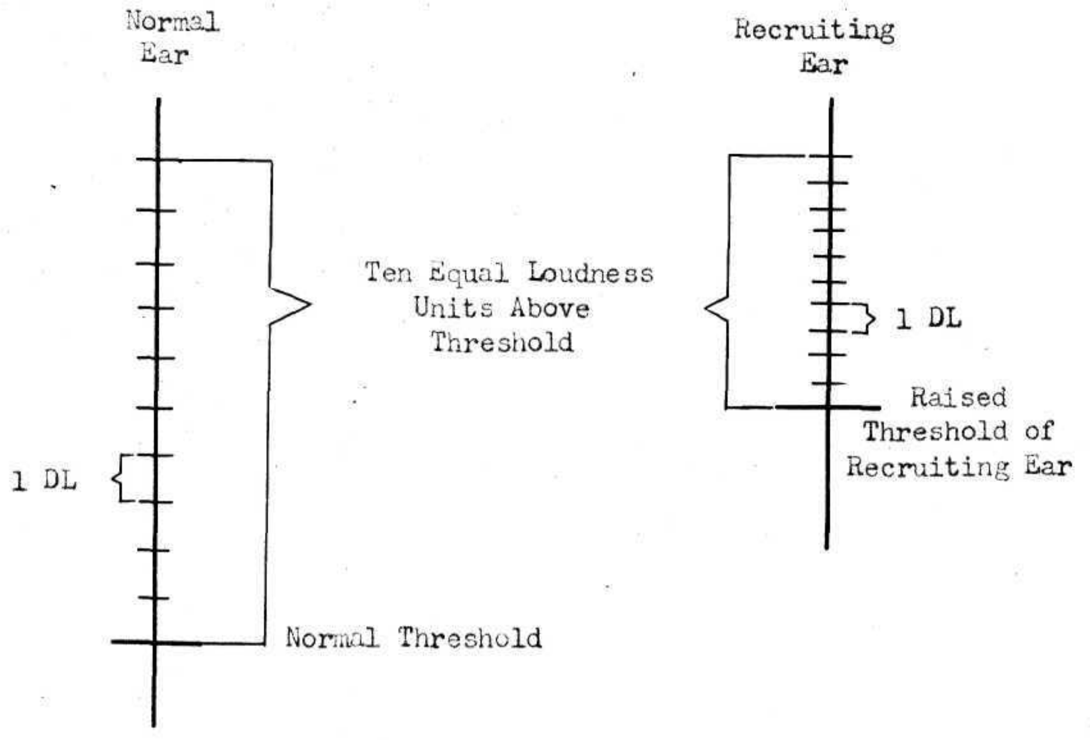


Fig. 5 Compression (within restricted range) of Difference Limens of Recruiting Ear in Contrast with Normal Range and Difference Limens of Normal Ear.

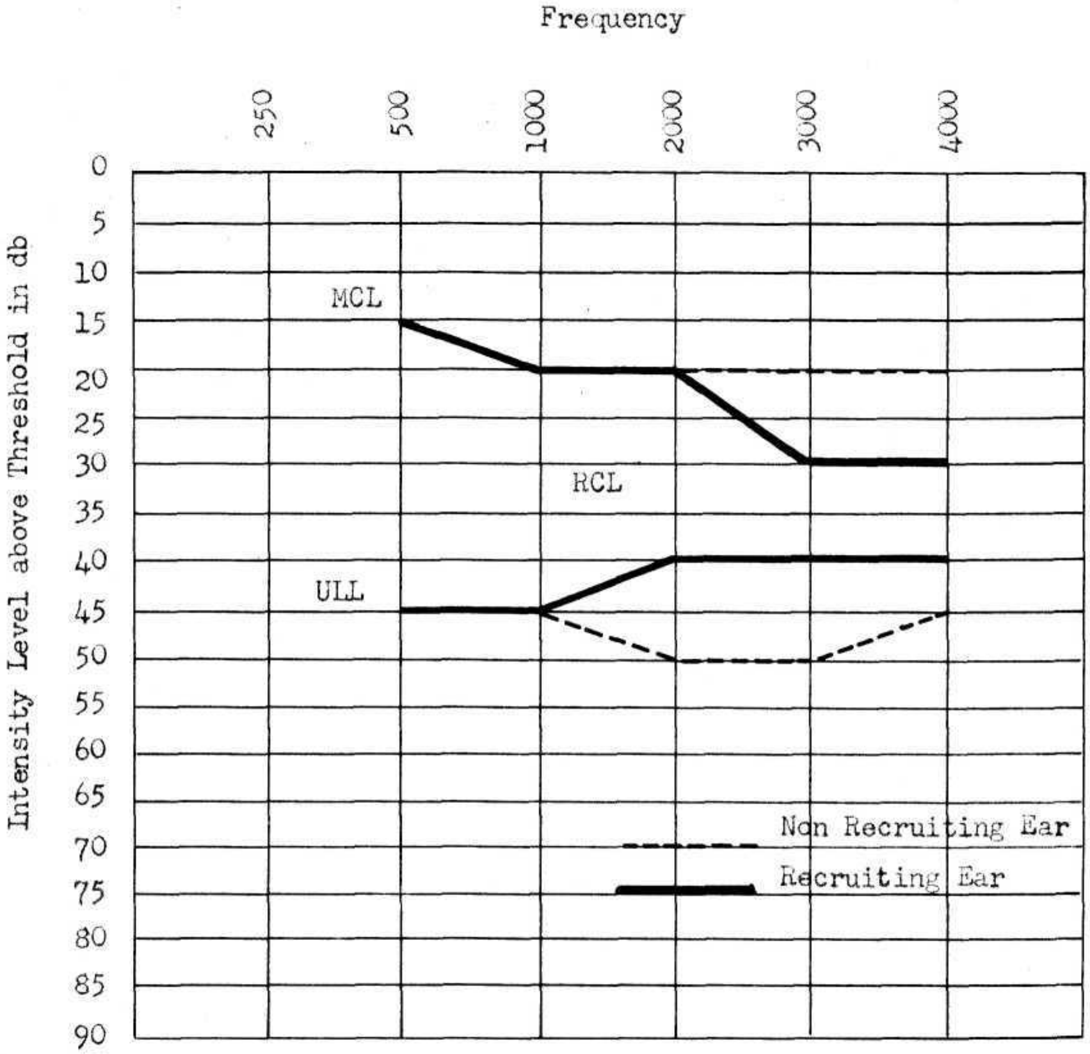


Fig. 6 Representative Ranges of Comfortable Loudness for Recruiting and Non-Recruiting Ears.

2. Range of Comfortable Loudneas testing
    a. Watson and Tolan Method
    b. Bangs and Mullins Method
3. Difference Limen testing
    a. Bekesy Method
    b. Luscher–Zwislicki Method
    c. Denes–Naunton Method
    d. Jerger Method

Fowler Binaural Method (14). A general deccription of the test procedure appears in a preceding section, Specifically, a tone to be matched is presented to one ear and a comparison tone of the same frequency is presented to the other ear. The standerd tone is then increased in intensity and the listener adjusts the comparison tone until an "equal loudness" judgement is made. The process is then repeated. If it ia found that succeusive intensity increments to the stimulus in one ear are "balenced" by smaller increment in the other, recruitment is said to be present. Figure 4 illustrates the atypical loudness balance of the rocruiting ear.

Rager Monsural Method(35). The Reger method is generally regarded as an improved version of the binaural method. The loudness acceleration at a given frequency is compared to the acceleration of some other frequency in the same ear. As in the previous methods, the subject makes successive loudness balences of standard and comparison tones. A common misrepresentation of this method is that the ear just respond nurually to one (the stsnder) of the test frequentcies. Actually, the test requires only that there be a substantial difference in hearing loss between the two ears at a given frequency. The results obtained from this method are charecterized by graphical plots similarly to those obtaind in the binaural metnod. As illustrated in Figars 4, non-parillel lines, emanating from a "tight" region are indicative of thu presence of recruitment. it is to be noted that both the monaural and binaural Methods are accepted as true measures of the recruiting phenomenon.

Da Bruine-Altes Masking Method (5). Two tones are introduced simultaneously into the same ear and the subject is required to detect the presence or absence of one of them. The lower tone is uaed to mask the tone of higher frequency. With the normal ear, each increase in the intensity of the lower pitched masking tone tends to produce some throshold elevation or shift in the higher masked tone. In cases displaying recruitment, increasing the intensity of the lower pitched masking tone does not produce a threshold shift on the nigher masked. tone of comparable size, while in the normal ear a shift in the lower frequency is balenced by an equal shift in the higher. Figure 7 is a graphical representation of the results obtained from application of this test to normal and recruiting ears. By comparing the slopes of corresponding lines of the two sides of the figure, a clear view is obtained of the difference in loudness function and also of the rate of recruitment.

Watson and Tolan Method (42). A techniqu for recruitment testing described by Watson and Tolan makes use of the subject's perception of tone at two levels, the threshold of audibility and the threshold. of discomfort or the uncomfortable Loudness Level. (ULL). The first threshold is found by conventional audiomatric procedures, the second by varying the intensity of the stimulus tone untill a point is reached at which discomfort is experienced. The Range of Comfortable Loudness (RCL) for the subject is the difference, in db, between the two threshold. At certain frequencies, larger RCL's are said to be charecteristic of normal ears, smaller RCL's characteristic of recruiting ears. However, no normative

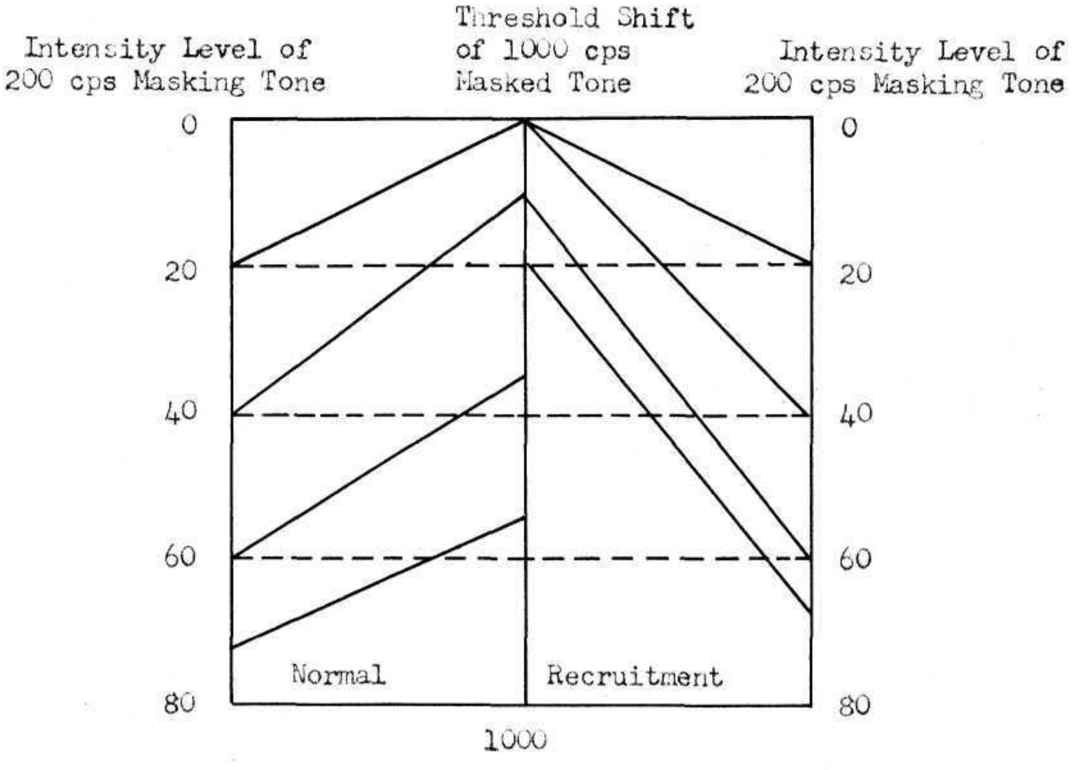


Fig. 7 Graphical Representation of De Bruine-Altes Masking Method, Revealing Different Threshold Shifts in Normal and Recruiting Ears in Presence of Masking Tones.

RCl values for normal and recruiting ears are reported by the authors.

Bangs and Mullins Method (1). This variation of the Watson and Tolan RCL also utilizes two perceptual levels. Replacing the threshold of audibility is the Most Comfortable Loudness Level (MCL), found by requiring the subject to adjust the intensity of the test tone to a level which he judges to be most comfortable for listening. As in the preceding method, the ULL constitutes the upper threshold and the difference in db between the two levels constitutes the RCL. Also as in the preceding method, the ULL constitutes the upper threshold and the difference in db between the two levels constitutes the RCL. Also as in the preceding method, the RCL at certain frequencies is considerably wider for the normal ear than for the recruiting ear. RCL's of 15 db and smaller are said to be indicative of the presence of the recruitment phenomenon.

Bekesy Method (3). This method takes its name from the audiometer used to administer the test. The automatic machinery of this instrument provides for a slow continuous change in the intensity of the test tone, increasing when a control button is depressed and decreasing when it is released. The changing intensity of the test tone is graphically recorded as a function of frequency and the excursion between the just-heard and the just-not-heard intensity gives an indication of the listener's variability about his absolute threshold. The subject, in effect, records his own audiogram and gives a rough measure of the DL for the particular frequencies being swept by the audiometer. Figure 8 shows a typical audiogram taken from the Bekegy audiometer for a recruiting individual. As can be noted, the normal response is indicated by the wide sweeping lines in the vertical direction. When the dispersion of the intensity becomes very small, an indication of the recruitment phenomenon is present. Discounting reaction time, at any given frequency

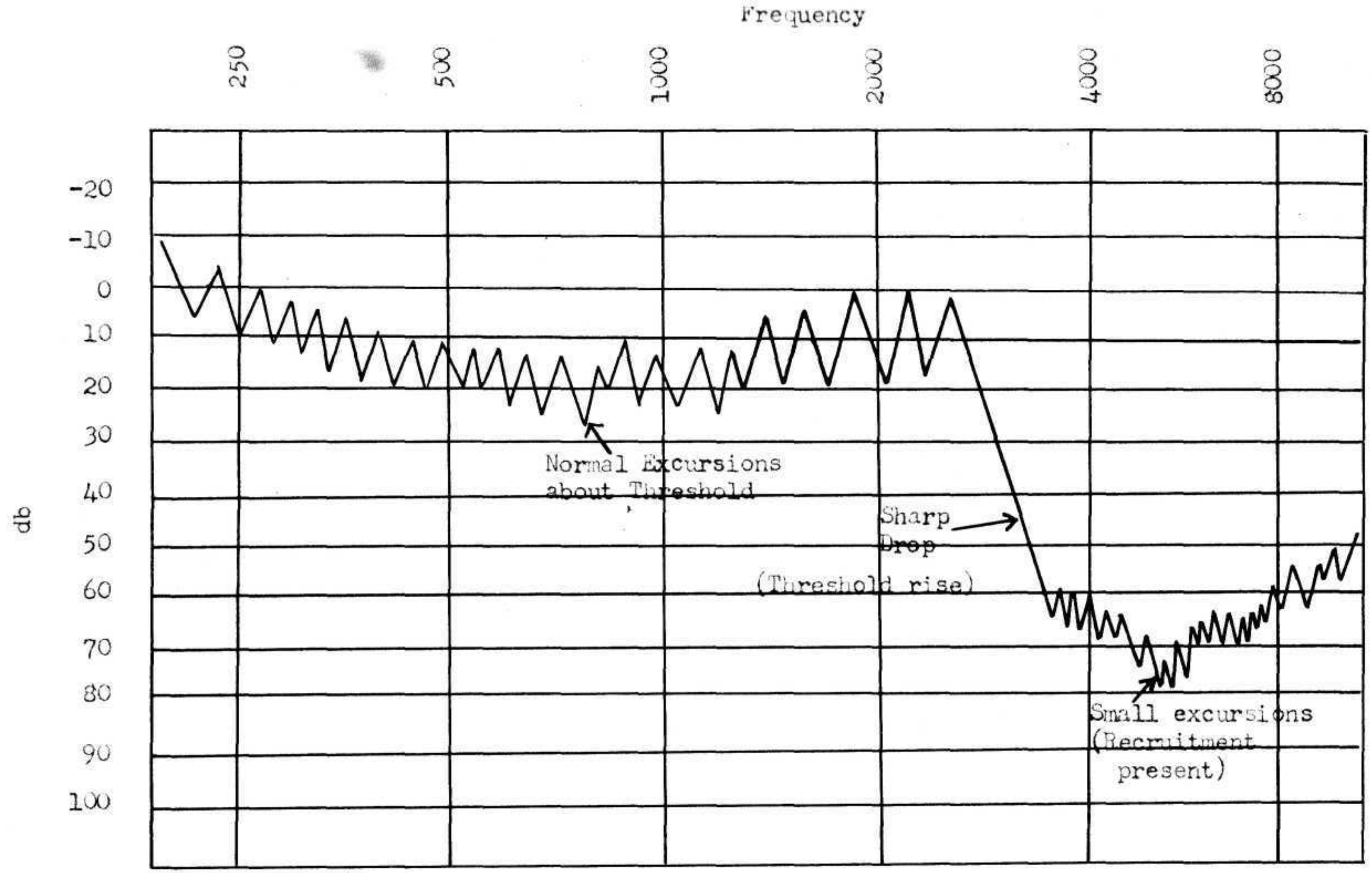


Fig. 8 Typical Bekesy Audiogram for Recruiting Ear.

a rough measure of the DL at threshold is revealed by the Bekesy audiogram.

Luscher–Zwislocki Method (32). As described by its authors, measurements of differential sensitivity are taken with a tone the intensity of which is alternated between two levels by an amplitude modulator. The tons is constant in frequency but varies in intensity around a midpoint at 40 db above threshold. The difference between the extromes of intensity of the tone is reduced until the subject responds that he hears no variation present. The difference is then recorded as the measure of the DL. size. This technique of Luscher and Zwislocki utilizes abrupt intensity changes. A summary of the results obtained in this Method indicates that at 40 db sensation lovel a normal DL would lie between 10 and 16 percent pressure modulation, a moderately recruiting DL -would lie somewhere between 6 and 8 percent, and an extreme recruitment would be indicated by a DL of less than 6 percent. Typical curves found for non-recruiting subjects and persons havina recruitment are shown in Figure 9. The drastic drop in the DL can be noted in the two ceses.

Denes-Naunton Method (7). These authors essentially present a refinement of the Luscher-Zwislocki method, excent that two supra-threshold points (four and 44 db sensation level) are tested, and the task of the subject is to identify the louder of two successive stimuli until such a discrimination cannot be made. The difference between the tones is then taken as the DL. Recruitment is indicated by the difference of the DL size at the two sensation levels. Figure 10 shows the types of curves obtained for a normal hearing individual and for one displaying recruitment. This method allows for the psychophysical concept of the decrease

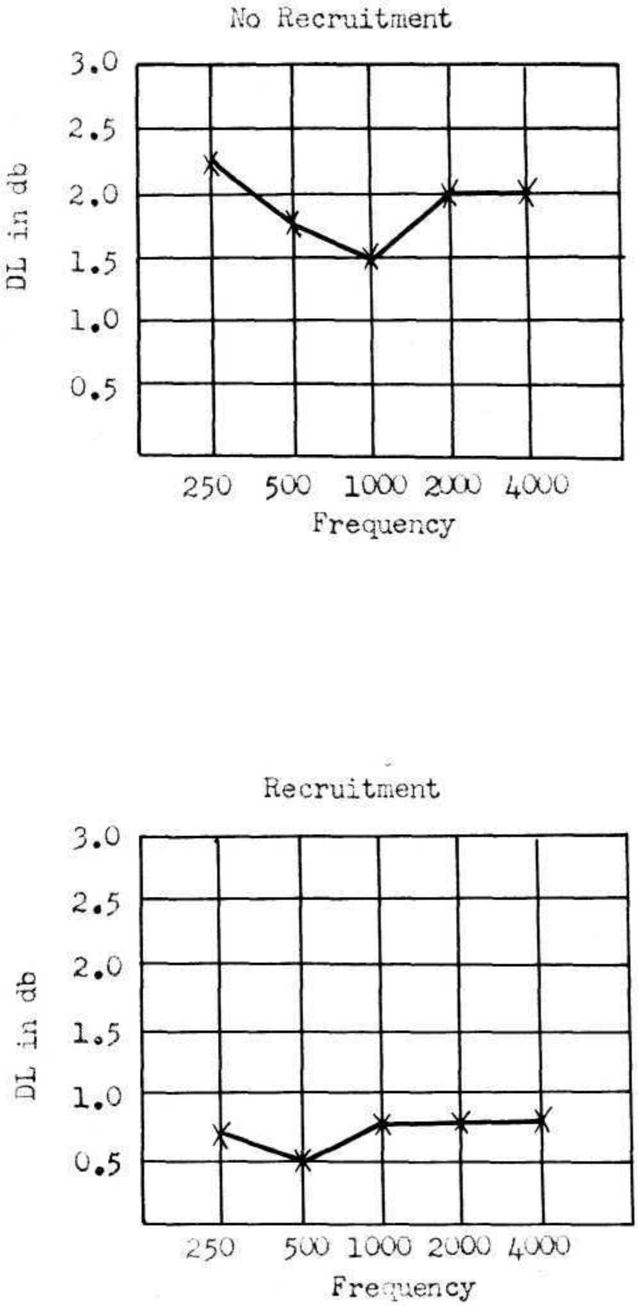


Fig. 9 Graphical Representation of Results Found in the Luscher-Zwislocki DL Test (Sensation Level at 40 db)

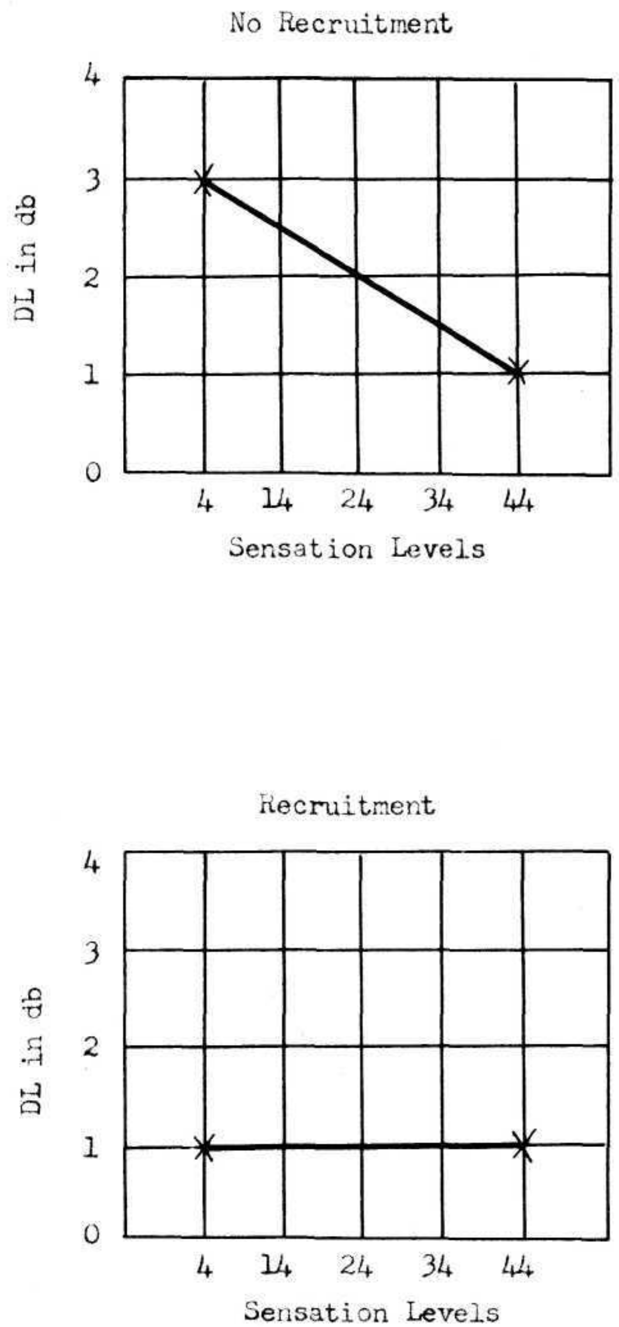


Fig. 10 Graphical Representation of Results Found in the Denes-Naunton DL Test (Frequency of Stimulus Tone 4000 cps).

in the DL with the increase in intensity. The slope of the line between the two sensation levels is indicative of the type of loss displayed by the subject. If, at 44 db, the DL is equal to or larger than the DL at four db, recruitment is said to be present. If it is smaller, recrait-ment is absent.

Jerger Method (-17). Another modification of the Luschar-Zwislocki method is found in the test reported by Jerger. Two features characterize the essential differences betweent the two techniques. First, Jerger meas-ures the DL at 15 db sensation level instead of at 40 db. Second, Jerger makes a gradua1 transition from. a steady-tone condition to one of increas-ingly wide excursions of modulating tone which the subject eventually re-cognizes as pulse-tone, the exact reverse of the Luscher-Zwislocki tech-nique. Figure 11 gives the graphic portrayal of results from this test, used to indicate the presence or absence of recraitment. Measurement at the lower sensation level is preferred by Jerger on the assumption that the loudness is changing most rapidly at lower levels and on the observa-tion that, with severe hearing losses, one cannot present tones as high as 40 db above threshold without penetrating the region of discomfort.

Speech Discrimination Tasting. A measurment of the recruitment which has Important clinical implications involves the use of speech test-ing. Huizing and Reyntjes (24), Palva (34), Dix, Hallpike and Hood (8), and Eby and Wi1liams (l0) have written about the relationship between type of hearing loss and performance on speech reception test. Figure 12 illustrates the speech reception (articulation function) curves asso-ciated with normal hearing and the principal types of hearing loss. Dis-crimination of speech stimuli composed of similar phonetic elements

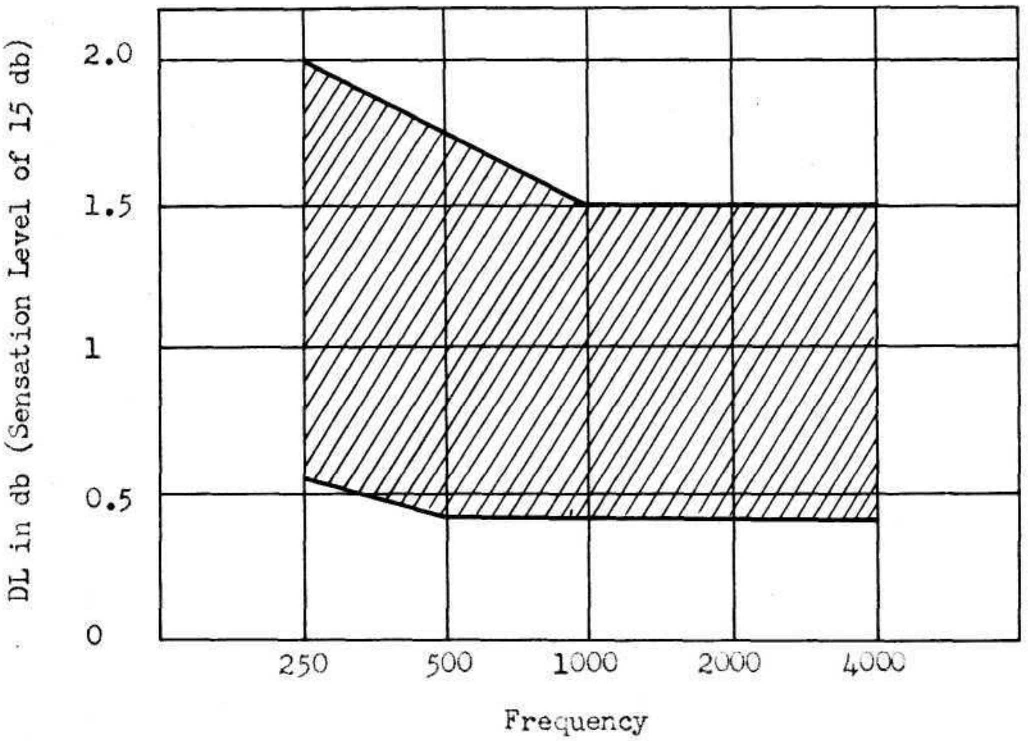


Fig. 11 DL Difference Record for Recording of Clinical Results; Shaded Area Covers Range of Variability of the DL Difference in Normal Ear (after Jerger).

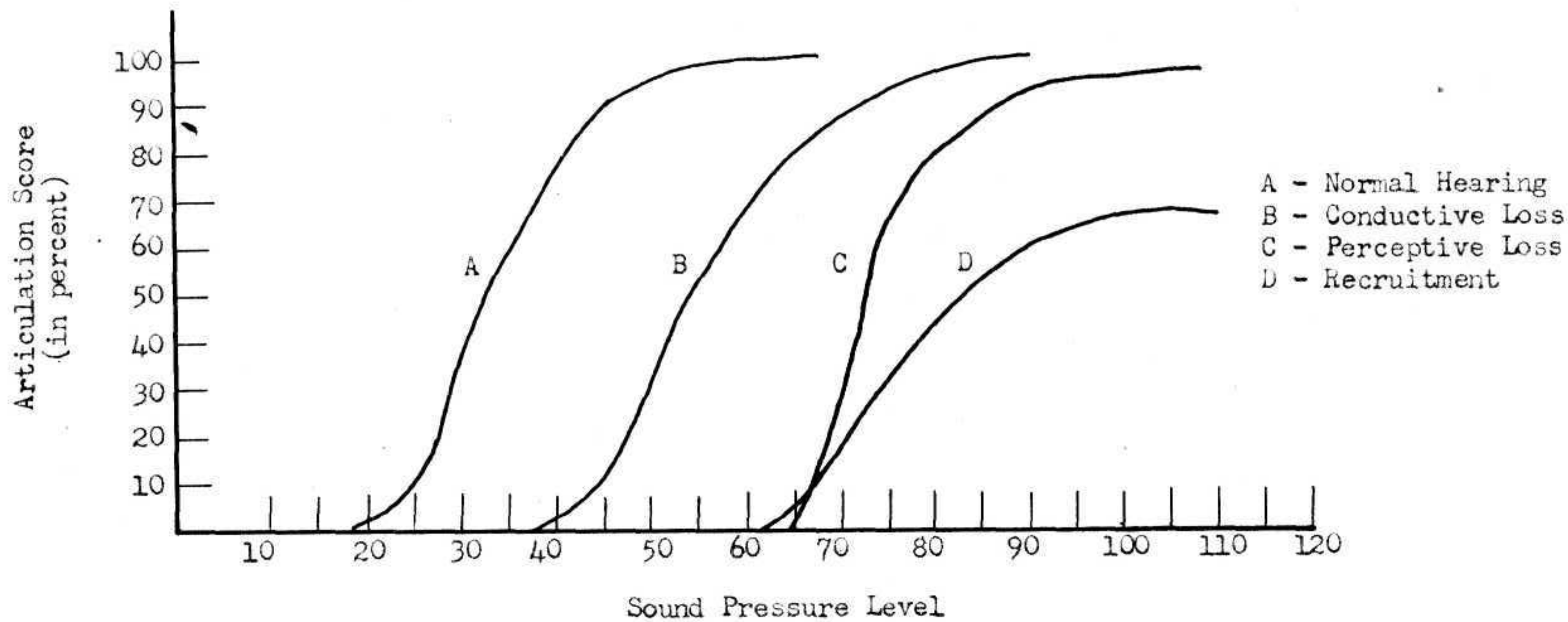


Fig. 12 Representation of Articulation Curves for Types of Hearing Loss (generalizations presented for comparison of slope and relative level, not as normative data)

theoretically is dependent upon the ability of the human organism to detect small acoustic differences in the speech signals being presented. Recruitment by definition, involves the capacity of the recruiting ear to detect smaller changes in sound pressure level than the normal ear. It might be reasoned, therefore, that an individual exhibiting the recruitment phenomenon may, by reason of his impairment, react to changes in his sound environment in a wanner which could be judged unfavorable. The four investigators cited above found that, in general, the discrimination of speech increases as the intensity at which the speech is presented is increased. To test the hypothesis that the recruiting curve deviates from the usual ogive, the majority of the investigators utilized prevailing word lists given at increasing intensity levels of 10 db. In recruiting cases the discrimination reaches a maximum of considerably less than 100 percent and then never goes higher even though the intensity is increased further. In many cases articulation scores apparently drop with intensity increases beyond a certain point. Moreover, the sharply rising curve at one point in the articulation function which would bo predicted for the recruiting ear is not found.

STATEMENT OF THE PROBLEM

In the preceding section the common tests for loudness recruitment were described, and the significant literature in the field was reviewed. It is noteworthy that in all the publications cited, no statistical evidence was offered that any one of the recruitment tests distinguishes the impaired from the normal ear. That the several tests have wide clinical acceptance is well known, but their differentiating characteristic, until subjected to statistical tests, appears to be open to question.

The purpose of this investigation was to establish, by means of more rigorous statistical analyses than have hitherto been employed, the capability of a series of tests to distinguish between normal hearing individuals and individuals whose auditory perception is characterized by recruitment in the loudness function. The following tests were subjected to such statistical analyses: 1) Range of Comfortable Loudness test; 2) Difference Limen test, and 3) Speech Sound Discrimination test.

Specifically, the attempt was made in this experiment to answer the following questions:

1. Are the effects attributable to groups (normal versus impaired hearing), subjects within groups, or the ear being tested significant in the Range of Comfortable Loudness test?

2. Are the effects attributable to groups, subjects within groups, frequencies, sensation levels, direction (ascending versus descending) of stimulus presentation, or the ear being tested significant in the Difference Limen test?

3. Are the effects attributable to groups, subjects within groups, sensation levels, or the ear being tested significant in the Speech Sound Discrimination test?

PROCEDURE

The three tests which comprised this experiment were administered serially to individual subjects. While a presentation in random order was a desideratum, restrictions on the availability of laboratory space made it necessary to administer the RCL Test initially. However, the DL and Speech Sound Discrimination Tests were administered randomly with respect to subjects. All tests were administered in the acoustically treated rooms of the Purdue Speech and Hearing Clinic.

Subjects

Two groups of subjects, control and experimental, were utilized in this investigation. The control subjects were five university students whose hearing, measured on a Sonotone, Model 21, audiometer, was normal, i.e., within five db of an audiometric reading of zero. Subjects in the experimental group were four in number, chosen on two bases: pattern of hearing loss, and performance on a Bekesy audiometric test. The pattern of loss for each subject, revealed in Table 1, was one of marked impairment in the higher frequencies, with the threshold breaking away from normal at 2000 cps or slightly higher. Although not an infallible diagnostic sign, this is said to be a typical pattern for the recruiting ear. On the Bekesy audiometric examination, the subjects manifested fine discrimination around the threshold, asserted to be characteristic of recruiting ears. None of the subjects in the control group had a medical history which would be predictive of hearing impairment, while two of the four experimental subjects related that they had been exposed, by reason of military experience, to severe acoustic trauma. The third subject had a history of severe fever diseases in infancy, sufficient to account for

TABLE, 1

Pure Tone Audiometric Thresholds

for Experimental Subjects

		Frequency				
subject	Ear	500	1000	2000	3000	4000
DC	L	-10*	-5	5	40	60
	R	0	0	15	35	55
CS	L	-10	-5	0	30	45
	R	-10	0	0	35	50
ES	L	-5	-10	0	30	60
	R	-5	-5	0	40	50
TH	L	5	0	0	35	45
	R	5	5	10	30	45

* Minus sign indicates above normal threshold.

the measured impairment, while the fourth subject was unable to relate any unusual hearing history. The age range for the control group was 19 to 21 years; for the experimental group, 22 to 37 years.

It is to be noted that in this experiment the two ears of each subject were considered to be independent, and separate auditory tests were administered to each. later statistical analysis of the data failed to substantiate the hypothesis of independence. However, two-ear testing was justified as a test for auditory fatigue. Threshold shift in the second ear, if found, would have been indicative of such fatigue.

Instrumentation

As previously stated, this investigation was divided into three parts. Each division of the investigation involved one of the three types of tests mentioned previously. The component instrumentation for each test is described in the following order: l) Range of Comfortable Loudness equipment; 2) Difference Limen equipment; and 3) Speech Sound Discrimination equipment.

Range of Comfortable Loudness equipment. As in previous investigations, a standard pure tone audiometer possessing a sweep characteristic on the intensity dial was used in this experiment. The Sonotone, Model 21, utilized in this investigation was checked for calibration in a manner specified by the manufacturer. Calibration checks were made by the use of an ADC Artifical Ear, with a modified circuit. A Hewlett-Packard Audio Signal Generator was used as the standardizing instrument with which the signal from the audiometer was compared. A Ballantine, Model 300, AC Voltmeter was utilized for the readings of the tones derived from the settings of the audiometer and signal generator.

The audiometer was used in conjunction with calibrated earphones, Permaflux, Type PDR-8, High Fidelity, in a manner which allowed only one of the phones to be activated by the tonal signal. A motor-driven gear reduction unit with a hand controlled reversing switch was employed as a remote control of the intensity dial of the audiometer. By virtue of the hand controlled reversing switch, the sweep intensity characteristic of the audiometer could be made to increase or decrease at a rate of two db per second. A coupling box was utilized in the circuit to enable the testing of either ear at any time without necessitating the removal of the headset. Figure 13 is a block diagram of the equipment utilized in the RCL test. Calibration checks were made before the testing of subjects was initiated and at a point approximately half way through the experiment. There were no significant differences found in the response of the instrumentation between the two calibration checks.

Difference Limen equipment. In the DL test utilized in this investigation, it was necessary to provide an auditory stimulus characterized by pulsations, regularly increasing and decreasing in magnitude. These would constitute both ascending and descending difference limen stimuli, providing the subjects with opportunity to discriminate both of the following stimulus characteristics: a) steady-state following pulsation; and b) pulsation following steady-state. The fineness of discrimination, or size of difference limen would be dependent upon the amount of amplitude modulation required for the subject to perceive "sameness" or "warble" in the stimulus.

A triangular wave from a Hewlett-Packard Low Frequency Function Generator and a sinusoidal wave from a Hewlett-Packard Audio Signal Generator, Model 205AG were used as the components of the test signal. The sine wave

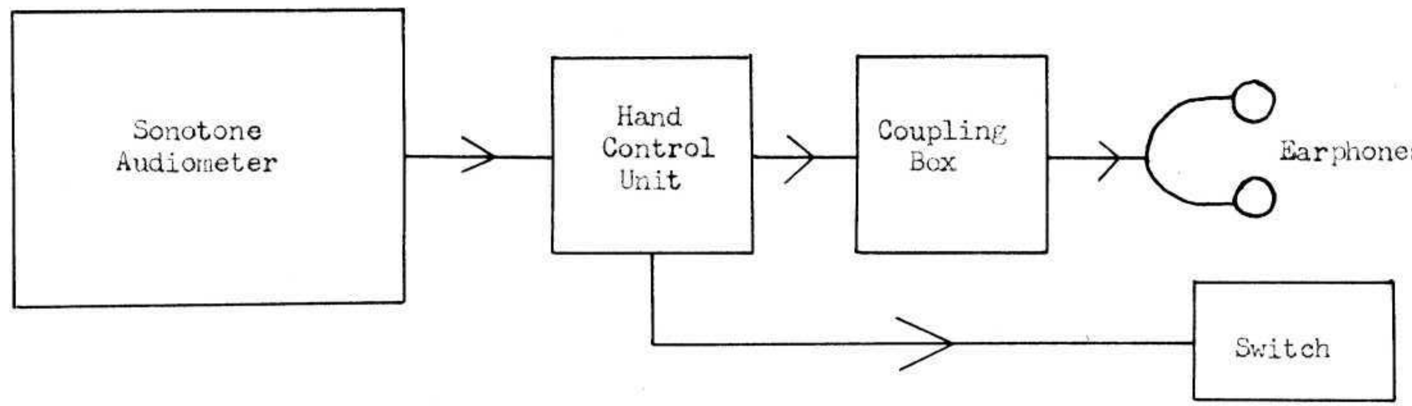


Fig. 13 Block Diagram of the RCL Test Instrumentation.

of 500 cps at a level of 60 db was used as a reference around which a triangular wave of 500 cps varied from 55 db to 65 db. Before the two waves were combined, a mechanical sampling device was inserted into the circuit of the two signal generators. Figure 14 shows a block diagram of the equipment used for making the DL test wave. Samplings of each wave source were then recorded by an Ampex, Model 400, Tape Recorder every tenth of a second, allowing a change of .25 db to occur in the triangular wave between samples. The resultant wave resembled a changing square wave with the reference value fixed and the excursion of the wave varying from a plus five db to a minus five db around the reference tone. The 1000 cps, 2000 cps, 3000 cps and 4000 cps test tones were then recorded in the same manner. With each change of the sinusoidal or reference wave there was also a similar change in the triangular wave with regard to frequency. Figure 15 gives a representation of the test stimulus as recorded by this instrumentation.

Figure 16 shows the block diagram of the instrumentation used for the DL test in this experiment. Before each subject was tested, the instrumentation was calibrated with regard to the voltage measured at the headset. As the recorded wave was being presented, the voltage differences, measured on a Ballantine Model 300 Voltmeter, were noted until the two tones could be seen to be the same intensity by the stationary position of the needle. With the aid of a Hewlett-Packard attenuator, Model 350A, a setting was then made in the circuit so that the voltmeter read .068 volts. This reading corresponded to a 60 db signal across the headset. From the reading taken from the attenuator, any further adjustments of intensity could be made by the subtraction or addition of attenuation. During the test presentations, the 60 db intensity level was checked at each frequency by means of the voltmeter. A voltage reading of .068 assured calibration

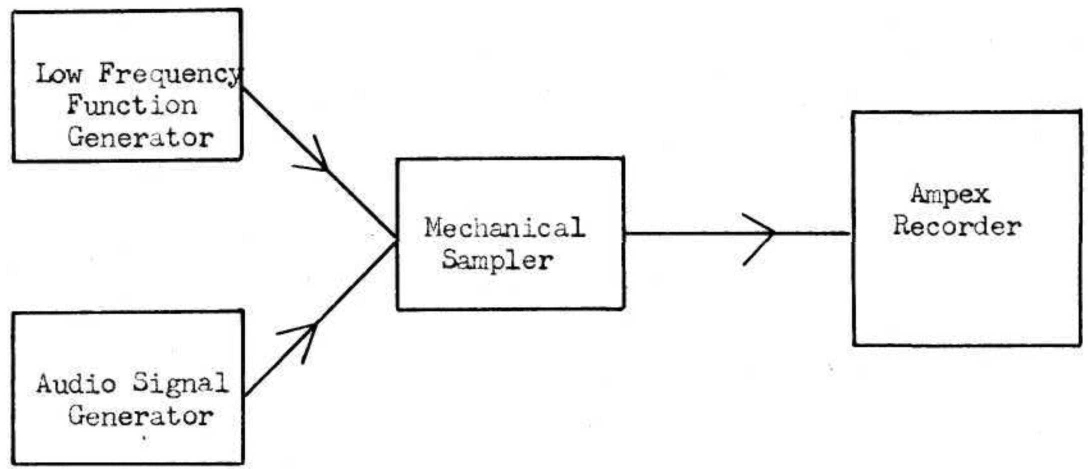
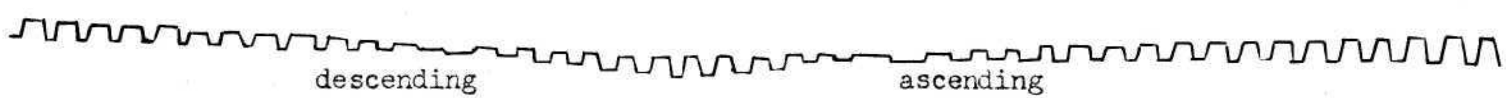


Fig. 14 Block Diagram of DL Test Wave Recording Equipment.



Travel - 10 mm/second

Fig. 15 Graphic Representation of Amplitude Modulation in Presentation of Difference Limen Stimulus.

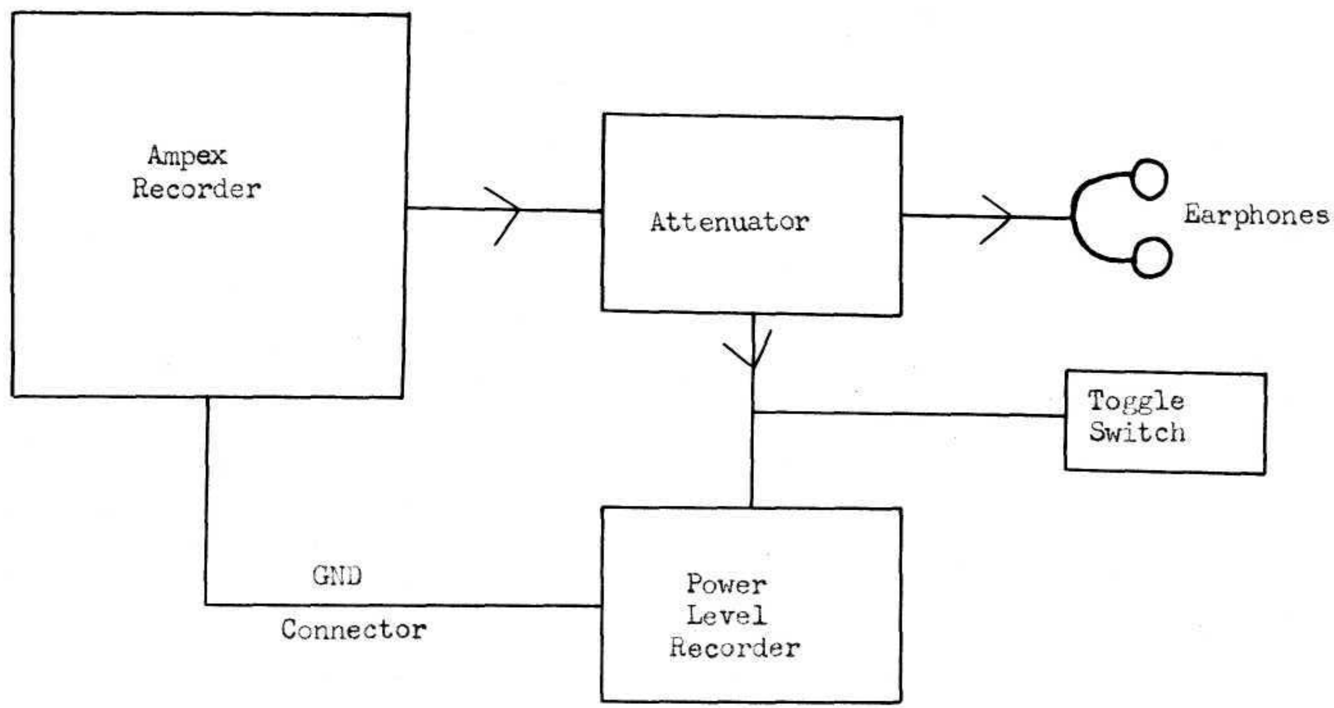


Fig. 16   Block Diagram of DL Test Instrumentation.

to the reference signal.

The Sound Apparatus Company High Speed Level Recorder, Model HPL-E, was employed as the response instrument in the DL Test. The HPL-E yields a graphic representation of the intensity variations of an input signal. The frequency response of this instrument, as specified by the manufacturer, is rated as flat within plus or minus 3 db from 50 cps to 20,000 cps. The signal recorded by the HPL-E was the stimulus presented to the subject, the tape recorded modulated test tone from the Ampex recorder. Control of the stimulus intensity was achieved by the Hewlett-Packard attenuator, Model 350A.

The subject listened to the signal from the tape by means of a Permaflux, Type PDR-8, High Fidelity headset. Since only one side of the headphone was used at any time, a 300 ohm resistor was inserted to replace the unused side of the headset and thus maintain constant impedance within the circuit. A toggle switch was placed between the attenuator and the HPL-E enabling the subject to short circuit the connection between the Ampex and the HPL-E. When the toggle switch was depressed, the connection was broken and the stylus would drop to the normal "off" position. This drop was observable on the waxed paper by a sharp demarkation line from the usual pattern being recorded by the HPL-E.

Speech Sound Discrimination equipment. The Speech Sound Discrimination test was presented to the subjects over the speech reception testing equipment of the Purdue Speech and Hearing Clinic. The instrumentation utilized was similar to that described by Lambert (28). Essentially it consisted of a pre-amplifier equipped with several inputs and a power amplifier with outputs for both speaker and headphones. Figure 17 presents a block diagram of the equipment as modified for this test. An

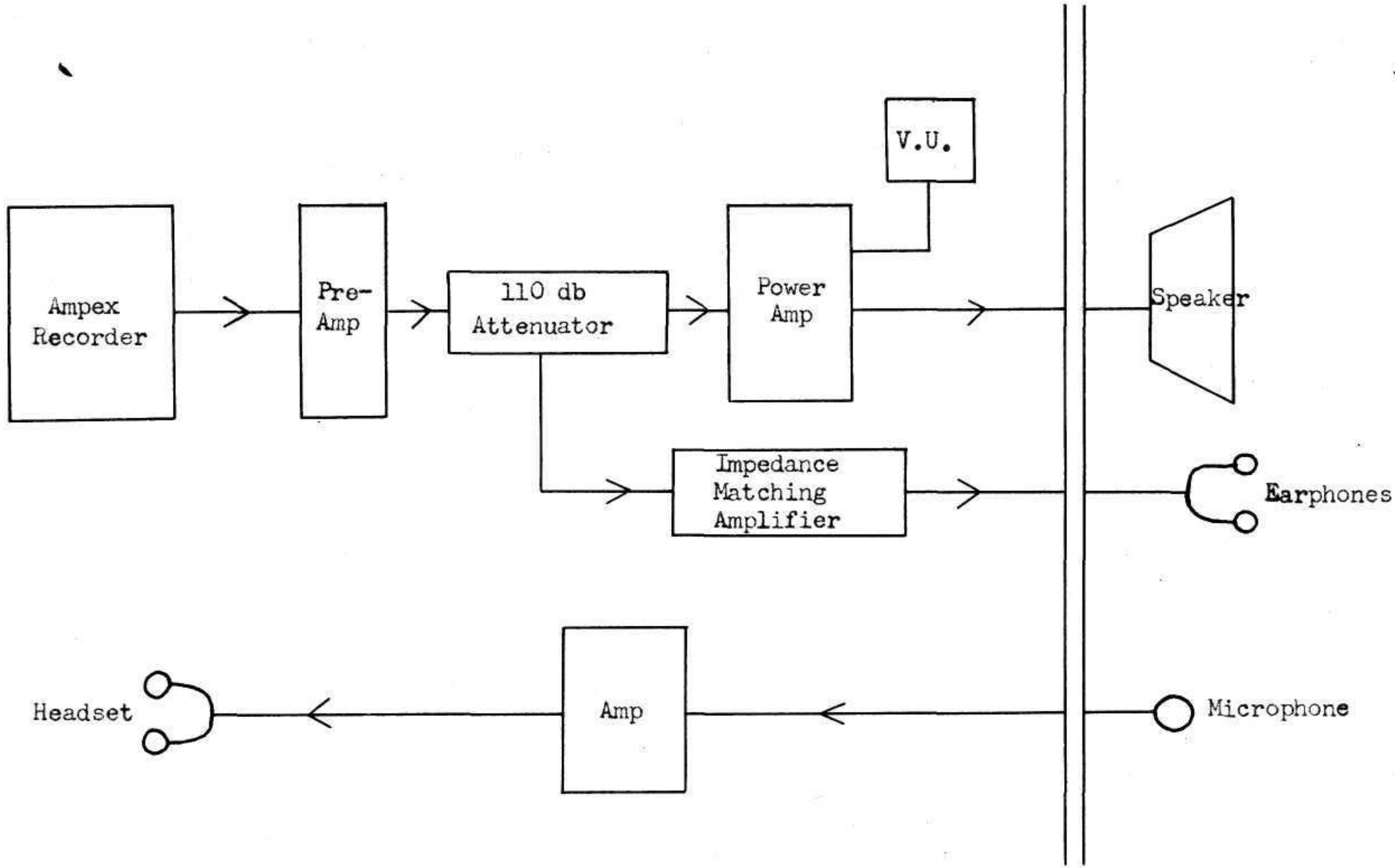


Fig. 17 Block Diagram of Instrumentation for Speech Sound Discrimination Test.

Ampex, Model 400, Tape Recorder was used to present the test to the subjects seated in a separate acoustically treated room. Only one side of a pair of Type ANB-H-IA headphones was used during the testing period.

The circuit reference level was adjusted by a V.U. meter and the intensity of the presentations of the test lists was controlled by a 110 db attenuator. Figure 18 shows the frequency response of the equipment for a 70 db (re. .0002 dyne/cm2) level.

Calibration of the test items was accomplished in the following manner. A 1000 cps tone of constant intensity was recorded at the beginning of each tape used in the test and at the same intensity as the test items. Prior to each presentation of a new tape the attenuation of the speech reception equipment was set at maximum and the pure tone signal was introduced into it from the Ampex recorder. The gain of the speech reception pre-amplifier was then adjusted so that, at minimum attenuation, the peaks of the speech signal would be at a level of llOdb (re. 0002 dyne/cm).

It was found that the V.U. meter indicated minus five V.U. for the 1000 cps tone at this gain setting.

The speech sound discrimination lists used in this test were some of those originally prepared for the Lambert study previously cited. They contained nonsense syllables of the consonant-vowel characteristic. The vowel remained the same throughout all the presentations. Ten syllables were chosen from the master list as being the most intelligible for use in speech sound discrimination testing. The ten consonants chosen were the [p], [t], [k] [g l [f], [s],[+s],[s],[dz]and [o]. A random presentation of the items was recorded onto tape by means of the Ampex recorder and divided into 20 groups of ten items, or a total of 20 lists. Each consonant was presented once in each of the 20 lists. A practice tape was

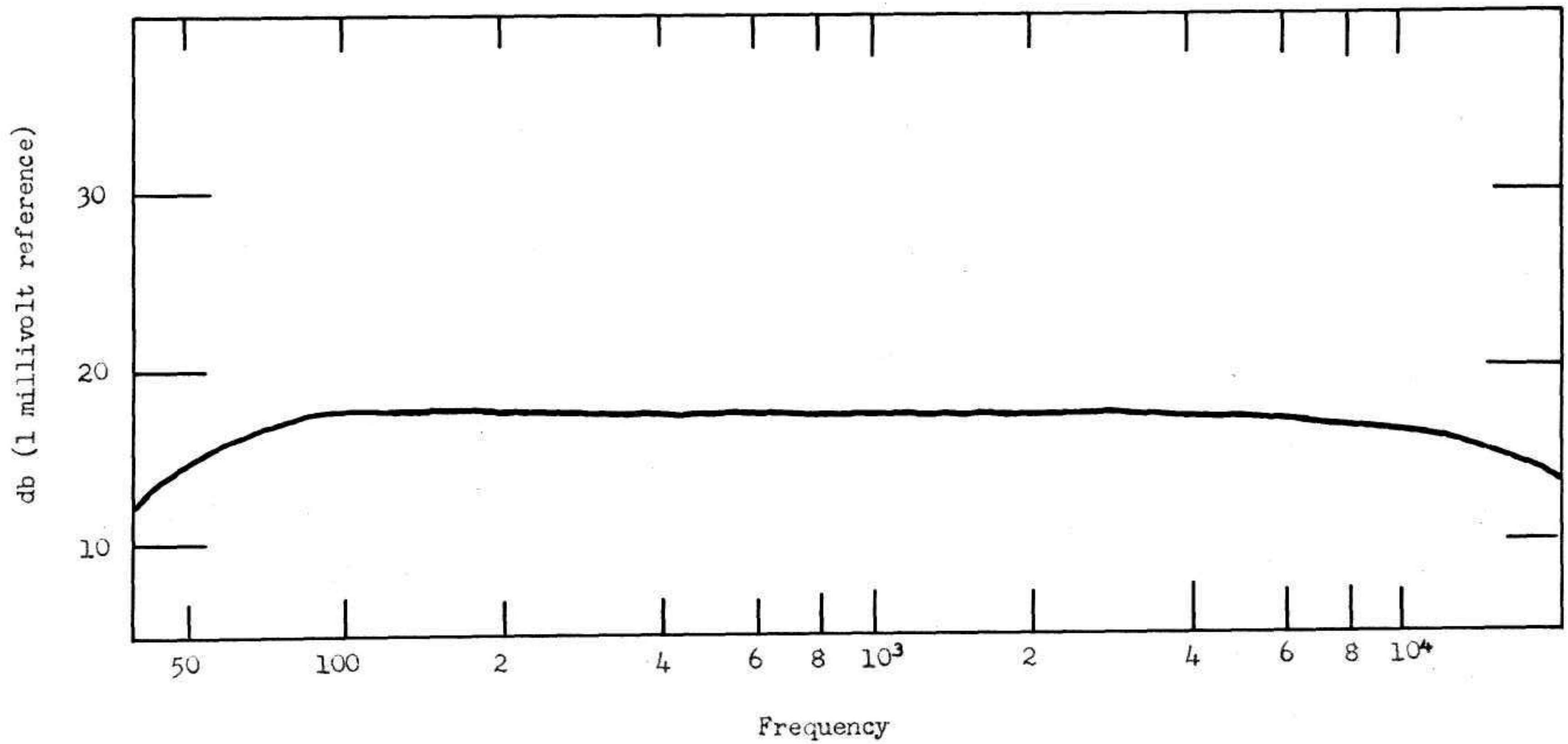


Fig. 18 Frequency Response of Speech Reception Test Equipment (across earphones).

also recorded with a random presentation of the consonants to be used in the test.

Method

Range of Comfortable Loudness. Subjects were tested individually in each section of the experiment. In the RCL test, the subject was seated facing away from the equipment. A general explanation of the test was made first. Then the earphones were placed on the subject's head and the control for the reversing switch was placed in his hand. The following instructions were then given to the subject:

> When the signal is given to begin, press the brown key and increase the intensity of the tone you will hear. The intensity of the tone is decreased by pressing the white key of the control.
>
> In the first section of this test, adjust the tone which you hear to a level which is most comfortable for you. If you had a radio which would play nothing but the one tone, set the intensity at a point to which you could listen for a long period of time. When you have set the level you believe to be most comfortable for you, nod your head. Then, at a hand signal from me, you will decrease the intensity of the tone until told to stop. At this time, you will repeat the procedure just described.
>
> Remember, wait for the signals before altering the settings.
>
> Are there any questions?

Questions were then answered and the frequency control on the audiometer was adjusted for 1000 cps.

Tones of five different frequencies were presented. The order of presentation was as follows: 1000 cps, 3000 cps, 500 cps, 2000 cps and 4000 cps. The staggered order of presentation was used in an attempt to prevent fatigue at specific points on the basilar membrane of the subjects. A further safeguard against fatigue was the experimenter's interruption of the tone after each MCL trial by a subject. The interrupter switch was used until the intensity dial indicated that a level between minus five and minus ten db had been reached. At this time the subject was told to start increasing the intensity and the interrupter switch was released.

Five readings were taken at each frequency. The "most comfortable" intensity levels found by the subjects were noted and if found to be within a 3 db range at a given frequency, the average of the responses was taken as the reading for that frequency. If any set of responses covered a wider range than the predetermined 3 db, further sets of five readings were taken until the responses fell within the required span. When the last frequency (4000 cps) had been tested in the first ear, a recheck was made of the 1000 cps tone to insure the consistency of the subject's evaluation. If the recheck was not within 3 db of the previous readings, the 1000 cps MCL was re-established and the next, or 3000 cps tone was rechecked. This rechecking was continued until the readings recorded were consistently within the 3 db range.

After the comfort levels had been selected in the first ear, MCL's were established in the same manner for the other ear.

After the MCL had been obtained for five frequencies in both of the subject's ears, the subject was given the following instructions:

> The next section of the experiment will be much the same as the one you have just completed. Again use the brown key to increase the loudness and the white key to decrease the loudness of the tones. Now you are to set the tone at a level that is uncomfortable. If you were to listen to the same radio playing one tone, set the loudness at a level to which you would not want to listen very long. A repetition of the signals employed in the previous test will be utilized.
>
> Remember, wait for the signals before altering the levels.

Questions were answered, followed by the presentation of the test stimuli in the same order with respect to ears and frequencies as in the MCL trials.

The signal intensity at the outset for each frequency was approximately the MCL reported previously by the subject. The same criteria were applied to the determination of the ULL as were applicable in the MCL. Five responses were noted in each of the test frequencies and the range of 3 db was used as the criterion for the determination of the ULL. When all five frequencies had been tested in the one ear, rechecks were made in the same manner as described for the MCL until the responses had been established. When the desired levels had been established, the signal was transmitted to the other ear and the same procedure was repeated.

When both MCL and ULL had been determined for the two ears of the subject in all frequencies, each MCL was subtracted from the corresponding ULL for that frequency. This difference was listed as the value of the RCL. for the subject. Table 2 illustrates the calculation of RCL's for one experimental subject.

Difference Limen. The subject was seated facing away from the instrumentation and use of the toggle switch was illustrated. The headset was placed on the subject's head and the following instructions were given:

> The test which you are about to take has two separate tones which are the sane pitch but are of different loudness. As you listen, you will first hear just one tone. Then, gradually an alternation of louder and softer tones will be neard, almost like a warble. They will then gradually became the same and then again different in loudness. Indicate, by pressing the toggle switch at each point, when you think you hear just one,tone and again when you begin to hear two tones.

The subject was then given a practice period until it was certain that he could perform what was expected of him. The exact length of the

TABLE 2

Example of Treatment of RCL Data

Subject ____________ Date ________________ Time ____________

	EAR					
	Left			Right		
Frequency	Mean ULL	Mean MCL	Diff. (RCL)	Mean ULL	Mean MCL	Diff. (RCL)
500	69	20	49	56	19	37
1000	71	25	46	55	15	40
2000	49	17	32	72	19	53
3000	52	33	19	70	44	26
4000	73	62	11	72	54	18

practice period depended upon the subject's ability to master the technique involved. During the practice period, a 1000 cps tone was used at a level comfortably above threshold. If necessary a graphic illustration (as in Figure 15) was shown to insure adequate knowledge of the test presentation. When the practice period had been completed, the subject was given the following instructions:

> You will now hear a series of tones at different frequencies. Indicate in the same manner the points you have just been responding to in the test. When the two tones become the same in loudness, push the toggle switch very quickly. Then as the two tones become different, push the switch once more. Continue doing this whenever you hear a change. As you listen, the tones will become louder and softer. If the tones become too loud for comfort or too soft to discriminate, raise your hand to stop the test.
>
> Remember to listen for the changes that will occur in the two tones you will hear.
>
> Are there any questions?

Questions were then answered and the test began at a level 15 db above the subject's threshold. The ascending order of frequency presentation was 500 cps, 1000 cps, 2000 cps, 3000 cps and 4000 cps. Eight intensity levels were tested in each frequency at five db intervals. They were 15, 20, 25, 30, 35, 40, 45 and 50 db above the subject's threshold. A graphic representation of the test wave was obtained from the HPL-E recording paper. With each change of frequency or intensity level, a notation by the experimenter was made upon the recording paper to insure proper reading of the results. When the toggle switch was used, a sharp demarkation line appeared on the recording paper, enabling the experimenter to determine accurately the points at which the subject perceived "sameness" and "difference" in the stimuli.

Following the testing of one ear of the subject, a ten minute rest period was given to reduce fatigue. After the rest period, the subject was again seated and the second ear was tested in the same manner described above.

When the test had been completed, results of the responses for each subject were noted. The representation of the wave on the recording paper was such that a 1 millimeter rise of the stylus equalled a 1 db rise in intensity. The readings from the recording paper were taken to the nearest millimeter. An ascending and a descending order of presentation was taken into consideration in the recording of the results. The ascending group was taken as the part of the wave which went from the tones of the same intensity to a warble tone and the descending group was taken as that part of the wave which went from a warble tone to tones of the same intensity. An average of each of the two readings for both the ascending and descending procedures was entered as a final result for the subject's ear.

Speech Sound Discrimination. Within an acoustically treated room separate from the test instrumentation, the subject was seated in a desk chair permitting him the freedom of movement needed in writing. The practice tape was then played over the loud speaker and the subject was asked to reproduce the sounds which he heard either in orthographic or phonetic symbols. The practice period for the subjects was approximately 20 minutes. If the subject exhibited any difficulty in distinguishing the sounds being presented, illustrations of the correct responses were given.

After the practice period had been completed, the headset was placed upon the subject's head and the forms needed for the responses were given to him. The doors to the acoustically treated room were then closed and the tape containing the first ten lists was then placed on the recorder.

Calibration of the equipment before each test presentation in the manner previously described was used to assure that the equipment was a constant factor from test to test.

The subject was then given the following instructions:

> The first section of this test will start with nothing coming through the earphones and then, while a list of words is being spoken, the loudness will be gradually increased. When you first hear a voice, say the word "yes." Each time thereafter that you hear the voice, say "yes" again. You do not have to write down anything for the first part of this test. Each time you hear the voice say "yes."
>
> Are there any questions?
>
> Ready? Here we go.

The first list presented was utilized for the determination of the threshold of detectability. At the outset, a level of full attenuation was used. Then the attenuation was reduced so that an increasing order of intensity was presented to the subject. The ascending order of presentation was made in two db increments initially for each test item presented until the subject responded that the signal was heard. At this time the attenuation was increased to a point below the threshold of the subject and the ascending technique was again utilized in one db increments for every two test items until the subject was able to perceive 50 percent of the presentations. The detectability for the subject was then recorded and the tape was reversed to the starting position. The following instructions were then given to the subject:

> You will now hear lists of words which have no meaning. Write in the answer sheet previously given you the words which you hear. These words, in effect, are only a consonant and a vowel. The vowel will remain the same throughout all of the tests.
>
> The level at which you hear the words some of the time, will be so faint as to render them almost unintelligible. Do

not worry about not being able to hear. Just try to hear as much as possible and write them down.

There are no numbers given in the test, such as 'Number 1 is,' or 'Number 2 is.' Rather you will hear the voice say, "You will write," and then the word is given. Please follow the order given. If you do not get one word, skip the space and place the next word presented in the following space.

The first two lists are likely to be at levels which will not be intelligible. Between the first and the second lists presented, an interruption will be made so that you may determine if you are following the sequence correctly.

Are there any questions?

Ready? Here we go.

The level was then adjusted so that the first list would be given at a level two db above the previously determined threshold of detectability. At the end of the first list, the tape was interrupted and the subject was informed that the second list was to begin. The second list was given at a level of four db above the subject's threshold. Each succeeding list was presented with an increment of two db until the fifteenth list had been completed. At this time, the intensity increment for the final five lists was increased to ten db. Thus, the range covered was from 2 to 82 db above threshold of detectability. During the test, the monitor system between rooms was utilized to answer any questions which arose.

After the presentation of the 20 test lists in one ear, the subject was given a brief rest period while the experimenter prepared to test the other ear. Following a period of approximately ten minutes, the subject was again seated and the threshold of detectability was run for the other ear in the same manner previously described. Then, in the determination of speech sound discrimination, the same 20 lists were presented in a manner identical to that described above.

The test lists were scored according to the number of items correct per list, with the number correct being entered appropriately in a table according to the subject, group, ear being tested and the intensity level of the presentation.

RESULTS

Results obtained for all of the subjects on each of the three tests were combined appropriately and arithmetic means were calculated for the main effects. In this study the main effects were those attributable to groups (experimental and control), frequencies, sensation levels, and ears. An analysis of variance technique was used to test for significance of the means computed.

In the case of the RCL test, a four factor analysis of variance technique was used in which groups, subjects within groups, frequencies, ear of the subject, and interactions among the main effects were tested for significance.

In the DL test, a six factor analysis of variance technique was applied in the statistical treatment of the data obtained. The factors involved were groups, subjects within groups, frequencies, sensation levels, the ear of the subject, and the direction (ascending or descending) of presentation of the test tone. The interactions among the main effects were also analyzed.

Finally, in the Speech Sound Discrimination test, two separate analyses were conducted. The dual analysis was selected to permit scrutiny at two specific points in the discrimination curve. The first point to be examined was the origin of the curve, which involved the initiating segment and the slope of the curve rising away from the origin. The second analysis was concerned with the plateau found at the upper end of the discrimination curve. Both analyses included a four factor treatment in which the main effects were groups, subjects within groups, sensation levels and the ear of the subject. Interactions among the main effects also were analyzed.

Null hypotheses were tested in each of the three sections of the experiment. In each application, the null hypothesis was that there were no significant differences in the variables measured due to the main effects or interactions.

Range of Comfortable Loudness

In the RCL experiment, the null hypothesis was rejected for results involving groups, frequencies and frequencies by groups. In Table 3 are presented the mean RCL values and standard deviations for groups and totals, including both groups, for each frequency tested. It may be seen in this table that the RCL's for the control group were nearly equivalent at all frequencies. The totals for both groups were found to decrease in magnitude with frequency, except for a reversal involving 500 cps. On closer inspection it is seen that the experimental group had the greater effect upon the decreasing size of the RCL with frequency. This observation is substantiated by the findings of 1 percent significance for the difference between groups (experimental and control) and 5 percent significance for the differences among frequencies and the interaction of frequencies-by-groups, revealed in the analysis of variance, Table 4. A graphic illustration of the groups-by-frequencies interaction is shown in Figure 19. The presence of the interaction is demonstrated by the non-parallel characteristic of lines drawn connecting RCL's for experimental and control groups at each of the frequencies tested.

Inspection of Table 3 shows that not only were the mean values for groups significantly different, but the difference apparently increased with frequency, most notably at 3000 and 4000 cps. The specific RCL values found for the experimental group were markedly different from re-

TABLE 3

Mean Scores by Frequency in RCL Test

Frequency

	500		1000		2000		3000		4000	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Control	47.4	6.5	49.4	6.5	46.9	7.8	45.7	5.0	46.4	7.8
Exper.	34.3	12.7	37.5	10.0	33.3	11.8	21.7	6.1	12.9	5.2
All Subjects	41.6		44.1		40.9		35.0		31.5	

TABLE4

Analysis of Variance of Average RCL

Source of Variation	df	Sum of Squares	Mean Squares	F	Significance Level
Gr *	1	16864.7	16364.7	55.79	1%
S c Gr *	7	2116.2	302.3		
Ear	1	2130.4	2130.4	1.57	
Ear x Gr	1	4283.6	4283.6	3.16	
Ear x S c Gr	7	9493.8	1356.3		
F *	4	3217.2	804.3	2.71	5%
F x Gr	4	3679.9	919.9	3.10	5%
F x S c Gr	28	8309.3	296.8		
F x Ear	4	2130.4	532.6	1.57	
F x Ear x Gr	4	1790.4	447.6	1.32	
F x Ear x S c Gr	28	9493.8	339.1		

* Gr - Groups
* S c Gr - Subjects within Groups
* F - Frequency

Table Values of F
.01 - (1, 7) df - 12.20
.05 - (4, 28) df - 2.69

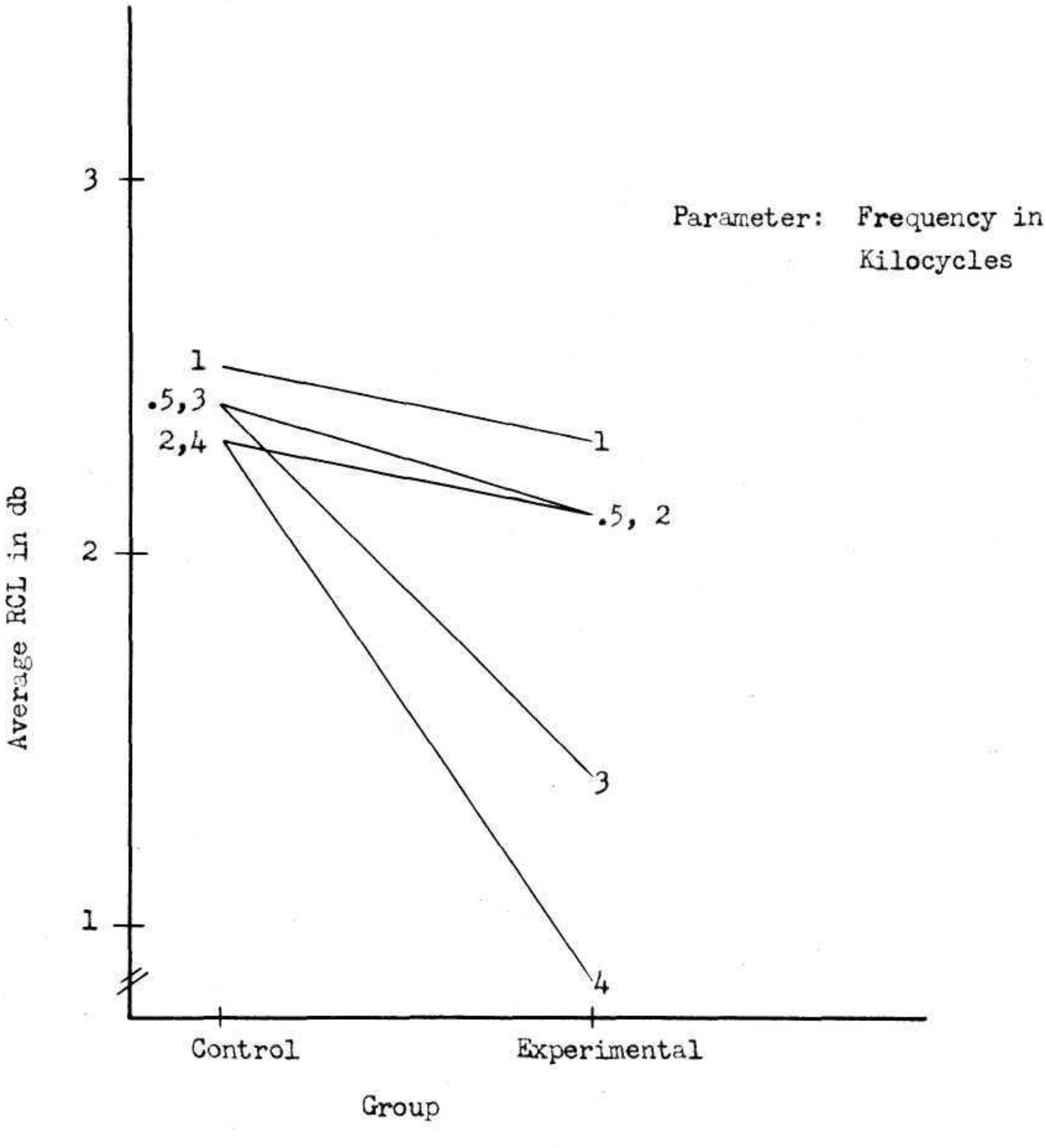


Fig. 19 Graphic Representation of Frequency - by - Group Interaction in RCL Test.

sults reported by previous investigators. It should be noted that the value of 15 db as the determinant of the presence of recruitment reported by Bangs and Mullins (l) could apply only to the results found in the 4000 cps tone in this experiment. The 3000 cps tone had a mean value of 21.7 and a standard deviation of 6.1. Examination of the individual results against the Bangs and Mullins criterion reveals that only two ears of the experimental group could be said to be recruiting at the 3000 cps frequency.

The dispersion of the standard deviations around group means for the tested frequencies can be seen to be fairly constant for the control group, while a decreasing trend with frequency may be observed in the experimental group.

The analysis failed to reveal any difference existing between ears for subjects.

Difference Limen

As recruitment has been described, the experimental group tested in this investigation should have displayed a smaller DL than the control group. As revealed in the means and standard deviations of the value of the DL for each test frequency in Table 5, significance was established at the 5 percent point for the effects of groups (experimental and control) and direction (ascending and descending) of presentation of the stimuli. Furthermore, the supposition that the DL would decrease as the sensation level and frequency would increase was supported. The null hypothesis of no significant difference was rejected at the 1 percent point for the effect both of frequencies and sensation levels in this experiment. Though the inverse relationship was found between the factors of frequencies and sensation levels, it should be noted that the values

TABLE 5

Mean Scores by Frequency and Sensation level on DL Test

Sensation Level in db.	500 Cont.	500 Exper.	1000 Cont.	1000 Exper.	2000 Cont.	2000 Exper.	3000 Cont.	3000 Exper.	4000 Cont.	4000 Exper.
15 mean	3.0	1.8	2.7	1.5	2.5	1.6	2.7	1.8	2.5	1.4
S.D.	.13	.18	.15	.16	.14	.18	.16	.22	.13	.13
20 mean	2.7	1.7	2.5	1.6	2.5	1.5	2.5	1.5	2.3	1.3
S.D.	.16	.21	.14	.19	.17	.17	.15	.17	.14	.14
25 mean	2.6	1.5	2.4	1.4	2.3	1.4	2.3	1.3	2.1	1.2
S.D.	.24	.19	.14	.17	.16	.14	.16	.16	.14	.15
30 mean	2.5	1.4	2.2	1.4	2.2	1.3	2.3	1.2	2.0	1.2
S.D.	.16	.18	.13	.21	.15	.14	.16	.13	.11	.16
35 mean	2.2	1.5	2.1	1.4	2.1	1.3	2.1	1.2	1.8	1.2
S.D.	.16	.17	.15	.18	.15	.17	.16	.19	.16	.17
40 mean	2.1	1.4	2.0	1.3	2.0	1.2	1.9	1.2	1.7	1.1
S.D.	.15	.17	.16	.18	.15	.15	.14	.15	.11	.16
45 mean	1.9	1.2	1.9	1.2	1.8	1.1	1.3	1.2	1.6	1.1
S.D.	.18	.23	.15	.18	.17	.16	.13	.14	.11	.18

found for the experimental group were consistently lower than those of the control group. Differences between ears for subjects were found not to be significant.

The interactions found to be significant were frequencies-by-groups at the 5 percent point, sensation levels-by-groups at the 1 percent point, direction of tone presentation-by-groups at the 5 percent point, frequencies-by-sensation levels at the 1 percent point, frequencies-by-direction at the 1 percent point and sensation levels-by-direction at the 1 percent point, as seen in Table 6. Illustrations of these interactions are presented in Figures 20 through 25. As in Figure 19, non-parallel lines between criterion points on the graph demonstrate the interactions found by statistical test to be present.

In Figure 20 it may be observed that the significant interaction of groups and frequencies probably resulted from the predicted inverse relationship of frequency and DL size for the experimental group, combined with a more random relationship of the parameters in the control group. The significant interaction of groups and sensation levels illustrated in Figure 21 no doubt is ascribable to the contrasting wide and narrow spread of DL's in control and experimental groups when sensation level was the parameter. Non-parallelism also is revealed in Figure 22, with a wider difference in response to ascending versus descending presentation of stimuli being characteristic of the experimental than the control group. The combination of experimental and control data for frequencies and sensation levels, illustrated in Figure 23, is shown to be almost entirely unpredictable. When results from normal and impaired ears were combined, as in that analysis, there was no combination of frequencies and sensation levels which provided the anticipated specific

TABLE 6

Analysis of Variance of Average DL

Source of Variation	df	Sum of Squares	mean Squares	F	Significance Level
Gr *	1	23708.7	23708.7	5.88	5%
S c Gr *	7	28243.9	4034.8		
F *	4	1468.9	367.2	3.43	5%
F x Gr	4	1544.8	386.7	3.60	5%
F x S c Gr	28	3000.3	107.2		
Ear	1	19757.6	19757.6	4.23	
Ear x Gr	1	22037.1	22037.1	4.72	
Ear x S c Gr	7	32699.	4671.4		
I *	6	7828.9	1304.8	3.91	1%
I x Gr	6	8477.6	1412.9	4.23	1%
I x S c Gr	42	14037.6	334.2		
D *	1	29124.4	29124.4	7.11	5%
D x Gr	1	30913.3	30913.3	7.54	
D x S 5 Gr	7	28689.3	4098.5		
F x Ear	4	19132.4	4783.1	1.79	
F x Ear x Gr	4	20617.3	5154.3	2.12	
F x Ear x S c Gr	28	74896.7	2674.9		

TABLE 6 (continued)

Analysis of Variance of Average DL

Source of Variation	df	Sum of Squares	Mean Squares	F	Significance Level
F x I	24	7828.9	326.2	2.97	1%
F x I x Gr	24	8477.6	353.2	3.22	1%
F x I x S c Gr	128	14037.6	109.7		
F x D	4	17626.3	4406.6	4.18	1%
F x D x Gr	4	20196.8	5049.2	4.79	1%
F x D x S c Gr	28	29526.8	1054.5		
I x D	6	19736.1	3289.4	4.33	1%
I x D x Gr	6	21196.8	3532.8	4.65	1%
I x D x S c Gr	42	31926.8	760.2		

*Gr - Groups
*S c Gr - Subjects within Groups
*F - Frequency
*I - Intensity
*D - Direction of Tone Presentation

Table Values for F
.01 - (4, 28) df - 4.02
.01 - (6, 42) df - 3.35
.01 - (24, 128) df - 1.61
.05 - (1,7) df - 5.59

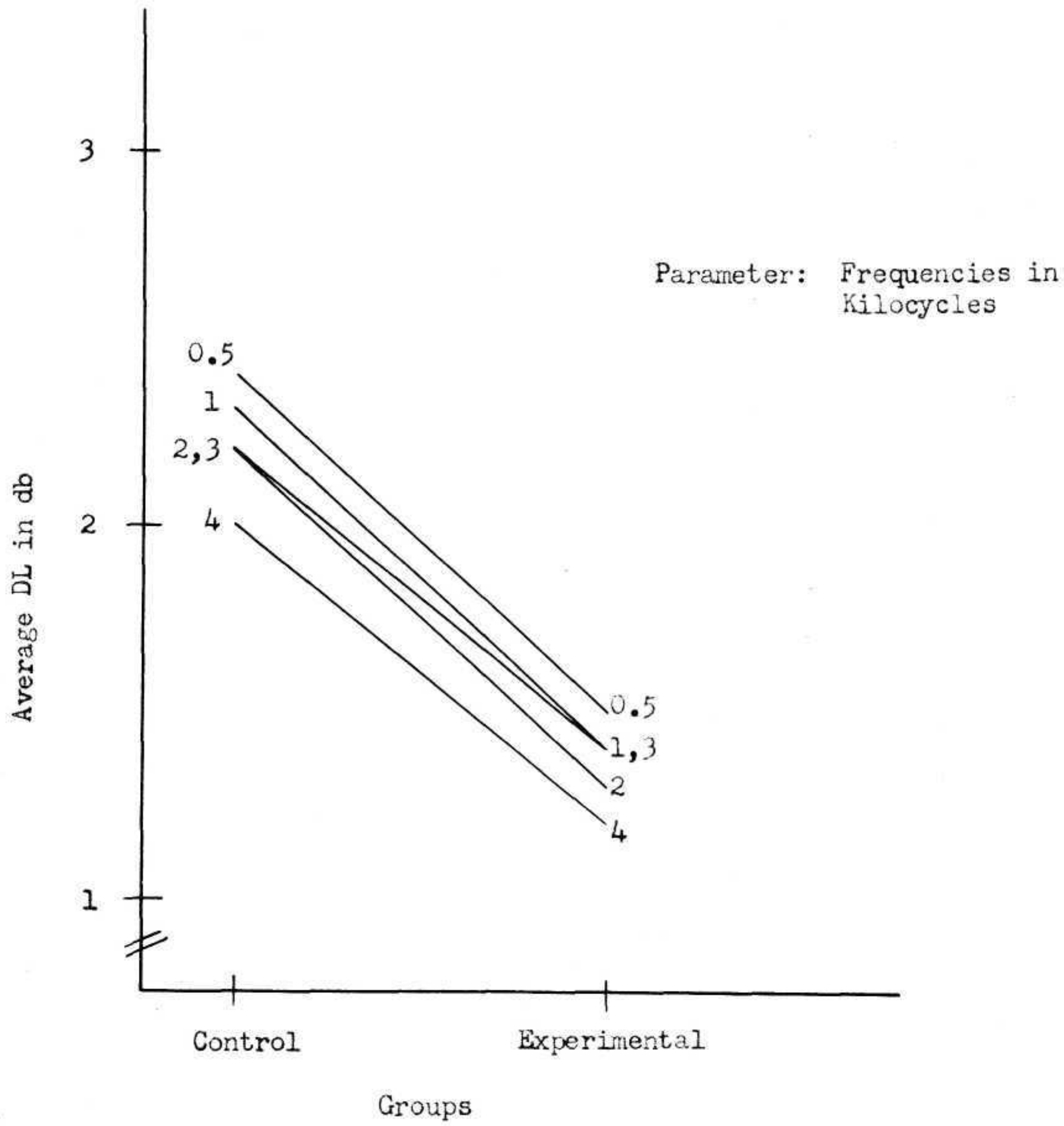


Fig. 20 Graphic Representation of Frequencies - by - Group Interaction ^ in DL Test.

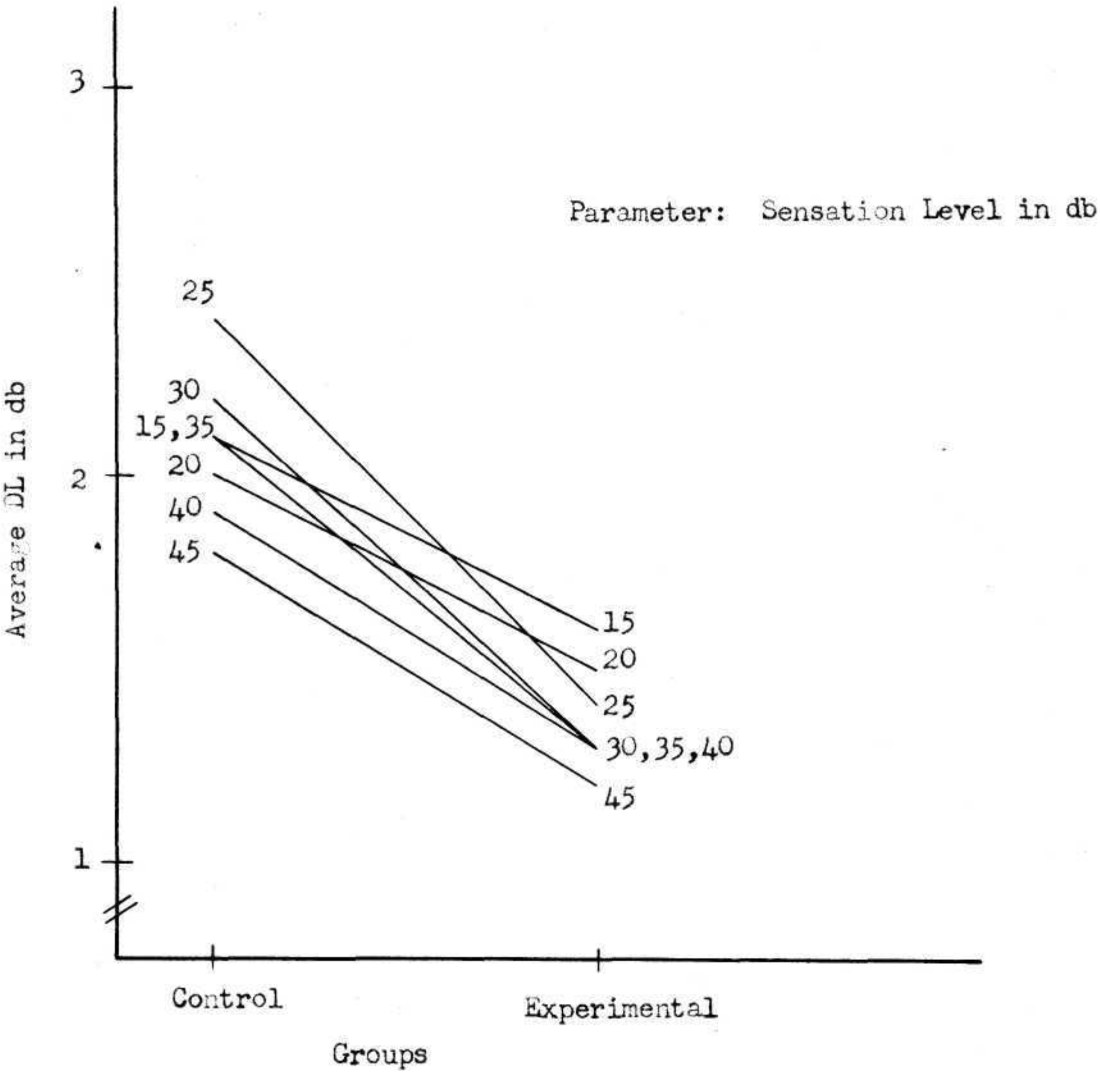


Fig. 21 Graphic Representation of Sensation Levels - by - Group Interaction in DL Test.

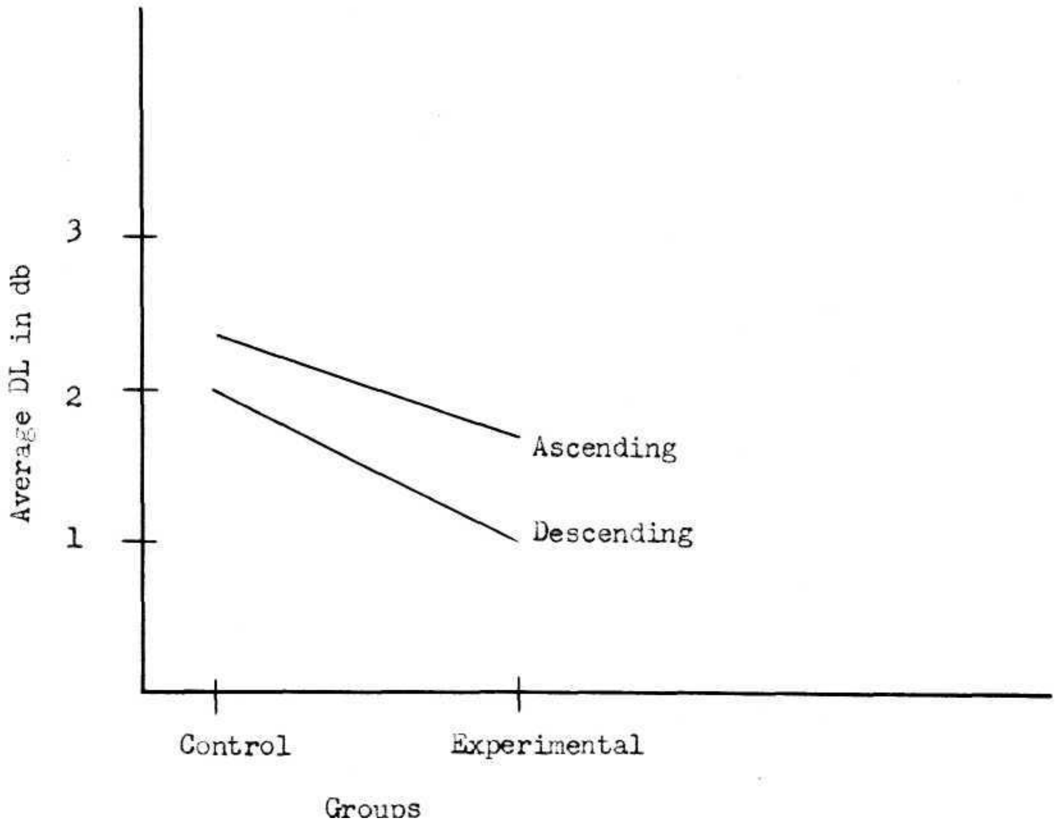


Fig. 22 Graphic Representation of Groups - by - Direction * Interaction in DL Test.

* See text for description of ascending-descending presentation of stimuli.

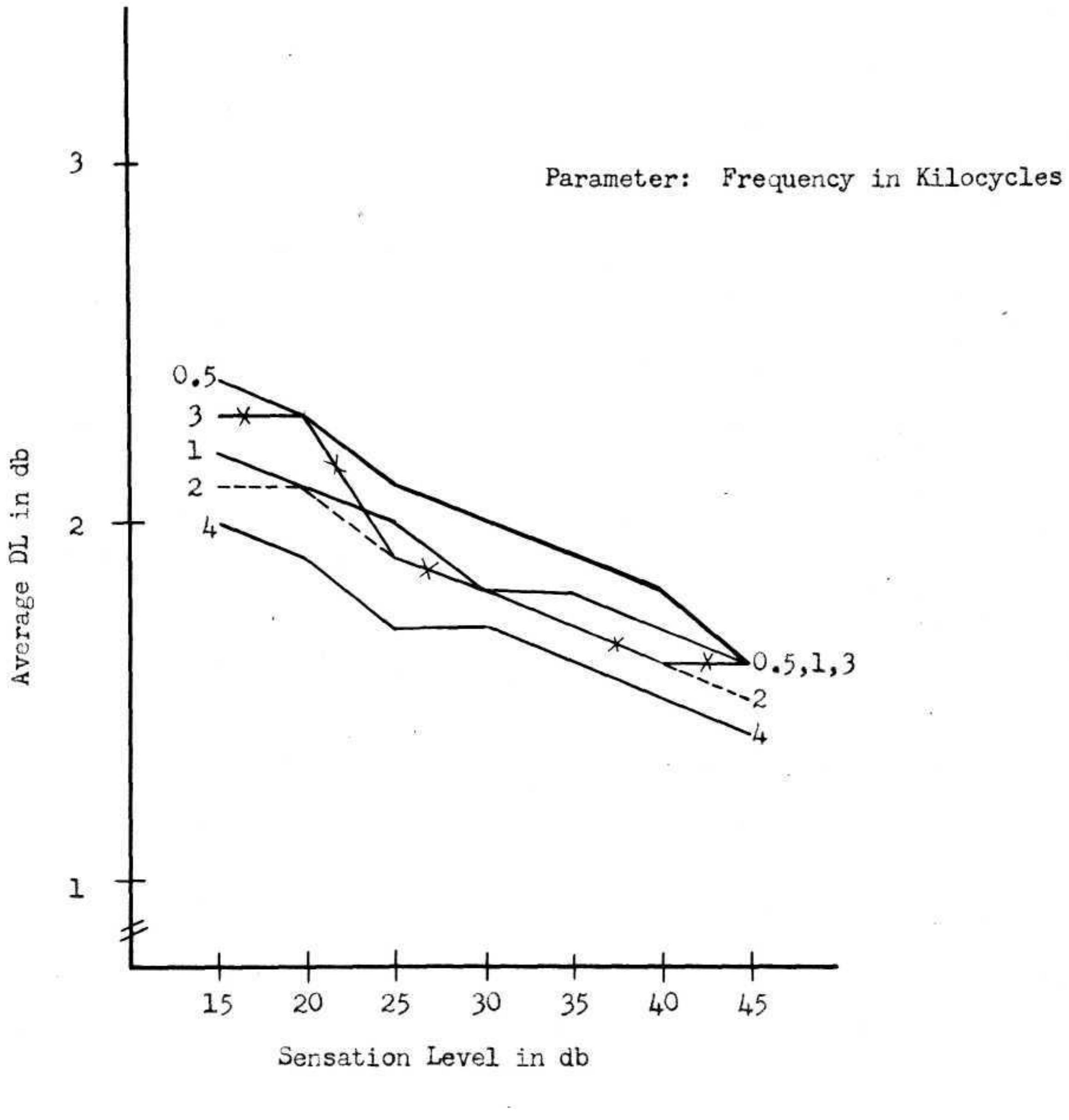


Fig. 23 Graphic Representation of Frequencies - by - Sensation Levels Interaction in DL Test.

inverse relationship of DL size with frequency, although the general trend was present. Similarly, the combination of experimental and control results in an analysis of frequency by ascending versus descending presentation (Figure 24) demonstrates that rank-ordering in DL size for frequencies differed, depending upon whether the ascending or descending presentation was used. Finally, Figure 25 reveals that the direction of stimulus presentation had a marked effect on the relative DL size for sensation levels (combined data). DL's for sensation levels are seen to be appropriately rank-ordered at uniform intervals on the ordinate in the ascending series in contrast to a cluster effect in the descending series.

A common level which can be used for a comparison of results from this and other studies is a tone of 40 db at 4000 cps. Jerger reported a DL of 0.5 for the recruiting subject (27), Denes-Naunton reported a DL of 2.0 (7), Luscher-Zwisloki reported a DL of 0.6 (32), and Palva reported a DL of 1.7 (37). It is interesting to note that where discrepancies exist in the literature, there are also differences in the experimental designs utilized. In the Jerger technique, as has been described previously, the subjects are asked to indicate a difference between the two tones while the presentation was given from a point of no modulation to a fully modulated value. Both Denes-Naunton and Palva reported results utilizing a dual tone, the modulation of which decreased in amplitude to a point of constant intensity. In the first instance, representation has been made in this investigation by means of the ascending presentation. The descending presentation was representative of the second technique described. As previously noted, the main effect, direction of the tone presentation to the subject, was found to be significant

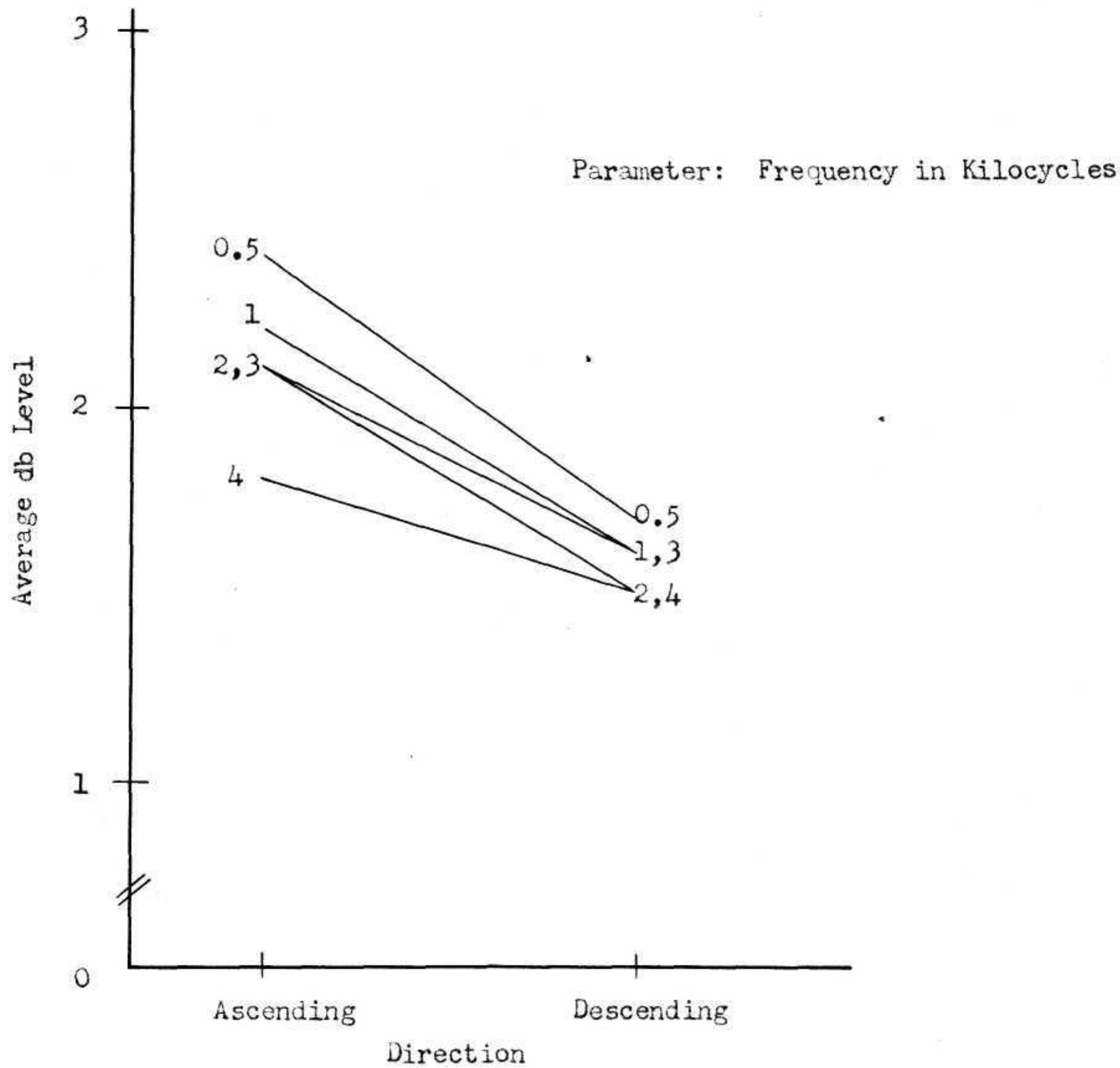


Fig. 24 Graphic Representation of Frequency - by - Direction* in DL Test.

* See Text for description of ascending-descending presentation of stimuli.

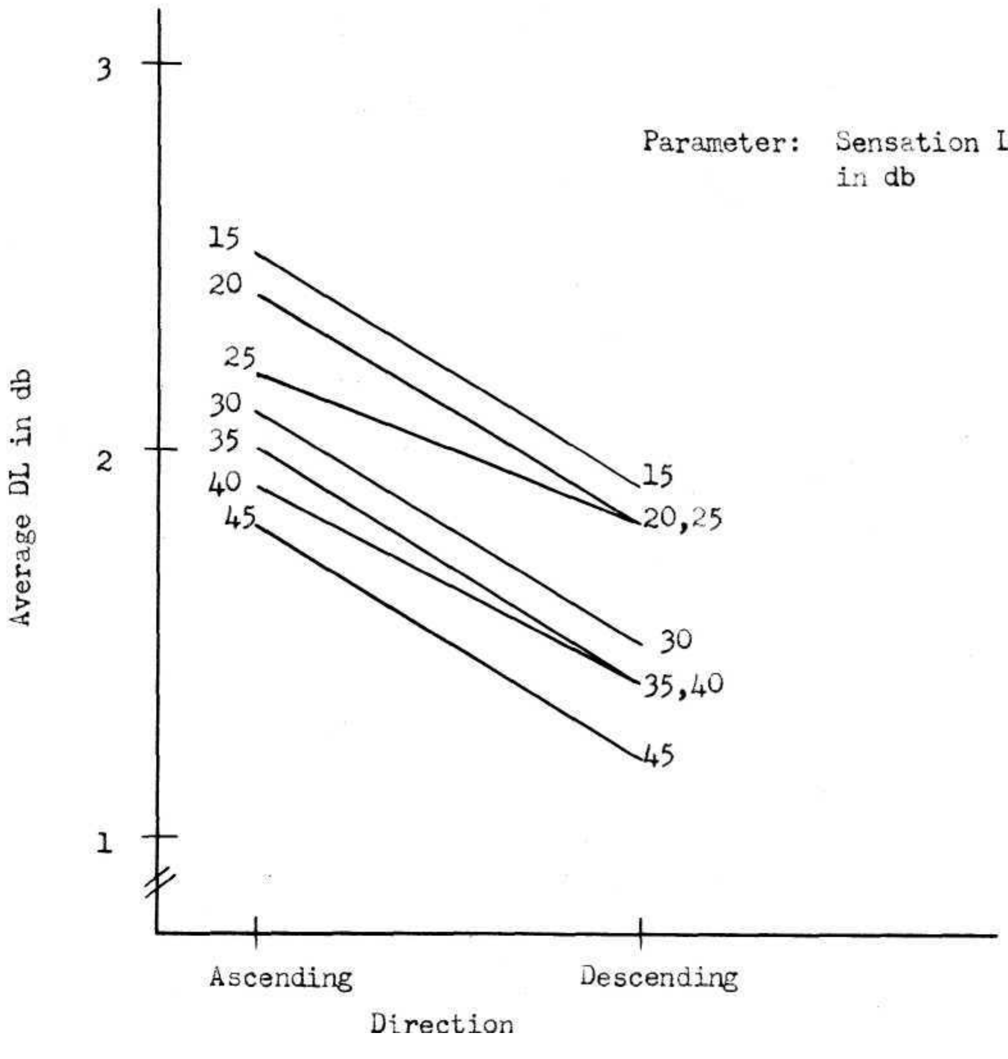


Fig. 25 Graphic Representation of Sensation Levels - by - Direction Interaction in DL Test.

both in the experimental group and in the control group in this experiment. The significance of the interaction of the direction of tone presentation by groups also was noted. The data in this experiment were analyzed with regard to the values obtained at 4000 cps at a sensation level of 40 db for both the ascending and descending presentation. A DL of 1.7 for the descending technique and a DL of 0.7 for the ascending technique were found for the experimental group, results which provide very close correspondence with the results cited above.

Speech Sound Discrimination

The concern of previous investigators has been with the plateau or ceiling reached near the top of the discrimination curve, rather than with any other segment. The first of two analyses in the present experiment, as shown in Table 7, revealed that the effects of groups, sensation levels and the interaction of groups-by-sensation levels were significant at the 5 percent, 1 percent, and 1 percent points, respectively, for the origin of the discrimination curve. Table 8 gives the averages for the correct responses of both groups at each sensation level tested and Figure 26 illustrates the discrimination curves for both groups. It can be seen that the experimental group had an origin higher than that of the control group. Moreover, the continued superiority of the recruiting ears up to a sensation level of 30 db is to be noted. Figure 27 illustrates the groups-by-sensation levels interaction for the entire discrimination curve. In this figure the relatively more regular progression of correct responses with increased intensity in the normal group is to be observed.

In the analysis of the top of the discrimination curve, no significant differences were found in any of the main effects. Table 9

TABLE 7

Analysis of Variance of Average Speed Sound Discrimination

Source of Variation	df	Sum of Squares	Mean Squares	F	Significance Level
Gr *	1	58.3	58.3	5.83	5%
S c Gr *	7	70.1	10.0		
I *	14	1086.1	77.6	4.62	1%
I x Gr	14	1254.4	89.6		5.33 1%
I x S c Gr	98	1641.5	16.3		
Ear	1	1104.5	1104.5	2.29	
E x Gr	1	1356.0	1356.0	2.81	
E x S c Gr	7	3381.1	483.0		

* Gr - Groups

* S c Gr - Subjects within Groups

* I - Intensity

Table Values for F

.01 - (14, 98) df - 2.33

.05 -(1, 7) df - 5.59

TABLE 8

Mean Scores by Sensation Level in

Bottom of Speech Sound Discrimination Test

Sensation Level in db	Control Mean	Control S.D.	Experimental Mean	Experimental S.D.
2	1.8	.13	2.8	.69
4	2.7	.63	4.3	.87
6	3.7	.89	4.6	.86
8	4.5	1.3	5.6	.13
10	5.6	1.1	6.9	1.1
12	6.8	1.3	7.0	1.0
14	6.0	1.0	7.0	1.1
16	6.2	.84	7.9	.89
18	7.3	1.2	8.3	.86
20	7.1	1.1	8.4	1.2
22	7.6	1.6	8.4	.80
24	7.9	1.2	8.5	1.1
26	8.9	1.3	8.8	.74
28	9.1	.63	9.1	.70
30	9.2	.95	9.0	.63

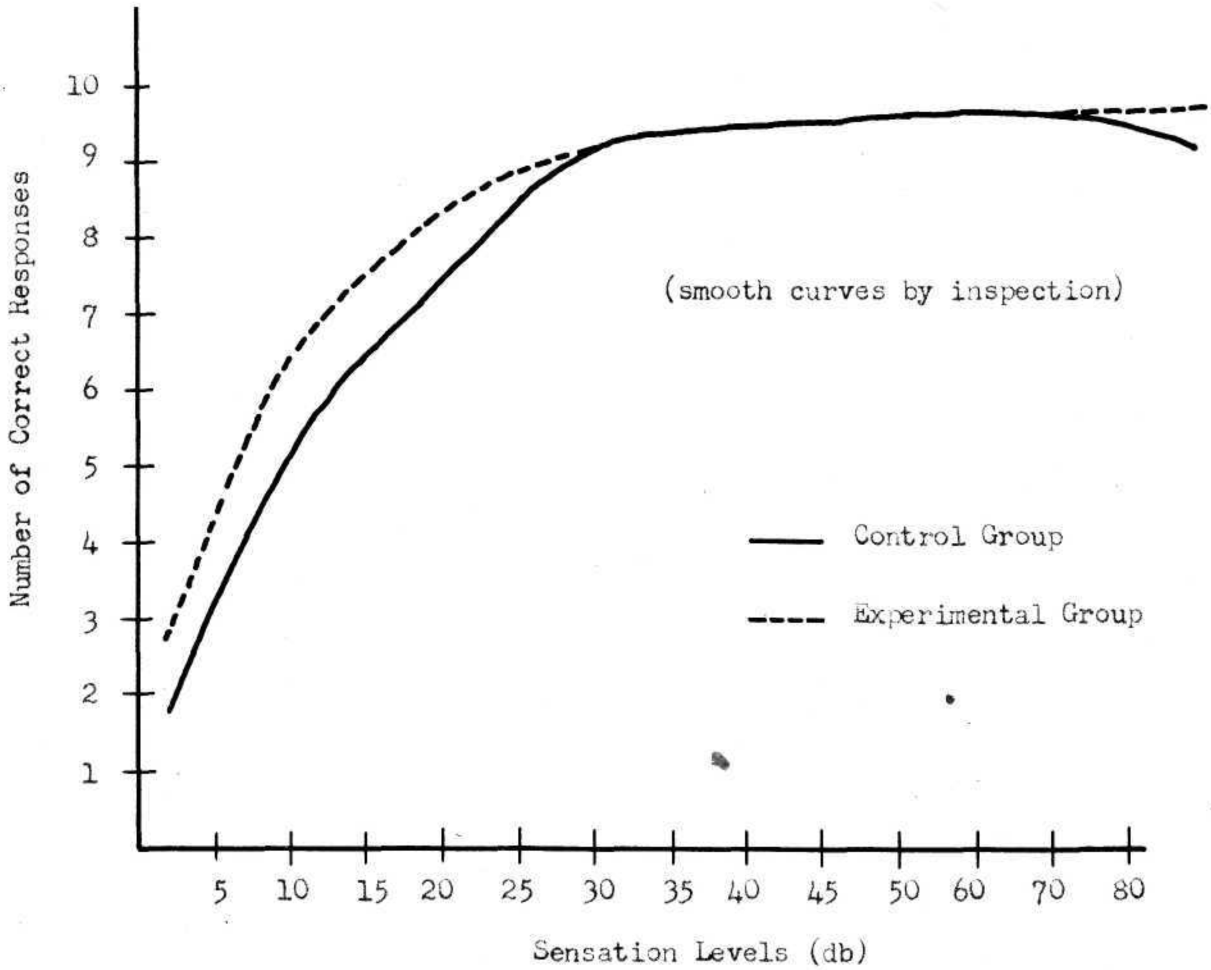


Fig. 26 Graphic Plot of Speech Sound Discrimination Test Results.

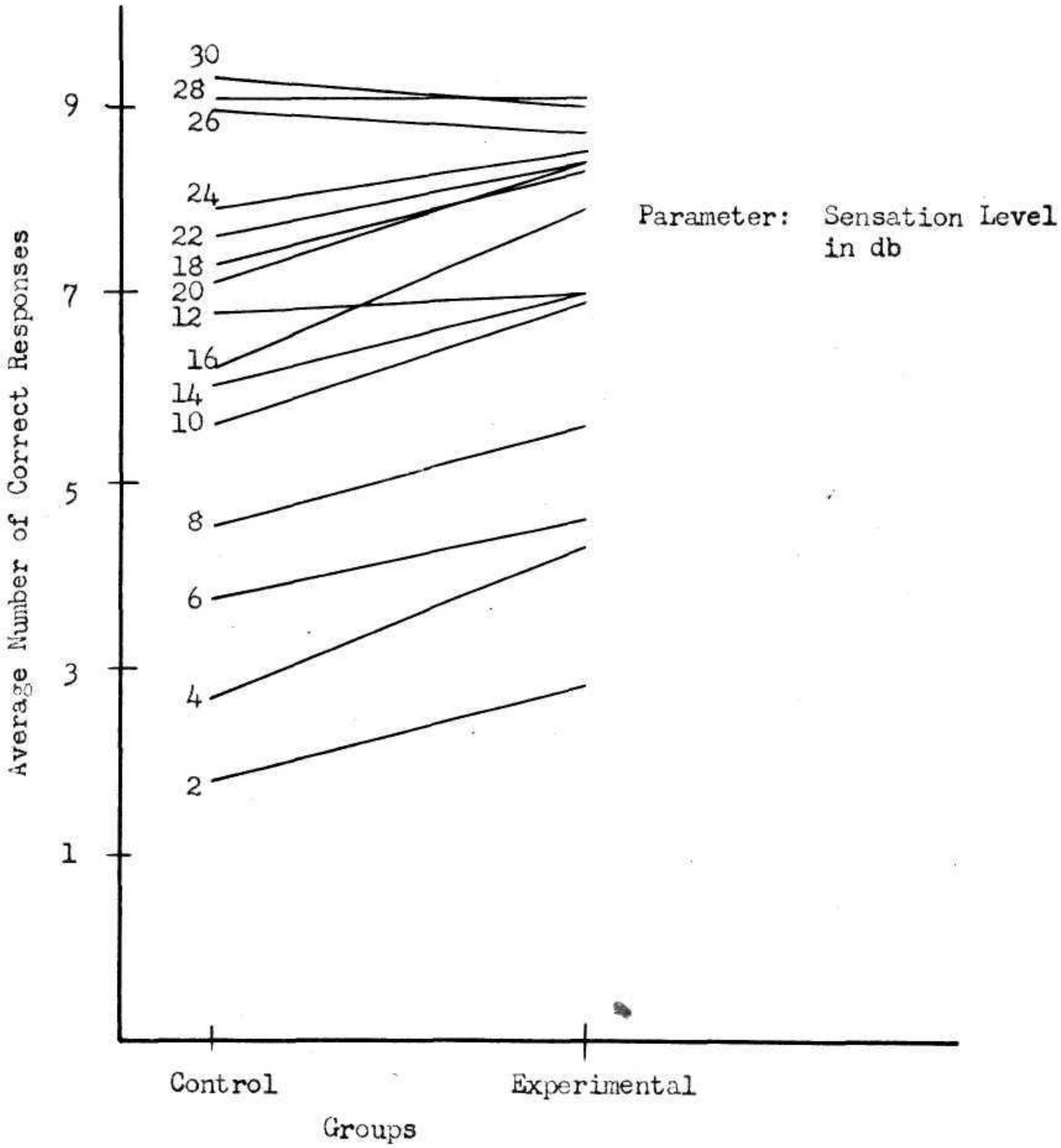


Fig. 27 Graphic Representation of Sensation Level - by - Group Interaction in the Speech Sound Discrimination Test.

Analysis of Variance of Upper End of

Speech Sound Discrimination Test

Source of Variation	df	Sum of Squares	Mean Squares	F	Significance Level
Gr *	1	0.2	0.2		
S c Gr *	7	12.9	1.84		
I *	14	0.9	0.06		
I x Gr	14	2.2	.16		
I x S c Gr	98	23.3	.24		
Ear	1	2.9	2.9		
E x G r	1	5.8	5.8		
E x S c Gr	7	37.3	5.34		

* Gr - Groups

* S c Gr - Subjects within Groups

* I - Intensity

presents the analysis of variance for the top of the discrimination curve, and the average number of correct responses for each group at each sensation level tested is given in Table 10.

The sound discrimination plateau asserted in previous publications to be characteristic of individuals exhibiting the recruitment phenomenon was found in this experiment, but at a higher level of correct discrimination than previously reported. Moreover, a virtually identical plateau was reached by the normal hearing subjects.

TABLE 10

Mean Scores by Sensation Level

in Speech Sound Discrimination Test

	Sensation Levels in db											
	30		40		50		60		70		80	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Control	9.2	.75	9.4	.66	9.5	.50	9.3	.64	9.3	.72	9.1	.83
Exper.	9.0	.62	9.1	.33	9.4	.49	9.5	.71	9.4	.51	9.5	.45
Total	18.2		18.5		18.9		18.8		18.7		18.6	

SUMMARY AND CONCLUSIONS

With the data presented in the preceding sections, it is possible to return to the questions posed at the outset of this investigation. These were the following:

1. Are the effects attributable to groups (normal versus impaired hearing), subjects within groups, or the ear being tested significant in the Range of Comfortable Loudness test?

2. Are the effects attributable to groups, subjects within groups, frequencies, sensation levels, direction (ascending versus descending) of stimulus presentation, or the ear being tested significant in the Difference Limen test?

3. Are the effects attributable to groups, subjects within groups, sensation levels or the ear being tested significant in the Speech Sound Discrimination test?

Before answers to these questions, in the form of conclusions to the study, can be offered, a brief review of the investigation is desirable, and a statement of the limitations is necessary.

Three tests, the Range of Comfortable Loudness, the Difference Limen, and a Speech Sound Discrimination test were administered to nine subjects. Five of these were normal hearing control subjects, and four, the experimental subjects, were individuals given a tentative diagnosis of recruitment.

Test results, analyzed by the analysis of variance technique, revealed that the experimental and control groups performed differently on all three tests, that the effects of frequency and sensation level were significant within the RCL and DL tests, that there were significant interactions among the main effects. A comparison of the test results from the experimental group with data previously reported for recruiting ears provided some instances of agreement and some of disagreement. The DL results were almost identical with previously reported difference limens (7, 27, 32, 37). However, the RCL's for the experimental group were wider than previously reported (1), and the speech sound discrimination was superior to that reported in an earlier investigation (8, 10, 24, 34).

Certain sources of error and possible bias in the results must be considered as limitations in the experiment. with allowance made for unanticipated and uncontrolled sources of error, and for interactions among known possible sources, the following limitations should be recognized:

1. The statistical techniques employed adequately demonstrated experimental and control group differences, but do not necessarily establish population parameter differences,
2. Only partial control could be exerted over extraneous noise present in the auditory test environment.
3. Reliance was placed upon manufacturers' specifications with regard to the frequency response and calibration of some of the instrumentation.
4. The instrumentation employed in the DL test was assembled in a unique array in the Purdue Voice Communication Laboratory. Hence, the results of this test are not predictably reproducible unless the instrument array is duplicated.
5. The test items used in the Speech Sound Discrimination test, nonsense consonant-vowel syllables, also were unique to this study. In previous investigations of this type spondiac words were used.
6. Although safeguards were taken to reduce fatigue effects, the possibility of such effects entering into the experiment

cannot be excluded.

7. The statistical tests in this investigation employed the assumption, among other criteria, of homogeniety of variance. This assumption was partially satisfied by inspection of the data. No formal test for homogeniety of variance was employed.
8. The order of presentation of the three tests was incompletely randomized.

Within the limitations imposed by the error sources listed above, as well as the limitations imposed by the restricted number of frequencies and sensation levels tested, the following conclusions are offered:

1. Normal hearing individuals are distinguishable from individuals with impaired hearing of the type diagnosed as recruitment on the basis of the following test performance:
   a) Range of Comfortable Loudness: A more restricted RCL is characteristic of the auditory perception of individuals exhibiting the recruitment phenomenon than individuals possessing normal hearing.
   b) Difference Limen: A smaller difference limen is characteristic of the auditory perception of individuals exhibiting the recruitment phenomenon than individuals possessing normal hearing.
   c) Speech Sound Discrimination: A higher number of correct responses in a restricted range immediately above the threshold of detectability is characteristic of the auditory perception of individuals exhibiting the recruitment phenomenon than individuals possessing normal hearing.

2. The extent of the range of comfortable loudness and of the difference limen depends upon the frequency of the stimulus tone. In general, smaller DL's and RCL's are found above 2000 cps than below that frequency.

3. In general, the extent of the DL is inversely proportional to the sensation level of the stimulus tone, while the number of correct speech sound discriminations is directly proportional to the sensation level.

4. Smaller difference limens are found when listeners must discriminate the onset of warble from a steady-state tone than when the presentation is from the warble tone to the steady-state tone.

BIBLIOGRAPHY

1. Bangs, J. L. and Mulling, C. J., Recruitment Testing in Hearing and its Implications, A.M.A. Archives of Otolaryngology, 58, 1953, 582-592.

2. Bekesy, G. V., A New Audiometer, Acta-Oto. Laryng.. Stockh. 35, 1947, 411-422.

3. Bekesy, G. von, The Recruitment Phenomenon and Difference Limen in Hearing and Vibration Sense, Laryngoscope. 57, 1947, 765-777.

4. Davis, H., Hearing and Deafness,. New York: Rinehart, 1947.

5. De Bruine-Alters, J. C. and Huizing, H. C, The Monaural Masking Method for Recruitment Testing in Symmetrical Deafness, Act Oto-Laryng.. Stockh., 37, 1949, 385-391.

6. Denes, P. and Naunton, R. F., Methods of Audiometry in a Modern Deafness Clinic, J. Laryng. 63, 1949, 251-275.

7. Denes, P. and Naunton, R. F., The Clinical Detection of Auditory Recruitment, J. Laryng. and Oto., 64, 1950, 375-398.

8. Dix, M. R., Hallpike, C. S. and Hood, J. D., Observations Upon the Loudness Recruitment Phenomenon, with Especial Reference to the Differential Diagnosis of Disorders of the Internal Ear and VIII Nerve, Proc. Roy. Soc. Med., 61, 1948, 516-526.

9. Dix, M. R., Hallpike, C. S. and Hood, J. D., Nerve Deafness: Its Clinical Criteria, Old and New, Proc. Roy. Soc. Med., 42, 1949, 527-536.

10. Eby, L. G. and Williams, H. L., Recruitment of Loudness in the Differential Diagnosis of End-0rgan and Nerve Fibre Deafness, Laryngoscope. 41, 1951, 4-414.

11. Egan, J. P., Hearing, Ann. Rev. Psychol.. 5, 1954, 98-105.

12. Fletcher, H. and Munson, W. A., Loudness,its Definition, Measurement and Calculation, JASA, 5, 1933, 82-108.

13. Fowler, E. P., Marked Deafened Areas in Normal Ears, Arch. Otolaryng., 8, 1928, 151-155.

14. Fowler, E. P., The Recruitment of Loudness Phenomenon, Laryngoscope. 60, 1950, 680-695.

15. Gardner, M. B., Short Duration Auditory Fatigue as a Method of Classifying Hearing Impairment, J. Acoust. Soc. Amer. 19, 1947, 178-190.

16. Garner, W. R. and Miller, G. A., Differential Sensitivity to Intensity as a Function of the Duration of the Comparison Tone, J. Exper. Psychol.. 34, 1944, 450-463.

17. Hallpike, C. S. and Hood, J. D., Some Recent Work on Auditory Adaptation and its Relationship to the Loudness Recruitment Phenomenon, J. Acoust. Soc. Amer., 23, 1951, 270-274.

18. Halm, T., Determination of the Difference Limen and the Latest Illustration Thereof in Audiometry, J. Laryng., 63, 1949, 464-466.

19. Harris, J. D., A Brief Critical Review of Loudness Recruitment, Psychol. Bull., 50, 1953, 190-203.

20. Harris, J. D., Haines, H. L. and Myers, C. A., Loudness Perception in Pure Tones and for Speech, Arch. Otolaryng., 55, 1952, 107-133.

21. Hirsh, I. J., Development of Materials for Speech Audiometry, J. Speech and Hearing Disorders. 18, 1952, 321-337.

22. Hirsh, I. J., The Measurement of Hearing. New York: McGraw-Hill, 1952.

23. Huizing, H. C., The Relation Between Auditory Fatigue and Recruitment, Acta Oto-Laryng., Stockh., 36, 1949, 346-355.

24. Huizing, H. C, and Reyntjes, J. A., Recruitment and Optimum Speech Intelligibility, Revue De. Laryngologia, September 1950.

25. Huizing, H. C. and Reyntjes, J. A., Recruitment and Speech Discrimination Loss, Laryngoscope, 62, 1952, 521-527.

26. Jerger, J. F., A Difference Limen Recruitment Test and Its Diagnostic Significance, Laryngoscope. 62, 1952, 1316-1332.

27. Jerger, J. F., DL Difference Test: An Improved Method for the Clinical Measurement of Recruitment, A. M. A. arch. Oltolaryng., 57, 1953, 490-500.

28. Lambert, J., Ph.D. Dissertation, Purdue University, 1954.

29. Lund-Iverson, L., An Investigation on the Difference Limen Determined by the Method of Luscher-Zwislocki in Normal Hearing and in Various Forms of Deafness, Acta Oto-Laryng.. 62, 1952, 219-224.

30. Lurie, M. H., Studies of Acquired and Inherited Deafness in Animals, J. Acoust. Soc Amer.. 11, 1940, 420-426.

31. Luscher, E., The Difference Limen of Intensity Variation of Pure Tones and its Diagnostic Significance, Proc. Roy. Soc. Med., 63, 1950, 1116-1128.

32. Luscher, E. and Zwislicki, J., A Simple Method for Indirect Monaural Determination of the Recruitment Phenomenon (Difference Limen in Intensity in Different Types of Deafness, Acta Oto-Laryng., Supp. 78, 1949, 156-168.

33. Luscher, E. and Zwislicki, J., Comparison of the Various Methods Employed in the Determination of the Recruitment Phenomenon, J. Laryng. and Otol., 65, 1951, 187-195.

34. Palva, T., Finnish Speech Audiometry, Acta Oto-Laryng. Supp. 101, 1952.

35. Reger, S. N., Difference in Loudness Response of the Normal and Hard-of-Hearing Ear at Intensity Levels Slightly Above the Threshold, Ann. Otol.. 45, 1936, 1029-1039.

36. Steinberg, J. C. and Gardner, M. B., The Dependence of Hearing Impairment on Sound Intensity, JASA. 9, 1937, 11-23.

37. Simonton, K. M., Diplacusis Binauralis Dysharmonica and Recruitment of Loudness: Their Clinical Significance, American Academy of Ophthalmology and Otolaryngology., 1951 Instruction Section, Course No. 476.

38. Stevens, S. S. and Davis, H., Hearing: Its Psychology and Physiology, New York: Wiley, 1938.

39. Tumarkin, A., A Contribution to the Theory of the Mechanism of the Auditory Apparatus, J. Laryng.. 60, 1945, 337-368.

40. Tumarkin, A., The Decibel, the Phon, and the Sone, J. Laryng., 64, 1950, 179-188.

41. Watson, L. A., A Manual for Advanced Audiometry. Minneapolis, Minnesota: Colorcraft Press, 1949,

42. Watson, L. A., and Tolon, T., Hearing Tests and Hearing Instruments. Baltimore: Williams and Wilkins, 1949.

43. Wever, E. G., Theories of Hearing. New York: Wiley, 1949.

44. Woodworth, R. S., Experimental Psychology, New York: Henry Holt, 1938.