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BAND-LIMITED SPEECH DISCRIMINATION ABILITY IN

NORMAL AND HEARING-IMPAIRED SUBJECTS

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DISSERTATION COMMITTEE

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BAND-LIMITED SPEECH DISCRIMINATION ABILITY IN NORMAL AND HEARING-IMPAIRED SUBJECTS

CHAPTER I

INTRODUCTION

Experiments in the area of filtered speech have been concerned primarily with dividing the audible spectrum into equally-contributing bands (1, 2, 12, 13, 29, 37, 46), with determining the effects of noise upon filtered speech (37, 46, 47), with finding the effects of filtering upon different types of speech stimuli (1, 19, 39), or with the assessment of higher auditory pathway integrity (3, 4, 5, 6, 16, 25, 33). A variety of experimental procedures and verbal stimuli have been employed. Most of the studies employed observers who were well trained for the tasks and had normal hearing. The studies of higher auditory pathway function were not concerned with peripheral hearing loss.

Huizing and Taselaar (22, 23) devised a filtered speech task which they used clinically with patients exhibiting a peripheral hearing loss. They tested speech discrimination ability in each of three frequency bands, which together, comprise the audible spectrum. Subjects with a conductive hearing loss were able to achieve scores within the normal range with any of the three bands. The reduction in discrimination ability exhibited for any band by a hearing-impaired subject indicates the extent to which he is unable to utilize the frequencies in that band. These experiments have all been conducted using the Dutch and German languages. Similar studies in English have not been reported.

Most commercially-available hearing aids exhibit varying degrees of high-frequency emphasis in their response curves due to the inherent electro-mechanical limitations of hearing aids. The Harvard Report (9), coincidentally, recommends a mild high-frequency emphasis in hearing aid response curves for most hearing aid users. In view of these facts, and the renewed interest in earmold venting to achieve increased high frequency emphasis (34, 35, 48), it seems pertinent to evaluate the importance of high frequencies for the speech discrimination ability of patients with a sensorineural hearing loss.

This study was designed to evaluate the contribution of high-frequency speech sounds to the speech discrimination ability of normal-hearing subjects and subjects with high-frequency, sensorineural hearing losses. The speech discrimination ability of all subjects was tested with lists of monosyllabic words presented in quiet at a single level of a low-pass band, at four different levels of a high-pass band, and with the low-pass band in combination with each level of the high-pass band.

CHAPTER II

REVIEW OF THE LITERATURE

Introduction

The investigation of speech intelligibility was initiated by Bell Telephone engineers interested in evaluating the capabilities of their equipment. The audiologist has adapted the principles and materials of the Bell Telephone Laboratories to evaluate the speech discrimination ability of the human auditory system.

Persons with normal hearing are able to discriminate speech which has been severely distorted by the elimination of the high frequency portion of the spectrum. On the other hand, some hearing-impaired listeners, who also perform with a frequency range limited primarily to the low frequencies, suffer severe discrimination problems. Hearing aids, which favor the higher frequencies, are often recommended for such impaired listeners although experience has not always demonstrated the advisability of this practice. It would seem profitable for the audiologist to devise a simple test to determine the value of high-frequency emphasis for potential hearing aid users.

The purpose of this study is to investigate the contributions of different levels of a high-frequency band, alone and in combination with a low-frequency band, to speech discrimination ability in subjects with normal hearing and in those with a high frequency, sensorineural hearing loss.

The sections which follow review the literature dealing with filtered speech. In addition, the studies which form the basis for the clinical application of tests of speech intelligibility are reviewed.

Development of Speech Materials

Much of the early information gained in the area of speech testing resulted from telephone engineers' investigations of the efficiency with which a communications system transmitted speech sounds. The accuracy of transmission of speech sounds through a system was measured by finding the per cent of syllables correctly identified by a listener. This per cent was called the syllable articulation, or simply, articulation of the system.

Fletcher and Steinberg (12) were among the first to publish standardized techniques to use in testing the articulation of a system. Their original work was concerned with the recognizability of various speech sounds when spoken in a manner representative of conversational speech. Meaningless monosyllables were used and the listeners were well trained for the task of identifying the phonemes they heard. Fletcher and Steinberg point out that by using a standardized procedure, "the articulation of the individual sounds may be converted into an index which indicates the speech capabilities of the system."

During World War II, considerable effort was directed toward the development of speech tests that could be used to evaluate military communication equipment. Most of the work was done at the Psycho-Acoustic Laboratory (PAL) at Harvard University and resulted in the development of PAL Auditory Test Nos. 9 and 14 (spondaic words) and

No. 12 (sentences) (20).

In 1948 Egan (10) published an article containing a series of monosyllabic word lists constructed to evaluate the effect of a communicative system on the intelligibility of speech. These lists were designed so that most sounds were present in proportion to their occurrence in conversational English. This technique, referred to as phonetic balance (PB), was an attempt to increase the face validity of the lists. During the later stages of the research conducted at the PAL, Egan's lists (called PB-50 lists) were used to assess the effects of hearing loss upon the intelligibility of speech. Hudgins *et al*. (20), using Egan's lists, constructed speech tests based upon the concept of a normal threshold of hearing for speech. The lists of PB monosyllabic words developed by Egan "were too difficult" to be appropriate for threshold determination, but they did lend themselves well to testing fine phonetic discrimination at suprathreshold levels (16).

Although the PB-50 lists were designed to be used in the evaluation of communication systems, they were soon applied to the testing of hearing. Egan (11) points out that, as he designed them, the PB word lists were to be examined by the listener prior to the test. As used in a clinical setting Egan's precaution often was not employed, resulting in reduced discrimination scores.

Hirsh *et al*. (18) found that the different lists of the PAL words (called PB-50 lists) did not give equivalent test scores and that the vocabulary of the PB test lists was so extensive that some words were included which occurred so infrequently in ordinary conversational speech that they were not recognized by some subjects. Hirsh *et al*. (18) devised new speech tests which purported to eliminate these deficiencies.

From the original 1000 words in the PB-50 lists, Hirsh et al. (18) selected 120 words. To these he added 80 new words. The total vocabulary of 200 words was divided into four lists of 50 words each. The phonetic composition of each list was representative of spoken English. Six randomizations of word order were generated for each list. These lists were called Central Institute for the Deaf (CID) Auditory Test W-22 (PB words). A new spondee list was formed by using the 36 most familiar words from the original 84 spondee words on PAL Auditory Test Nos. 9 and 14. From this revision came the CID Auditory Tests W-1 (constant-level spondees) and W-2 (attenuated spondees).

These lists formed by Hirsh and his colleagues result in lower thresholds for both spondee and PB words than the original lists. Also, the PB words of the W-22 test allow higher discrimination scores than the older PB lists. The thresholds in decibels (dB) re: 0.0002 microbar for the various tests are presented below:

Speech Test	Threshold in Decibels (dB) re: 0.0002 Microbar
PAL No. 14 (constant-level spondees)	24
PAL No. 9 (descending-level spondees)	22.46
PAL PB-50 (1000 PBs)	33.20
CID W-1 (constant-level spondees)	14.20
CID W-2 (descending spondees)	17.70
CID W-22 (200 PBs)	24

(Threshold for PBs and spondees is defined as that intensity where the listener can correctly identify 50 per cent of the words.)

Another major step toward the refinement of speech testing material was the development of new monosyllabic word lists by Lehiste and Peterson (30, 36). These lists are composed of consonant-nucleus (vowel or diphthong)-consonant (CNC) words. The structure of the word utilized resulted from Lehiste and Peterson's clarification of criteria for phonetic balance. As they point out, phonetics refer to the physiological and acoustical properties of speech. The PB-50 and CID W-22 lists are not in reality phonetically balanced, but rather were designed to be phonemically balanced, since phonemic refers to perceptual aspects of phonetics. Lehiste and Peterson contended that neither the CID nor the PAL lists had very good phonemic balance. Each of their lists of 50 CNC words was edited to achieve the phonemic balance which characterized the total of the 1,263 monosyllabic words from which the 10 lists were drawn, rather than the phonemic structure of spoken English as a whole. This, they believed, gave each list the face validity not found in the earlier lists. They also took precautions to assure that the words they used were as familiar as was practical.

Despite the advantages of these lists over the earlier PB-50 and W-22 lists, the reliability and interchangeability of the 10 lists was questioned by Carhart and Tillman (41). These alleged shortcomings led to the development of the Northwestern University (NU) Auditory Test No. 4, composed of two lists and 6 randomizations of CNC monosyllabic words (41). The limitations imposed by having only two interchangeable lists soon became restrictive and NU Auditory Test No. 6 was developed (42). This test is composed of four 50-word lists of the CNC structure, each list having four randomizations. Tillman and Carhart (42) found that on both normal-hearing and sensorineural hypo-acousic subjects, NU Auditory Test No. 6 had good inter-list equivalence and high test-retest reliability. Sommerville (38), using her own recordings of Lists 2, 3, and 4 of NU Auditory Test No. 6, found articulation-gain functions equivalent to the PB word lists developed by Hirsh et al. (18). The results of Tillman and Carhart and of Sommerville led to the decision to use NU Auditory Test No. 6 in the proposed study.

Filtered Speech

In their attempts to find the effects of the frequency response of a communication system on speech intelligibility, telephone engineers also pioneered in the area of filtered speech. The following paragraphs summarize their efforts to quantify the relationship between frequency response and the associated intelligibility of a communication system.

The crossover frequency, or equal intelligibility point, was used to indicate the most important area for discrimination of speech elements. (The equal intelligibility point is the point in the frequency spectrum which, when used as the cut-off frequency, results in equal intelligibility for both low- and high-band-pass filtered speech.) Some of the test levels are expressed in dB of Orthotelephonic (OT) gain. For ease of comparison, 0 (zero) Orthotelephonic gain is assumed to be approximately equal to 65-dB Sound Pressure Level (SPL).

French and Steinberg (13), using filtered consonant-vowel-consonant (CVC) nonsense syllables (NSS), found the crossover frequency in quiet to be 1900 Hertz (Hz). At + 50 OT gain, low-pass 1900 Hz and high-pass 1900 Hz each gave articulation (discrimination) scores of 68 per cent. The filter employed for this study had an attenuation rate of almost infinite cut-off after the 6 dB down point at the cut-off frequency. Typical examples of intelligibility scores obtained were: low-pass 1000 Hz at + 50 OT gain allowed a score of 27 per cent; with the gain dropped to + 30, the score was 24 per cent.

Beranek (2) used both filtered NSS and monosyllables (MS) with the same filter slope as French and Steinberg. He found the crossover frequency to be 1660 Hz in quiet and 800 Hz in noise.

Employing the same words and filters as French and Steinberg, Pollack (37) found the crossover frequency to be 1620 Hz when the words were presented in quiet and 800 Hz when the speech was presented in a noise background. A filter setting of low-pass 1050 Hz at + 40 OT gain allowed a 44 per cent intelligibility score. A score of 22 per cent was achieved with high-pass 1800 Hz at + 40 OT gain.

In 1954 Hirsh et al. (19) evaluated the effects of filtering on a number of different verbal stimuli. The lists employed were: PB words from CID Auditory Test W-22, nonsense syllables, disyllabic words, and polysyllabic words. With a filter attenuation rate of 60 dB per octave, the crossover point for all lists was 1700 Hz. Monosyllabic words at 95 dB SPL measured before the filters and low-passed at 1000 Hz allowed a correct discrimination score of 68 per cent; nonsense syllables under the same conditions yielded a score of 53 per cent. Subjects listening to monosyllables high-passed at 2000 Hz, with 95 dB SPL before the filters, achieved a score of 88 per cent. The same condition with nonsense syllables allowed 68 per cent correct discrimination.

In 1959 Black (1) performed a filtered speech study to find 20 frequency bands which contributed equally to speech intelligibility. He utilized two sets of speech stimuli: one was a multiple-choice PB test he devised and the other was CID Auditory Test W-22. Subjects were required to circle the correct word on the former and to write their response on the latter. He used a filter attenuation rate of 36 dB per octave and found the crossover point to be 1500 Hz for multiple-choice

PBs and 1700 Hz for write-down monosyllables. At low-pass 1000 Hz, subjects correctly wrote down 58 per cent of the monosyllables. The same filtering and intensity allowed subjects correct identification of 76 per cent of the PBs.

Speaks (39) found the crossover frequency for synthetic sentences to be 725 Hz. He used a filter with an attenuation rate of 24 dB per octave. Examples of Speaks' results are: low-pass 1000 Hz at 15 dB SPL allowed 88 per cent correct identification; low-pass 350 Hz at 25 dB SPL allowed 96 per cent identification; with low-pass 125 Hz at 62 dB SPL, subjects achieved a score of 100 per cent. A high-pass 2000 Hz at 25 dB SPL allowed subjects to identify 65 per cent of the sentences.

The data of French and Steinberg (13) suggest that the important frequencies for intelligibility of nonsense monosyllables lie between 1500 and 2500 Hz. The findings of Black (1) and Beranek (2) also place the important frequency region for speech discrimination in this range. The results of filtered-speech experiments with noise masking (37, 46, 47) suggest that the important frequency region may lie as much as an octave below the region determined in quiet. Webster (47) and Pollack (37) both showed that the shift of important frequencies to a lower region was only true in the presence of high levels of noise masking. They explain this finding by pointing out that a white noise masks the less intense high-frequency speech sounds before the more intense low-frequency sounds.

The earlier filtered-speech studies (2, 13, 37) all used crews of well-trained listeners who were required to identify correctly all three components of meaningless monosyllables of the CVC type. Black (1) used lists of multiple-choice PBs and write-down monosyllables as his speech stimuli. Hirsh _et al_. (_19_) used a variety of speech materials to find the effects of filtering upon speech intelligibility. Like the other investigators, Hirsh also employed well-trained listeners. Speaks (_39_), in 1967, investigated the effects of filtering upon the identification of synthetic sentences. He used a closed-response set paradigm (multiple-choice from ten alternative sentences) and a more gradual cut-off slope from his filter than the other investigators.

It appears from the summarized results of previous filtered-speech experiments presented in the preceding paragraphs that the type of speech stimuli used and the experimental procedures employed significantly influences the results. It appears that the easier speech tasks, or speech in a noise background, have a lower frequency crossover point.

In 1960 Kryter (_28_) performed a study to determine which portions of the speech spectrum could be eliminated without intelligibility falling below an acceptable level. He passed lists of PB-50 words and sentences through one, two, or three filters with a 500 Hz bandwidth and varied the center frequency of the band (or bands). The region around 1600 to 1700 Hz appeared to contribute most to speech intelligibility when using a single 500 Hz band. When two bands were passed, maximum intelligibility occurred by centering the low band at 500 or 750 Hz and the high band at either 1500 to 1750 Hz or 2500 to 2750 Hz. Passing three bands gave optimum intelligibility when the bands were centered at 500, 1500, and 2500 Hz. In terms of relative importance to discrimination, the low frequencies contributed most and the high frequencies least.

The maximum score obtained by Kryter for passing one band was around 35 per cent; two bands yielded approximately 75 per cent correct discrimination; three bands allowed as high as 95 per cent correct speech discrimination.

Various tests have been devised utilizing speech in a modified form to evaluate the auditory system (3, 5, 25, 33). Of the different means of modifying speech, filtering has been one of the more popular. A large portion of the work in this area has been concerned with the binaural integration of filtered speech sounds (4, 6, 33). Filtering has been used primarily as a tool in the evaluation of "central" rather than peripheral auditory mechanisms.

As a result of the work of Kruisinga (27) and Huizing and Kruisinga (21) in the area of whispered voice, a new concept in the clinical use of filtered speech emerged. Huizing and Taselaar (23, 24) noticed that the discrimination scores obtained with spoken and whispered voice varied with different types of hearing impairments. They devised a procedure which utilized a more easily specified qualitative change in speech as a test of auditory function. Since normal speech is characterized by redundancy, due not only to cues associated with context (16, 17, 20, 31) but also to the multiplicity of frequencies associated with the spectrum of speech, Huizing and Taselaar divided the audible spectrum into three frequency bands and maintained normal intelligibility in each band. The bands they used contained (1) only the frequencies below 900 Hz, (2) only the frequencies between 900 Hz and 1800 Hz, and (3) only the frequencies above 1800 Hz (23). The speech material (either spondees or sentences) was presented at a most comfortable loudness (MCL) level. When this procedure was employed with subjects manifesting a conductive hearing loss, normal discrimination was maintained in each band. Although they did not state it explicitly, it is implied that this was the same finding as was obtained with normal-hearing subjects. When patients with a sensorineural hearing loss attempted this task, their discrimination ability in the three bands was dependent upon the band under test. Usually the band with the least pure-tone loss yielded the best discrimination score and the band with the most pure-tone loss gave the poorest score. Although it is implied (23) that subjects with a sensorineural hearing loss will have a reduced discrimination ability in any band that has a pure-tone loss, in a later article Huizing, Kruisinga, and Taselaar (24) point out that some patients with a sensorineural hearing loss are capable of achieving normal discrimination scores in some or all of the three bands.

With a low-, medium-, and high-frequency band to test discrimination ability, Huizing and Taselaar were able to draw inferences about the patient's partial discrimination ability. They also believed they are better able to make decisions regarding the remedial approach to be taken, particularly in terms of amplification and auditory training.

In summary, the literature on filtered speech reveals that the important frequency region for the discrimination of monosyllables, when tested in quiet, is from 1500 Hz to 2500 Hz. Monosyllables in noise and sentences in noise or quiet are more dependent upon the frequencies in the 300 to 1000 Hz region. The clinical use of the discrimination of filtered speech for peripheral hearing problems has been limited primarily to the Dutch and German languages (21, 22, 23, 24, 27).

This study was designed to test the speech discrimination ability of normal and hearing-impaired subjects employing limited-frequency bands. To this end, speech discrimination scores were obtained under nine different conditions of filtering and intensity.

CHAPTER III

DESIGN OF THE INVESTIGATION

Introduction

The literature on filtered speech experiments reveals that the important frequency region (or regions) for speech discrimination is dependent upon the verbal stimuli used, the signal-to-noise ratio, and the experimental techniques employed. The important frequency area for sentences and noise-masked monosyllables lies approximately an octave below the 1500 to 1900 Hz region found critical for maximum intelligibility of monosyllables presented in quiet (1, 2, 12, 19, 29, 37, 46, 47).

Huizing and Taselaar (22, 23) and Huizing, Kruisinga, and Taselaar (24) have devised a clinical speech discrimination procedure utilizing filtered speech. They divided the audible spectrum into three bands, each allowing subjects with normal hearing to achieve excellent discrimination scores when the words were presented at a most comfortable loudness level (MCL). With this procedure, they determined the ability of hearing-impaired individuals to utilize the different frequency bands.

The most prevalent type of sensorineural hearing loss is a sloping loss with more impairment in the high frequencies. People with this type of loss may experience difficulty in understanding speech.

Therefore, it was decided to limit this study to the evaluation of speech discrimination ability using only a single intensity level of a low-frequency band and four levels of a high-frequency band. These two bands were presented singly and the low band was combined with each level of the high band. A pilot study was performed to find the cut-off points on three frequency bands that would singly allow normal speech discrimination at a MCL level. It was assumed that by manipulating the level of the high band, both by itself and in combination with a low band, it would be possible to achieve the goal of determining to what extent a subject utilizes higher frequencies in a speech discrimination task. The upper cut-off frequency for the low band was 1000 Hz while the lower edge of the high-frequency band was 2000 Hz.

Using these bands, the discrimination ability of two groups of subjects was measured; subjects with normal hearing and subjects with a sensorineural hearing loss.

Subjects

A total of 24 subjects was used for this experiment, twelve normal-hearing subjects and twelve subjects with a sensorineural hearing loss. The twelve normal-hearing subjects met the following criteria:

(1) Pure-tone thresholds of 10 dB (ISO) or less at octave frequencies from 250 through 8000 Hz as measured by standard audiometry.

(2) A negative history of ear pathology.

(3) Completion of at least a formal high school education.

The test ear of the twelve hearing-impaired subjects met the following criteria:

(1) An air-conduction loss of 20 to 70 dB (ISO) at 2000 Hz.

(2) No more than 15 dB discrepancy between the air-conduction and bone-conduction thresholds at all frequencies.

(3) Speech discrimination scores of less than 85 per cent when tested with a 50 word recorded list from CID Auditory Test W-22 presented at a 40 dB sensation level (SL).

(4) No suggestion of a retrocochlear lesion as evidenced by previous audiometric tests, tests performed in the selection of subjects, or from historical information.

The test ear for each subject was always the ear with the better discrimination ability. It was assumed that this policy would minimize any contribution to intelligibility by the non-test ear due to cross-hearing.

The group of normal-hearing subjects was comprised of five males and seven females, with a mean age of 24.67 years. Eleven males and one female were in the hearing-impaired group. Their mean age was 54 years.

The normal-hearing subjects were friends and associates of the investigator. The hearing-impaired subjects were drawn from the patients visiting the ENT department of the Oklahoma City Clinic. Appendix A contains subject identification information and audiometric data.

Apparatus

All screening and experimental testing was conducted in a sound-isolated suite at the Speech and Hearing Center, University of Oklahoma Medical Center. The test-suite consisted of two adjacent rooms, a test chamber and a control room.

Noise levels in the test room were measured with a Sound Level Meter (General Radio, Type 1551-C) in conjunction with an Octave-Band Noise Analyzer (General Radio, Type 1558). Levels in the octave bands centered at the customary test frequencies were below the level recommended by USASI for air and bone-conduction testing (45).

The test room contained the subjects' earphones and bone vibrator while all other screening and experimental apparatus was located in the adjacent control room. Visual contact was maintained with the subject by means of a glass window located between the two rooms. Appropriate auditory contact was provided by a talk-back system incorporated in the speech audiometer used in the experimental portion of the study.

Screening Apparatus, Speech Stimuli, and Procedures

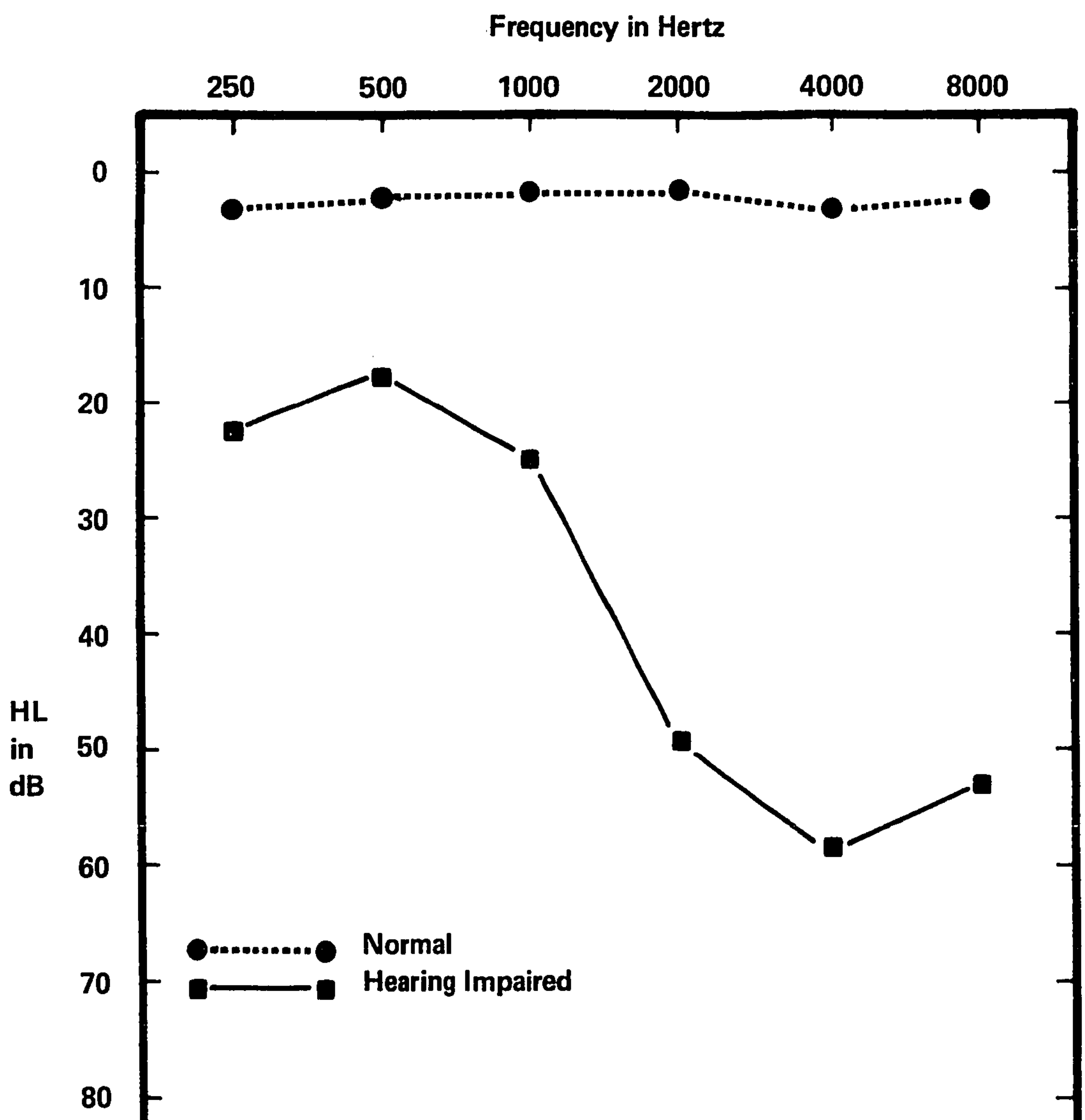
Pure-tone hearing tests were administered to all subjects using a Beltone Model 15C Audiometer, the output of which terminated in either of two Telephonics Type TDH 39-10Z earphones enclosed in MX-41 AR cushions and mounted in a standard headband, or in a Radioear B-70A low impedance bone-conduction vibrator held by the headband (Maico) routinely employed for forehead bone-conduction testing. The acoustic output of the air-conduction system was monitored by means of an audiometer calibration unit (Allison, Model 300). The output of the bone-conduction system was evaluated periodically employing an artificial mastoid (Beltone, Model 5A), using the Hearing Aid Industry Conference (HAIC) Interim Standard (32). Pure-tone thresholds were obtained by means of an ascending technique (7) using 5 dB steps.

Both speech reception thresholds and discrimination scores were obtained with recorded lists presented through a speech audiometer (Grason-Stadler, Model 162). Speech reception thresholds were obtained with spondaic words from CID Auditory Test W-1. The words were presented in two-dB steps using an ascending technique (8). Threshold was defined as the lowest level at which the subject correctly repeated at least three of six words presented to him. Speech discrimination testing utilized 50-word lists from CID Auditory Test W-22 presented at a 40 dB SL. The 1000 Hz calibration tone provided on each record was peaked at 0 on the speech audiometer VU meter.

Figure 1 presents the mean pure-tone thresholds, speech reception thresholds, and discrimination scores for the normal and hearing-impaired groups.

Experimental Test Material and Apparatus

The experimental test material consisted of consonant-nucleus-consonant (CNC) words from Lists 2, 3, and 4 of NU Auditory Test No. 6 which have been previously recorded and standardized at the University of Oklahoma (38). Four randomizations (A, B, C, D) of each of these lists were employed. The master tapes were re-recorded utilizing an Ampex tape recorder (Model 354) as the source and a Sony tape deck (Model 600) as the recorder. The second generation tapes were played on the Sony tape deck, the output of which was connected in parallel to a pair of variable electronic filters (Spencer-Kennedy Laboratories, Model 302). Each of the filters had two sections capable of performing as a high- or low-pass filter with an attenuation rate of 18 dB per octave. The two sections of each filter were connected in series to provide a total attenuation of 36 dB per octave. One filter was set to reject all frequencies above 1000 Hz and the other set to reject all frequencies below 2000 Hz. The output of the two filters went to the tape inputs of a speech audiometer (Grason-Stadler, Model 162) which provided the mixing, switching, and intensity control of the stimuli. The test material was delivered to the subjects through a TDH-39 earphone.



Standard Speech Test Results

	SRT	Per Cent 25SL	Discrimination 40SL
Normal	3.67		97.0
Hearing Impaired	28.75	62.83	75.08

Fig. 1 – Mean pure-tone thresholds for test ear of normal and hearing-impaired subjects.

Experimental Control Procedure and Apparatus

The following procedure was employed to adjust the filters to the desired cut-off frequency. A probe tone equal to the desired cut-off frequency was introduced to one of a pair of filters. The level of the cut-off frequency was adjusted on the first section of the filter until a 3 dB loss was noted on the vacuum tube voltmeter. The second section of the filter was then adjusted until a 6 dB loss was noted. A probe tone one octave into the rejected region was then introduced and a voltage drop of 36 dB (plus or minus 0.5 dB) was verified.

An audio oscillator (Hewlett-Packard, Model 200 ABR) provided the tones in this procedure. A 600-ohm resistor was used to load the output of the oscillator. Frequency specification of the probe tone was accomplished with an electronic counter (Transistor Specialities Co., Model 360). Measurements of the insertion loss were made with a vacuum tube voltmeter (Ballantine, Model 300). Figure 2 provides a simplified diagram of the apparatus employed in this investigation.

Procedure

The purpose of this study was to investigate the contribution of high frequencies to speech intelligibility in normal-hearing subjects and subjects with a sensorineural hearing loss as measured by their performance on a limited-frequency-band speech discrimination task. The investigation consisted of two phases. In the first phase, the subjects' speech discrimination ability was measured with a single intensity level of a low-frequency band and two different intensity levels of a high-frequency band. This phase served two purposes. First, it allowed the examiner to verify specific limits of discrimi-

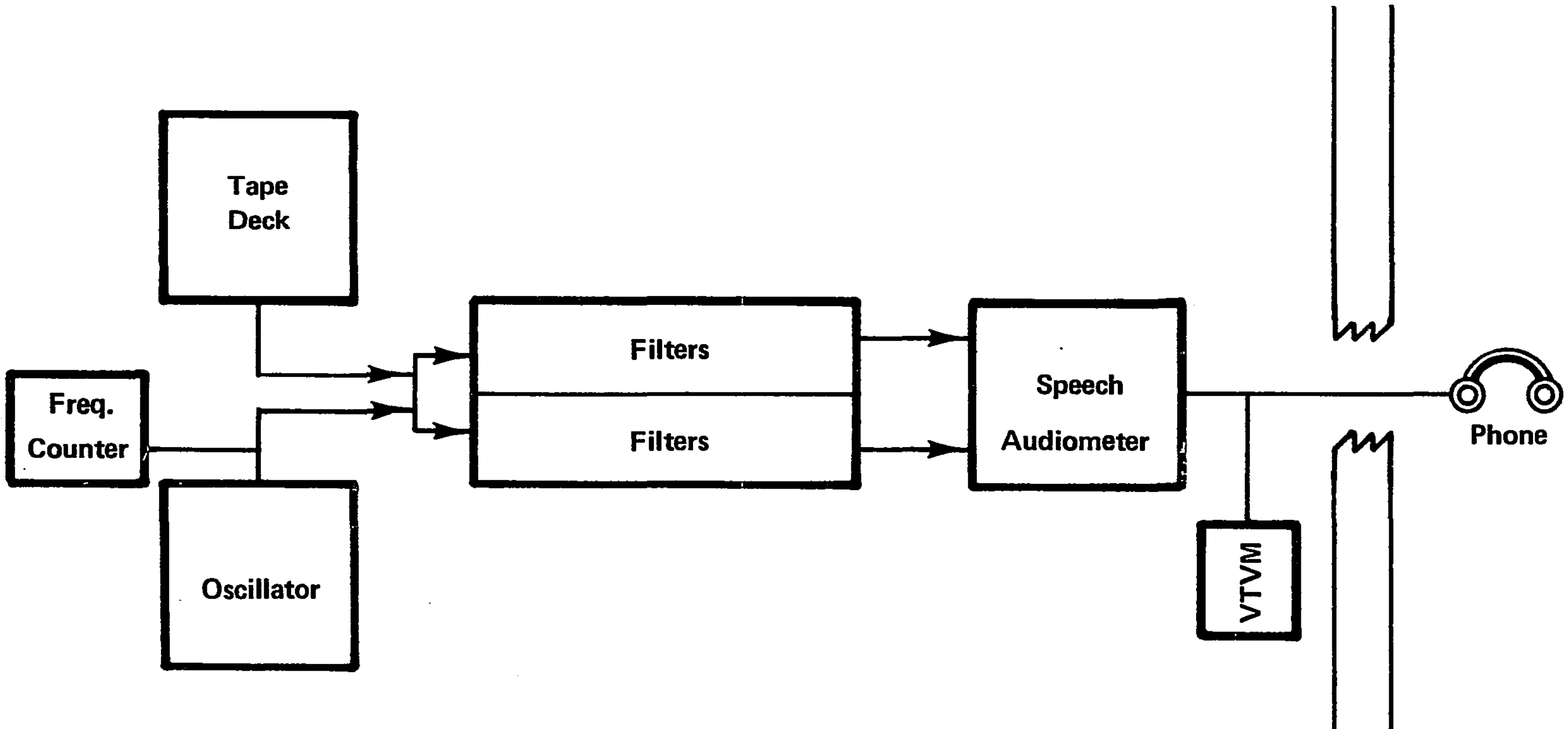


Fig. 2 — Block diagram of experimental apparatus.

nation ability which were used to set base-line intensity levels for the speech signals. Second, it provided a means for determining whether the speech discrimination scores of subjects improved following experience with the task. This was accomplished by repeating the three conditions of Phase I as integral parts of the second phase.

In Phase I the speech discrimination ability of both groups was evaluated under each of the following three conditions:

(1) Low-pass, 1000 Hz at a single intensity level.

(2) High-pass, 2000 Hz at two different intensity levels.

The intensity levels to be used were set individually for each subject. For the low-pass band, a level was determined at which the subject was able to repeat correctly three to five out of a total of ten PB words from recordings of CID Auditory Test W-22 presented to him. A preliminary study performed by the investigator revealed that this would be equal to approximately a 30 to 50 per cent discrimination score when the subject received a full list of CNC words. The data confirm the validity of this procedure, with only two subjects of the 24 deviating by more than 10 per cent from the desired range. All scores outside the planned range were below 30 per cent.

The lower intensity level to be used in the high-frequency band was determined by finding that level at which the subject could correctly repeat either one or two from a total of 10 PB words presented. As with the low-pass band, preliminary data suggested that when tested with a full list of 50 CNC words the subject could correctly discriminate approximately 10 to 20 per cent of the words. The data revealed that the scores of only three subjects, all from the normal-hearing group, missed the range by more than 5 per cent. Their discrimination scores were all between 25 and 35 per cent. The second level of the high frequency band used in Phase I was 18 dB above the low level.

The level of the low-frequency band and the low level of the high band were set for performance ranges so that changes in speech discrimination ability could be measured as a function of increased levels of the high band or with band-combination conditions. Therefore levels were used that allowed 30 to 50 per cent discrimination with the low band and 10 to 20 per cent with the lower levels of the high band. Errors in level setting, of the direction and magnitude noted in the preceeding paragraphs, do not appear to have compromised the data.

In Phase II of the experiment, the three conditions of the first phase were repeated, and, in addition all subjects were presented lists of CNC words at two additional levels of the high band (6 and 12 dB above the low level) and with the low band combined with each level of the high band.

Each subject was instructed to write the last word he heard in the sentences presented to him. The sentence was: "Say the word ____." Subjects were told to guess if uncertain of any words. Responses were written by the subject on a printed form. Each word error decreased the total discrimination score by two per cent. Response forms were graded by the investigator during the time that the subject was listening to the next experimental condition. When difficulties arose in reading a response word the investigator asked the subject to identify it during the next break between conditions.

The experimental conditions used in Phase I were counterbalanced such that each condition appeared an equal number of times in each position (i.e., first, second, and third). Table 9 in Appendix B presents the presentation order of lists and conditions. The order of the nine conditions presented in Phase II was randomized without replacement for each subject.

All four randomizations of each of the three lists appeared an equal number of times. The order of presentation of lists and randomizations was systematized, in both the first and second phase, to prevent different randomizations of the same list from appearing twice in succession. This arrangement resulted in each subject receiving all 12 list randomizations once. (Table 9 in Appendix B presents the order of list and condition presentations.)

All subjects were given a rest between the preliminary hearing evaluation and the beginning of the experimental session. They also received a short rest between successive experimental conditions while the apparatus was readjusted.

Means, variances, and standard deviations of the discrimination scores of each group for each condition were obtained. Analysis of variance and other inferential statistics were used to compare the speech discrimination ability of the two groups. The results are described and discussed in the following chapter.

Summary

This study investigated the ability of twelve normal-hearing subjects and twelve subjects with a high-frequency, sensorineural hearing loss to discriminate band-pass filtered speech. The subjects responded to a single intensity level of a low-frequency band, four intensity levels of a high-frequency band, and the low band combined with each level of the high band.

CHAPTER IV

RESULTS AND DISCUSSION

The purpose of the present investigation was to evaluate the limited-frequency band speech discrimination ability of normal and hearing-impaired subjects. Thus, speech discrimination scores were obtained from twelve normal-hearing subjects and twelve subjects with a sloping, high-frequency sensorineural hearing loss. Each subject listened to 50-word lists of NU Auditory Test No. 6 under two filtered conditions: low-pass 1000 Hz and high-pass 2000 Hz.

The study was divided into two phases. In Phase I the low-pass speech was presented at an intensity level which was predicted to yield discrimination scores of 30 to 50 per cent. The high-pass speech material was presented at two intensity levels. The lower level was selected to allow discrimination scores of 10 to 20 per cent and the higher intensity level was 18 dB above the lower level. Details of the procedure and information regarding the effectiveness of the procedure in allowing the desired discrimination scores may be found in Chapter III.

The three conditions of Phase I were repeated in Phase II. The two sets of data were compared to determine the effects of practice with filtered speech materials.

Phase II, in addition to the above three conditions, included two intermediate intensity levels of the high-pass band (6 and 12 dB above the lower intensity level) and the low-pass band combined with each intensity level of the high-pass band. The order of presentation of the nine conditions was separately randomized for each of the subjects.

Subsequent sections will present the results of repeated and filtered speech articulation-gain curves for the high-pass band alone and the high-pass band in combination with the low-pass band. A discussion of the results follows the presentation of data.

The differences in discrimination scores between the normal- and hearing-impaired subjects for each condition were compared by means of a t-test with unequal variances. (The significance levels associated with the t-scores obtained must be interpreted with caution because of the limitations imposed by the non-independence of the samples.) Based on the results of this study, the hearing-impaired group was divided into two subgroups (I and II) and these subgroups were compared using a t-test. The articulation-gain curves were analyzed by means of orthogonal polynomials (40) to determine whether the response curves could best be described by a linear, quadratic, or cubic function. The raw data and statistical analysis tables are located in Appendices C and D.

Phase I Results and Analysis of Learning Effects

Table 1 reveals that the average discrimination scores for both the normal- and the hearing-impaired subject groups fall within, or close to, the planned range of performance on the low-pass band (LP) and the low level of the high-pass band (HP) for the first presentations of those conditions. When the second presentation of the three

TABLE 1

MEANS, STANDARD DEVIATIONS, AND t-SCORES FOR NORMAL AND HEARING-IMPAIRED SUBJECTS FOR LOW-PASS, HIGH-PASS$_1$, AND HIGH-PASS$_4$ CONDITIONS OF PHASES 1 AND 2

	Condition		
Normals	LP	HP_1	HP_4
Phase 1	31.33	21.67	74.17
Phase 2	38.50	32.17	84.17
$s.d._1$	11.61	7.48	7.98
$s.d._2$	11.82	13.28	6.63
t'-score	1.50	2.38	3.34

	Condition		
Hearing-Impaired	LP	HP_1	HP_4
Phase 1	34.17	13.83	52.33
Phase 2	42.67	25.17	56.83
$s.d._1$	9.48	4.93	16.80
$s.d._2$	9.20	9.90	15.45
t'-score	2.23	3.52	0.68

t' required for 0.05 level of significance = 2.20

conditions used in Phase I are compared to the initial presentation, an increase in performance is evident for both groups on all three conditions. The t-tests comparing the performance on the two presentations of the three conditions (LP, HP_1 and HP_4) revealed that both the normal and hearing-impaired subjects performed significantly better ($p < .05$) on the second presentation for two of the three conditions (see Table 1).

The first three conditions presented to all subjects (those in Phase I) were in effect, practice for the subjects in listening to filtered speech. It was anticipated that this practice, plus the counterbalancing of lists and randomization of conditions, would prevent learning effects from influencing the results. The curves presented in Figure 3 represent discrimination scores averaged across subjects and conditions as a function of presentation order for Phase II. It does not appear from these curves that learning occurred in Phase II, since the discrimination scores do not improve systematically as a function of presentation order.

The procedure employed for setting levels in the high-pass conditions appears to be justified even though the HP_1 scores of Phase II are slightly higher than desired, since no subject in either group was able to achieve 95 per cent discrimination at any of the levels.

Phase II Results

Single Bands

Table 2 reveals that the mean discrimination scores for the normal and hearing-impaired groups on the low-pass condition were comparable and well within the desired 30 to 50 per cent performance range. The performance of the two groups on this condition, compared with a

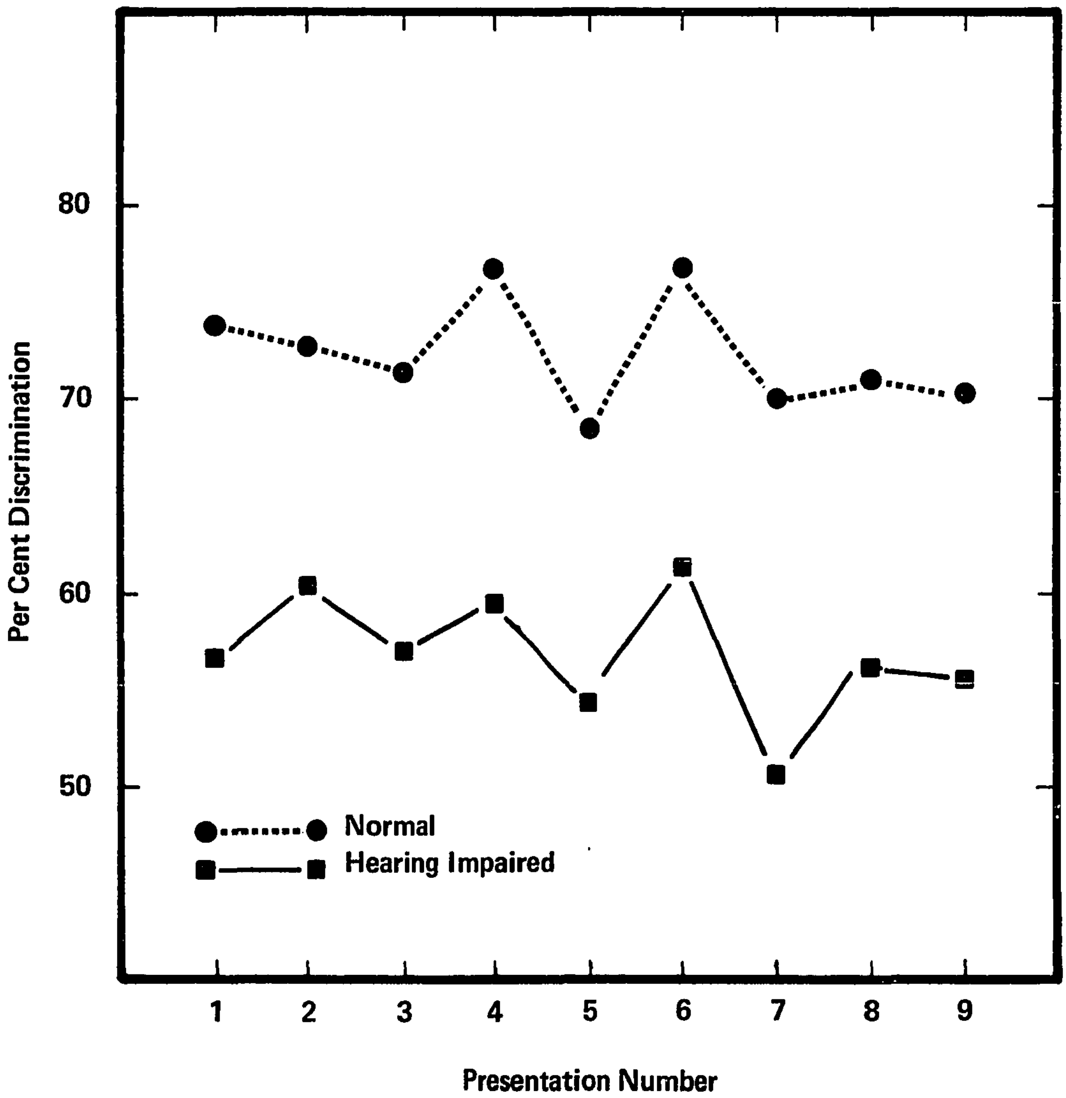


Fig. 3 – Mean discrimination scores by order of presentation for all subjects across all conditions in phase II.

TABLE 2

MEANS, STANDARD DEVIATIONS, AND t-SCORES FOR NORMAL AND HEARING-IMPAIRED SUBJECTS ON SINGLE-BAND CONDITIONS

	Condition				
	LP	HP_1	HP_2	HP_3	HP_4
Normals					
Mean	38.50	32.17	63.83	76.00	84.17
s.d.	11.82	13.28	10.69	14.37	6.63
Hearing-Impaired					
Mean	42.67	25.17	35.33	51.33	56.83
s.d.	9.20	9.99	10.60	16.61	15.45
Difference between the Means	4.17	7.00	28.50	24.67	27.34
t'-score	.97	1.46	6.57	3.89	5.64

t' required for .05 level of significance = 2.20

t-test, did not show a significant difference ($P > .05$).

Figure 4 and Table 2 present the results of the two groups' performance on the four levels of HP. Although the performance of the normal-hearing subjects improved with each increase in the level of the high band, the amount of increase in discrimination ability was less for each successive level (decreasing from a 5.27 per cent/dB increase between HP_1 and HP_2 to a 2 per cent/dB increase between HP_2 and HP_3 and finally dropping to a 1.36 per cent/dB increase between HP_3 and HP_4).

The hearing-impaired subjects also exhibited improved performance with added level of the HP band, but their greatest improvement was between HP_2 and HP_3 (a 2.67 per cent/dB increase). The increase between HP_1 and HP_2 was 1.67 per cent/dB, while only a 0.92 per cent/dB gain occurred between HP_3 and HP_4. As with the normals, the smallest increase in discrimination scores occurred between HP_3 and HP_4.

Comparison of the performance of two groups, by means of a t-test, indicates they did not differ significantly ($P > .05$) at HP_1, as designed, but they did differ significantly at HP_2, HP_3, and HP_4 ($P < .05$).

The nature of the response curves for the normals on the HP conditions was analyzed by using an orthogonal polynomial comparison. This procedure revealed significant Linear and Quadratic effects ($P < .005$). This finding supports the observation that the increase in performance with added intensity is progressively less for each level. The orthogonal polynomial analysis on the hearing-impaired subjects revealed a significant F ($P < .005$) for Linear effects only.

In summary, the two groups did not differ significantly in their performance on the LP or HP_1 conditions, as designed, but they did

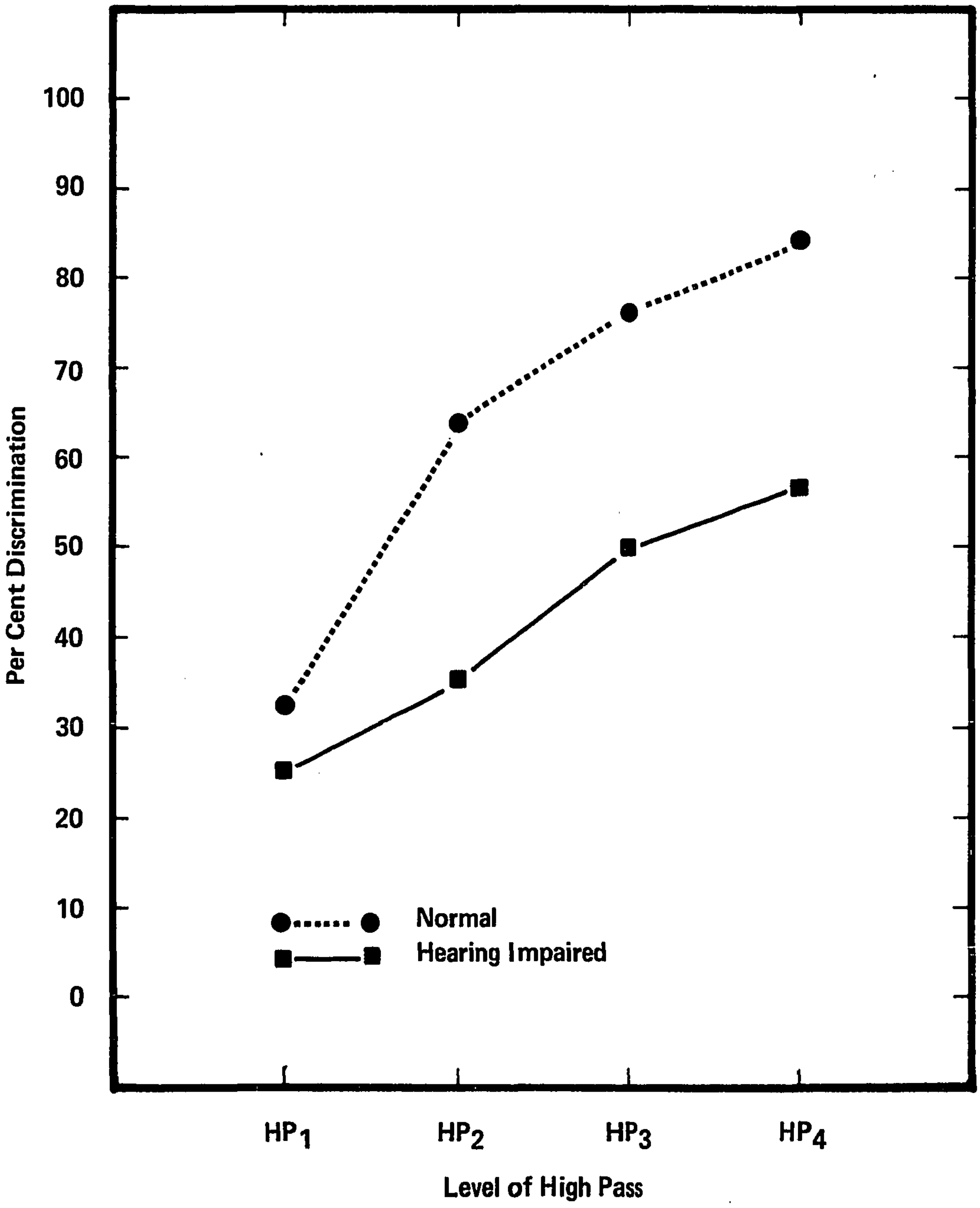


Fig. 4 – Discrimination scores for four levels of high-pass.

differ significantly on the other three HP conditions. The performance of both groups increased as the intensity was raised, but the normal-hearing subjects were able to utilize the higher levels better than the hearing-impaired subjects.

Combination Bands

The results of testing under the LP condition and the band-combination (BC) conditions are presented in Figure 5 and Table 3. The data show that the normal-hearing subjects exhibit a maximum increase in performance (42.00 per cent) between LP and LP plus HP_1 (BC_1). After the HP is added to the LP, each successive level of HP results in less improvement. The performance increments decrease from 1.33 per cent/dB between BC_1 and BC_2 to 0.83 per cent/dB between BC_2 and BC_3 and finally to 0.22 per cent/dB between BC_3 and BC_4.

If the discrimination scores on the band-combination conditions were the result of the simple addition of the performance scores on the single bands, the predicted score on BC_1 would be 70.67 per cent. The obtained score of 80.16 per cent may indicate that more than the simple summation of acoustic information in the single bands occurs. Predicted scores for the other band-combination conditions, based on summation of single bands, all fall above 100 per cent.

The performance of the hearing-impaired subjects on the BC conditions is characterized by slight improvement with added intensity in the high band. As with the normals, the greatest improvement in performance (23.50 per cent) is between LP and BC_1. The increase in the performance of the hearing-impaired subjects with added intensity in the high band is less for each additional step, going from an increase of

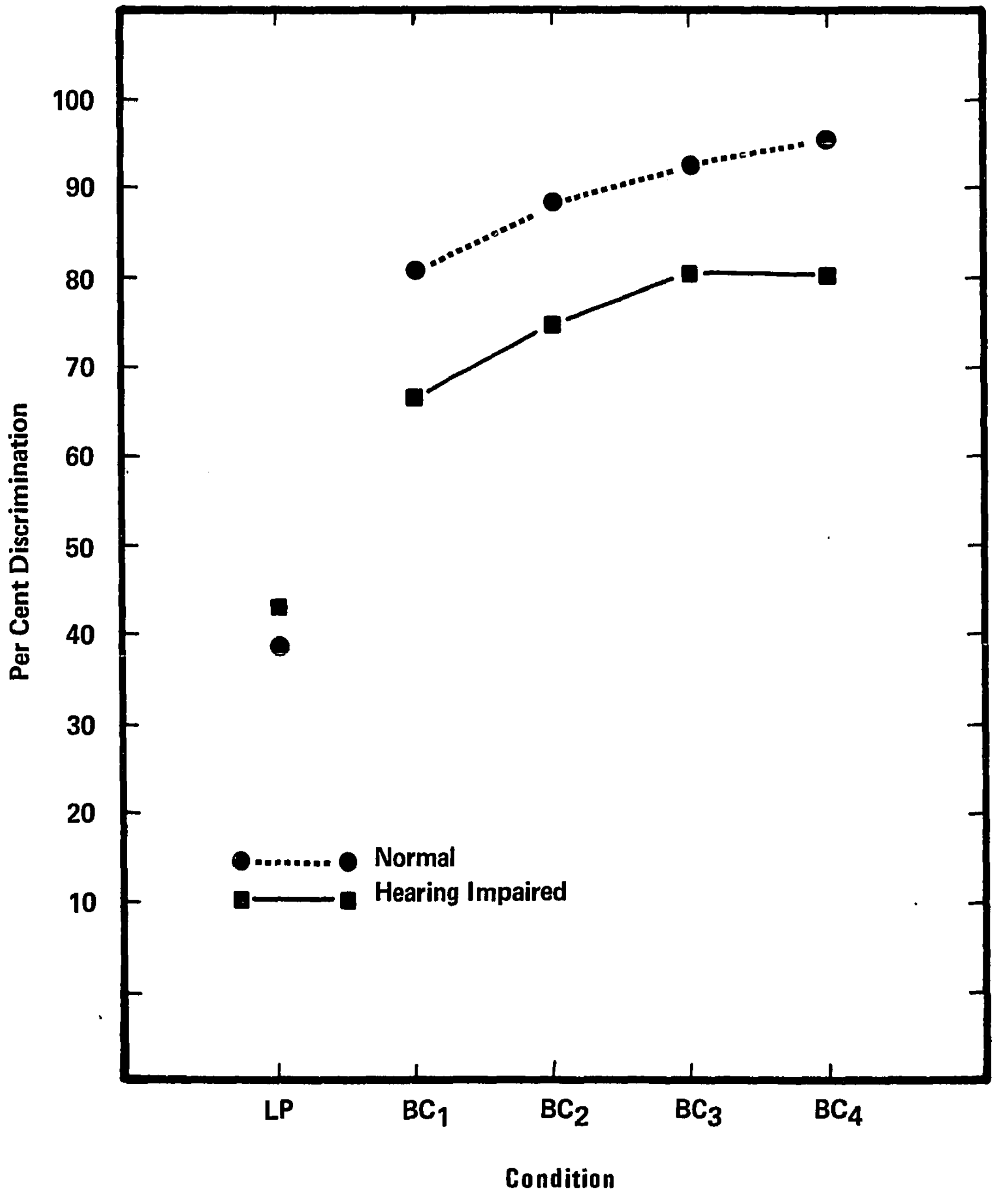


Fig. 5 – Discrimination scores for low-pass and band-combination conditions.

TABLE 3

MEANS, STANDARD DEVIATIONS, AND t-SCORES FOR NORMAL AND HEARING-IMPAIRED SUBJECTS ON THE BAND-COMBINATION CONDITIONS

	Condition				
	LP	BC_1	BC_2	BC_3	BC_4
Normals					
Mean	38.50	80.16	88.16	93.17	95.60
s.d.	11.82	10.97	9.55	3.46	4.34
Hearing-Impaired					
Mean	42.67	66.17	74.67	80.67	80.50
s.d.	9.20	4.63	6.05	11.45	18.51
Difference between the Means	4.17	13.99	13.49	2.50	15.10
t'-score	.97	4.07	4.11	3.62	2.75

t' required for .05 level of significance = 2.20

1.42 per cent/dB between BC_1 and BC_2, to 1.00 per cent/dB between BC_3 and BC_4, and then reversing to a 0.03 per cent/dB decrease between BC_3 and BC_4. Prediction of the score for BC_1 based on the summation of the LP performance (42.67 per cent) and the HP_1 score (25.17 per cent) is 67.83 per cent, whereas the actual performance was 66.17 per cent. A prediction of the BC_2 score on the basis of single bands is 78.00 per cent, while the obtained score was 74.67 per cent. The predicted scores for BC_3 and BC_4 approach 100 per cent. The observed discrimination scores for the hearing-impaired group approximate the predicted score at the lower two levels of the band-combination conditions, whereas the normal-hearing group exceeded their predicted score by 10 per cent.

Comparison of the performance of the two groups by a t-test revealed that they performed differently ($P < .05$) on each of the four BC conditions. Analysis of the performance curves with orthogonal polynomials revealed a significant F score ($P < .005$) only for Linear effects for each group. The observation that the improvement in performance of each group is less for each additional level of the high band is not supported by a significant F score for Quadratic effects also.

In summary, both groups had their maximum increase in performance between LP and BC_1, and then had smaller increases with added levels of the high band. The exception to this was the performance of the hearing-impaired group on condition BC_4 which exhibited a slight decrease compared to BC_3.

Inspection of the individual data in the hearing-impaired group revealed that some subjects continued to improve in performance at successive HP levels in the BC conditions, while others did not. The hearing-impaired group was divided into Subgroups I and II on this basis.

Subgroup I is composed of the seven subjects whose speech discrimination scores continued to improve as the level of the high band was raised in the BC conditions. The five subjects of Subgroup II did not continue to show improvement in performance at BC_4. (The results of the standard audiometric tests for Subgroups I and II are presented in Figure 6.)

Results of the Subgroups

Single Bands

The discrimination scores for the two subgroups on the four single-band conditions are presented in Table 4 and Figure 7. Table 4 shows that although the difference between the mean scores of the two subgroups on the LP condition is 8.2 per cent, this difference is not significant ($P > .05$).

The performance curve for Subgroup I presented in Figure 7 shows a continuing increase in performance as the level of the high band is raised. Maximum improvement in performance (a 3.52 per cent/dB increase) is between HP_2 and HP_3. Smaller increases occur between HP_1 and HP_2 and between HP_3 and HP_4 (1.95 and 1.33 per cent/dB respectively).

The discrimination ability of Subgroup II also improved as the level of the high band is increased. As with Subgroup I, maximum improvement in performance occurs between HP_2 and HP_3. The improvement, however, is less than that demonstrated by Subgroup I, being but 1.47 per cent/dB. Only 1.33 per cent/dB improvement occurs between HP_1 and HP_2 and 0.33 per cent/dB between HP_3 and HP_4.

Both subgroups perform similarly on the HP_1 condition, as de-

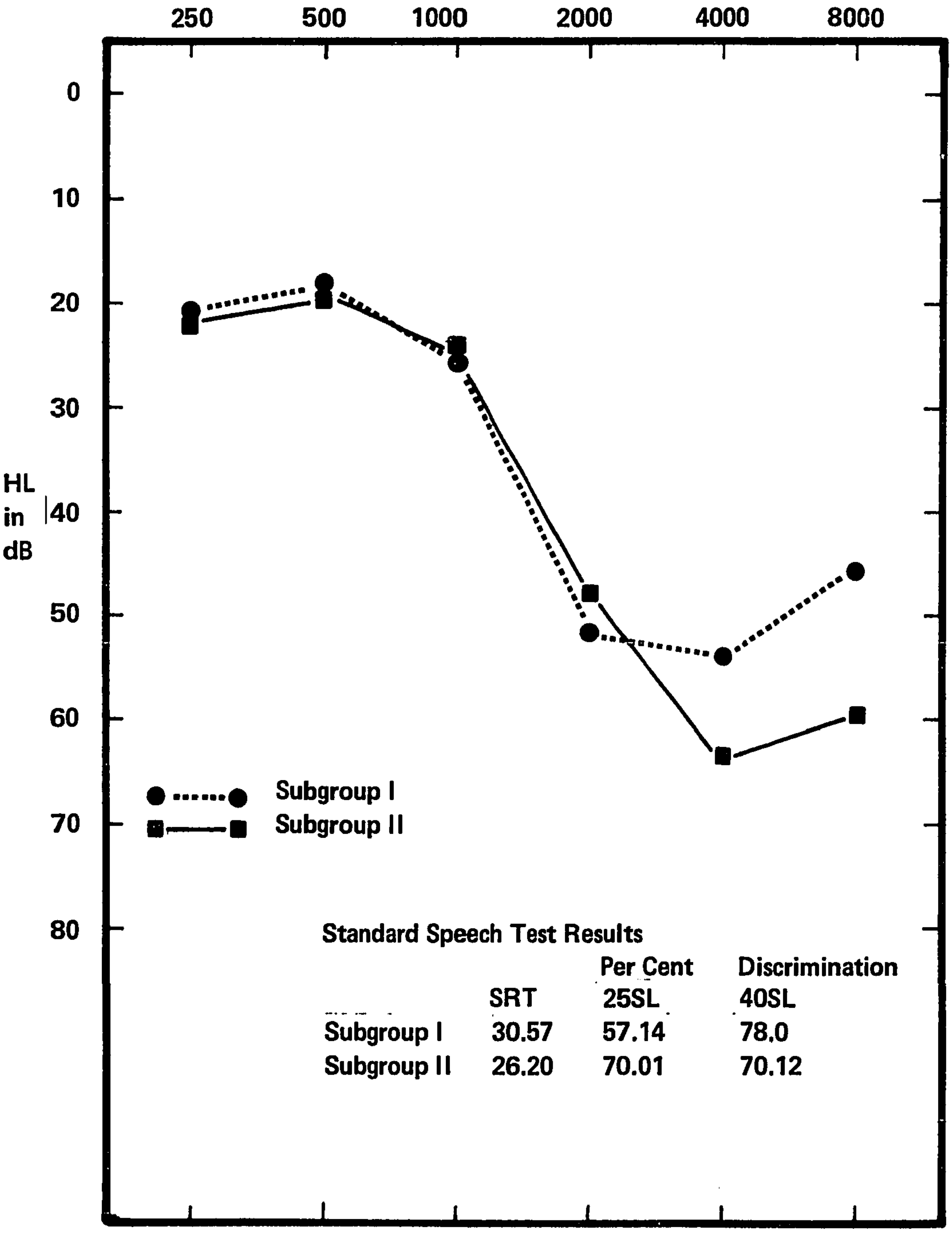


Fig. 6 – Mean pure-tone thresholds for test ear of subgroups I and II

TABLE 4

MEANS, STANDARD DEVIATIONS, AND t-SCORES FOR SUB-GROUPS I AND II ON THE SINGLE-BAND CONDITIONS

	Condition				
	LP	HP_1	HP_2	HP_3	HP_4
Sub-Group I					
Mean	39.40	26.29	38.00	59.14	67.14
s.d.	10.54	5.13	11.72	13.90	6.25
Sub-Group II					
Mean	47.60	23.60	31.60	40.40	42.40
s.d.	3.85	9.31	8.50	14.60	11.78
Difference between the Means	8.20	2.69	6.40	18.74	24.74
t'-score	1.89	.46	1.09	2.24	4.29
t' required for significance (.05)	2.50	2.62	2.59	2.65	2.72

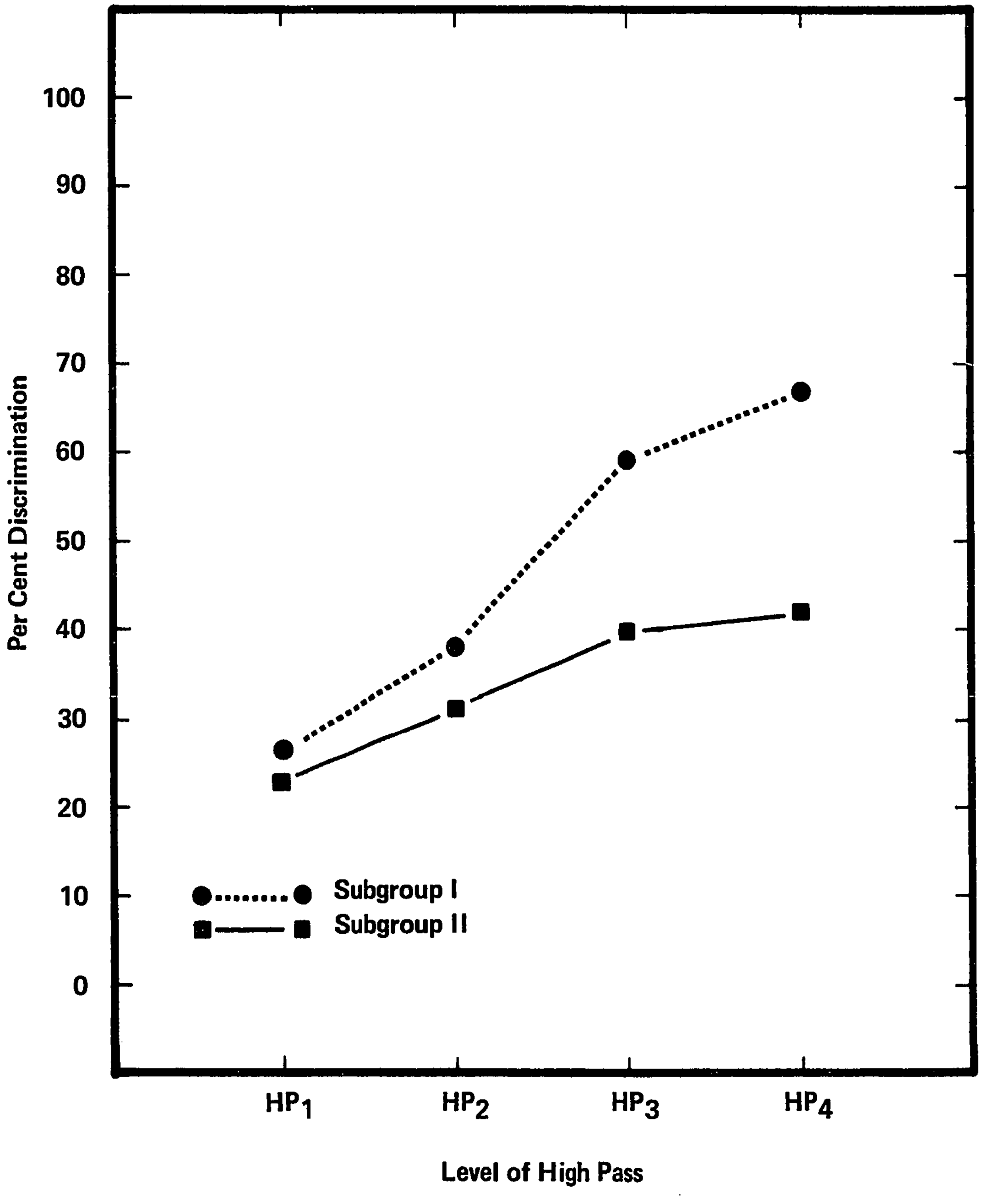


Fig. 7 – Discrimination scores for all levels of high-pass for subgroups I and II.

signed, and they show essentially the same amount of improvement between HP_1 and HP_2. They both show their greatest gain in performance between HP_2 and HP_3. Even though the performance of each subgroup improves with added intensity, the differences between subgroups increase at each successive level, reaching a maximum of about 25 per cent. Statistical analysis of the performance of the two subgroups indicates a statistically significant difference only for HP_4 ($P < .05$). Employing orthogonal polynomial comparisons, the performance of each subgroups may be described by a Linear function ($P < .005$).

Band-Combination Conditions

The data obtained from each subgroup on the BC conditions are presented in Table 5 and Figure 8. Inspection of Table 5 reveals that the greatest gain in discrimination score for each subgroup results from the addition of HP_1 to the LP band (i.e., the BC_1 condition). Increasing levels of HP continue to enhance the discrimination scores of subjects in Subgroup I although the gain is less than 2 per cent/dB. Subgroup II, on the other hand, represents those subjects whose discrimination scores decreased between BC_3 and BC_4. Increases for this subgroup from BC_1 through BC_3 are less than 1 per cent/dB.

With perfect summation of performance, based on the single band results (LP score plus HP score), the predicted scores for BC_1 are 66 per cent for Subgroup I and 70 per cent for Subgroup II. The actual scores obtained are 66.86 per cent and 65.20 per cent respectively. The predicted scores for BC_2 are 77 per cent for Subgroup I and 78 per cent for Subgroup II, compared to the obtained scores of 78 per cent and 70 per cent respectively. At the higher two levels of HP in combination

TABLE 5

MEANS, STANDARD DEVIATIONS, AND t-SCORES FOR SUB-GROUPS I AND II ON LP AND BAND-COMBINATION CONDITIONS

	Condition				
	LP	BC_1	BC_2	BC_3	BC_4
Sub-Group I					
Mean	39.40	66.86	78.00	85.71	92.57
s.d.	10.54	5.50	3.60	2.90	4.40
Sub-Group II					
Mean	47.60	65.20	70.00	73.60	63.60
s.d.	3.85	3.35	5.89	15.50	17.30
Difference between the Means	7.80	1.66	8.00	12.11	29.17
t'-score	1.89	.646	2.71	1.72	3.65
t' required for significance (.05)	2.50	2.56	2.70	2.77	2.76

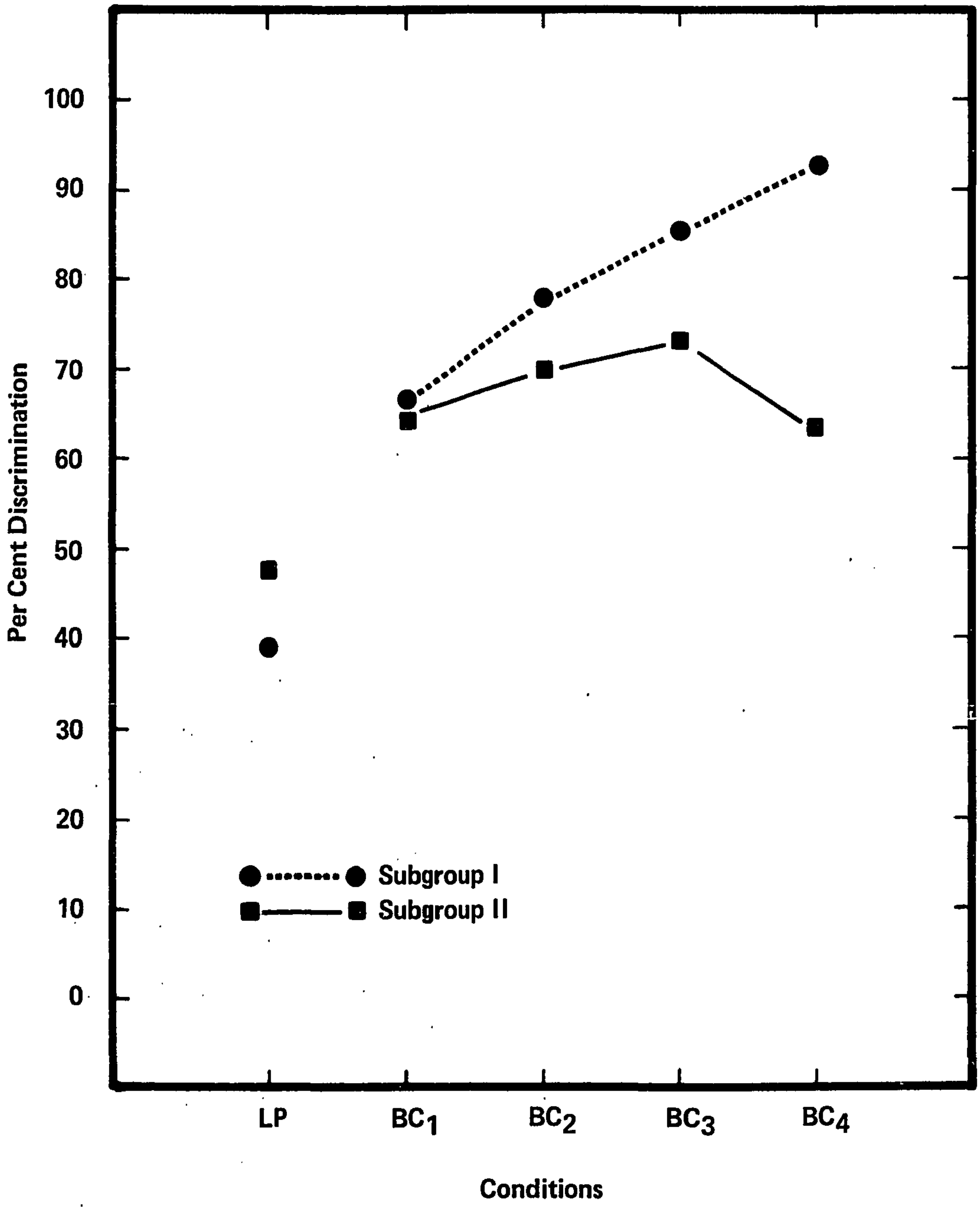


Fig. 8 – Discrimination scores for subgroups I and II on low-pass and band-combination conditions.

with LP, the obtained scores fall well below the predicted scores.

Statistical analysis comparing the performance of the two subgroups revealed that they performed differently ($P < .05$) at the BC_2 and BC_4 conditions. In Table 5 it is noted that the standard deviations for the higher two levels for Subgroup II are much larger than the other standard deviations yielded by that, or the other, subgroup. This variability may have prevented the observed 12 per cent difference between subgroups at BC_3 from being statistically significant. Examination of the curves for the BC conditions, using orthogonal polynomials, revealed a significant F score ($P < .005$) for a Linear effect for Subgroup I. Subgroup II had no significant F scores, but the largest value obtained was for Quadratic effects, the score falling slightly below significance at the $P < .05$ level. Again, the large variability observed under BC_3 and BC_4 probably preclude a significant Quadratic effect.

In summary, Subgroups I and II perform comparably on the LP and BC_1 conditions. On the next two levels of the BC conditions, both groups show improvement, but Subgroup I scores are higher at each level. At BC_4 Subgroup I continues to improve while Subgroup II had a sizeable decrease in performance.

Relationship of Discrimination Scores and Presentation Levels

In the following paragraphs the discrimination scores obtained from the normal and hearing-impaired groups under the preliminary and experimental procedures will be compared. The relationship between discrimination score and presentation level will also be discussed.

Table 6 displays the mean SPLs used in the presentation of the

TABLE 6

MEAN SOUND PRESSURE LEVELS (IN dB) USED IN THE PRESENTATION OF FILTERED WORDS FROM N.U. AUDITORY TEST NO. 6

	LP	HP_1	HP_2	HP_3	HP_4
Normals	36.00	16.67	22.67	28.67	34.67
Hearing-Impaired	51.00	56.67	62.67	68.67	74.67
Sub-Group I	49.30	52.00	58.00	64.00	70.00
Sub-Group II	53.20	63.20	69.20	75.20	81.20

filtered speech material. The SPLs reported for the band-combination conditions were calculated employing the values in Table 6. The SPLs to be reported for the standard audiometric procedures are interpolated from the mean SRTs found in Figures 1 and 6.

It will be recalled that the normal-hearing group achieved near-perfect discrimination scores at 40 dB SL on the standard audiometric procedures. Although not specifically examined in this study, it is not unreasonable to expect the discrimination scores of the normal-hearing group at 25 dB SL to approximate the observed scores at 40 dB SL.

Even though the SPL at HP_4 (34.67 dB) is approximately 30 dB less than the SPL used in full-fidelity testing, a discrimination score of 84 per cent was obtained. The scores obtained under the BC_3 (93.17 per cent) and BC_4 (95.60 per cent) conditions approach perfection. The sums of the SPLs in the LP and HP bands for these two conditions were 36.7 dB and 38.3 dB, respectively. These levels are more than 10 dB fainter than the SPL associated with a 25 dB SL presentation level at which comparable discrimination scores could be expected.

In the preliminary testing, hearing-impaired subjects achieved a mean full-fidelity discrimination score of 59.8 per cent at 25 dB SL, improving to 71.8 per cent at 40 dB SL. They achieved a mean discrimination score of 56.8 per cent under the HP_4 condition. The SPLs associated with the 25 dB SL and HP_4 conditions were 75 and 74.67 dB, respectively. Thus, essentially equivalent discrimination scores were obtained at comparable SPLs, despite the fact that one was a full-fidelity presentation and the other was limited to only the frequencies above 2000 Hz. At BC_3 and BC_4 they obtained mean scores of 80.7 and 80.5 per cent, respectively, surpassing their 40 dB SL performance by 9 per cent.

The SPLs at which BC_3 and BC_4 were presented were 21 and 16 dB, respectively, below the SPL of the standard 40 dB SL full-fidelity mean discrimination test material.

Similar comparisons on Subgroup I revealed mean discrimination scores of 57.14 per cent and 78 per cent at 25 and 40 dB SL, respectively. The SPLs associated with these SLs averaged 76 and 91 dB. The HP_4 condition, presented at 70 dB SPL, allowed a discrimination score of 67.14 per cent. Thus, the latter condition, although presented at a SPL 6 dB less than the full-fidelity 25 dB SL preliminary test, resulted in 10 per cent better discrimination scores. The higher two levels of the band-combination conditions (BC_3 and BC_4) allowed discrimination scores of eight and fifteen per cent above the better full-fidelity response scores, although the SPLs were 27 and 21 dB less than the presentation level of the 40-dB SL discrimination test.

Subgroup II achieved discrimination scores of 70.8 and 71.2 per cent at 25 and 40 dB SL, respectively. These scores were obtained at SPLs of 74 and 89 dB. The HP_4 condition, presented at 81.2 dB SPL, allowed a mean score of only 42.4 per cent. Combining the LP band with HP_4, resulting in the same SPL as HP_4 alone, raised the discrimination score to 63.6 per cent. With a 6 dB decrease in the HP band (BC_3), performance improves by 10 per cent. Maximum performance with the limited-frequency band condition is but slightly better than the full-fidelity scores.

As shown in the preceeding paragraphs, some of the mean discrimination scores obtained under the frequency-limited conditions in this study surpassed those obtained under the full-fidelity presentations in the preliminary testing. There are several possible explanations for this behavior, but insufficient information is available at this time to present the most likely explanation.

Although the SRTs for the two subgroups are equivalent, Subgroup I achieved a mean discrimination score of 57.14 per cent at 25 dB SL, while Subgroup II scored 70.80 per cent at this level. Increasing the SL to 40 dB allowed Subgroup I to achieve a discrimination score of 78.0 per cent, while Subgroup II had no change in their score.

Although the design of the study required the two subgroups to perform comparably at the HP_1 condition, Subgroup II required 11 dB greater SPL to achieve performance comparable with Subgroup I. This 11 dB difference is, of course, maintained for all HP and BC conditions. Inspection of Figure 6 reveals that Subgroup II has approximately 10 dB poorer hearing at the frequencies above 2000 Hz than Subgroup I.

Inspection of Table 4 reveals that the observed difference of 8.2 per cent between the two subgroups performance on the LP condition is not significant. The better score of Subgroup II was obtained with an SPL 4 dB greater than the level required by Subgroup I. If the discrimination scores obtained in the BC conditions are expressed as per cent of improvement over the LP band performance alone, the differences between subgroups in their ability to use high frequencies become even more evident (see Figure 9). The ability of Subgroup I to utilize higher levels of the HP bands approaches that of the normals. The best performance of Subgroup II (BC_3), as displayed in Figure 9, is slightly poorer than the performance of Subgroup I at BC_1. Furthermore, the performance of Subgroup II (as expressed in Figure 9) at the highest level (BC_4) is no better than their performance under BC_1.

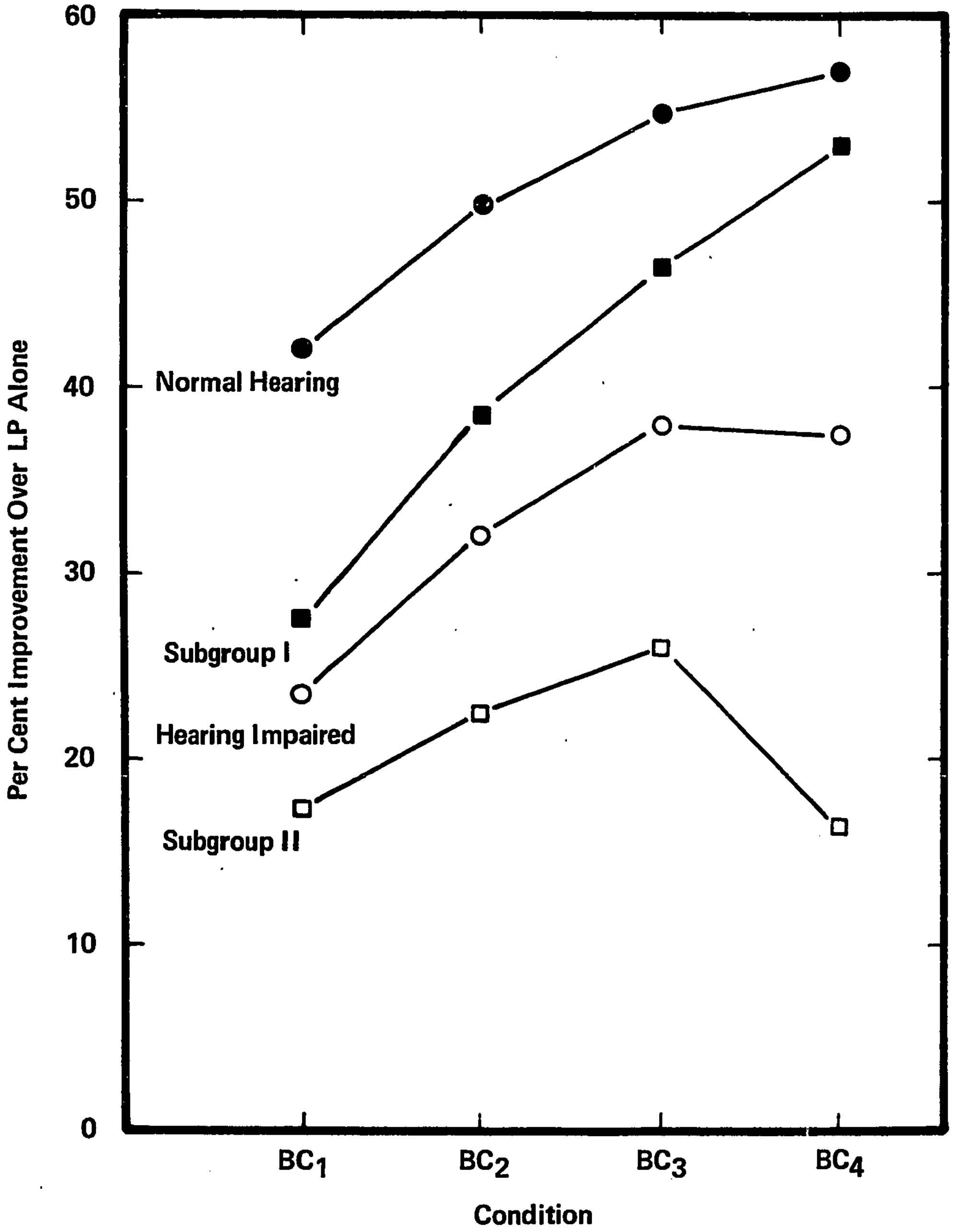


Fig. 9 – Mean difference in discrimination scores between BC conditions and LP conditions alone for each group and each subgroup.

Conclusions

The limited-frequency-band speech discrimination conditions employed in this study dichotomized subjects with a sensorineural hearing loss into two subgroups.

Subgroup I was able to utilize increasing levels of high-frequency speech sounds in combination with a low-level, low-frequency band. Using limited-frequency bands, this subgroup was able to surpass their full-fidelity discrimination performance. Subgroup II is characterized by an inability to continue to improve their discrimination scores with increasing levels of the HP band in combination with the LP band. The highest level of the HP band, in combination with the LP band, was detrimental to their speech discrimination ability.

Inspection of the clinical records of the subjects in the hearing-impaired group as to age, etiology, age of onset, etc. did not yield any information which would explain the differences in performance of the two subgroups on the band-limited speech tasks. Thus, the only observed differences between Subgroups I and II, other than their performance on the experimental conditions, are:

(1) The mean discrimination score of Subgroup I was approximately 13 per cent poorer than that of Subgroup II at 25 dB SL.

(2) Subgroup I demonstrated a mean improvement in discrimination score of approximately 21 per cent when the SL was increased from 25 dB to 40 dB, whereas Subgroup II did not show any improvement.

(3) Subgroup I exhibited essentially no greater loss at 4000 Hz than at 2000 Hz, while Subgroup II demonstrated a 17 dB greater loss at 4000 Hz than at 2000 Hz.

It would appear that the BC conditions used in this study are a more sensitive indicant of the ability to utilize higher frequencies in a speech discrimination task than are the HP filtering conditions alone. Before conclusions can be drawn concerning the clinical applicability of these BC conditions, it will be necessary to evaluate a large number of potential hearing aid users employing full-fidelity speech discrimination testing at 25 and 40 dB SL and the band-combination conditions devised for this study. The results of these different speech tests should then be correlated with relative success with hearing aids of varying frequency response characteristics.

CHAPTER V

SUMMARY

The purpose of the present investigation was to evaluate the limited-frequency band speech discrimination ability of normal and hearing-impaired subjects. Filtered speech discrimination scores were obtained from twelve normal-hearing subjects and twelve subjects with sloping high-frequency, sensorineural hearing losses. Each subject listened to 50-word lists of NU Auditory Test No. 6 under nine different conditions of filtering and intensity. These included a low-pass 1000 Hz band at a single intensity level, four levels of a high-pass 2000 Hz band, and four conditions with the high- and low-pass bands combined. The performance of all subjects was equated on the low-pass band and the low level of the high band by manipulation of the intensity levels prior to presentation of the experimental conditions. In this way it was possible to observe the use subjects made of increasing levels of a high-frequency band alone and in combination with the low band.

The major findings were as follows. Normal-hearing subjects were able to obtain essentially normal discrimination scores with the high level of the high band alone. With the two higher levels of the high-frequency band in combination with the low band, they were able to achieve nearly perfect discrimination scores.

The hearing-impaired subjects were able to profit from increasing levels of the high-frequency band alone, but fell below the performance levels of the normal-hearing subjects. This was also true for the band-combination conditions, where the hearing-impaired subjects were able to attain a score approximately five per cent better at the highest level of the combined bands as they did under the full-fidelity 40 dB SL speech test.

The hearing-impaired subjects were subgrouped on the basis of their performance under the band-combination conditions. Subgroup I subjects continued to show improvement in scores as the level of the high band was increased in the band-combination conditions. The subjects of Subgroup II improved in performance with increases in the level of the high band in combination, but at the highest level they had a decrease in discrimination score.

Comparison of the performance of the two subgroups on the high band alone revealed that they both had improved performance as the level was raised, but the performance of Subgroup I was superior at each level.

The performance of the two subgroups was even more divergent under the band-combination conditions. Subgroup I not only had improved performance as the level of the high band was raised, but they were able to achieve a mean discrimination score well within normal limits at the highest level of the band-combination conditions (92.57 per cent).

Subgroup II, on the other hand, achieved a maximum discrimination score on the band-combination conditions that was approximately the same as their better full-fidelity mean discrimination score. This was obtained at the next to highest level of the high band in combination with the low band. At the highest level of the combined bands their performance regressed by 10 per cent.

On the basis of the performance of the two subgroups on the band-combination conditions, it was suggested that this type of task may be useful clinically in predicting the ability of a potential hearing aid user to profit from a hearing aid with a high-frequency emphasis.

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APPENDICES

Appendix A

Normal and Hearing-Impaired Subject Identification and Audiometric Data

TABLE 7

NORMAL-HEARING SUBJECT IDENTIFICATION AND AUDIOMETRIC DATA

Sub-ject	Sex	Age	Pure Tone Thresholds 250	500	1000	2000	4000	8000	SRT	Per Cent Discrimination at 40 SL
MM	M	27	10	10	10	10	15	0	8	92
PC	F	25	0	0	0	0	0	0	2	96
JT	M	25	10	10	0	5	15	10	6	96
DN	F	25	0	0	0	0	0	0	0	100
DS	M	24	0	0	0	0	0	0	2	96
BP	M	29	0	0	0	0	0	0	2	98
MF	F	21	10	10	10	0	0	0	0	100
LT	F	25	5	0	0	0	0	0	2	100
BM	M	29	5	0	0	5	10	15	4	98
JB	F	18	0	0	0	0	0	0	0	98
FD	F	18	0	0	0	0	0	0	0	92
JS	F	30	0	0	0	0	0	0	0	98

TABLE 8

HEARING-IMPAIRED SUBJECT IDENTIFICATION AND AUDIOMETRIC DATA

Subject	Sex	Age	Pure Tone Thresholds 250	500	1000	2000	4000	8000	SRT	Per Cent Discrimination at 25 SL	40 SL
(II) RS	M	25	20	20	45	50	45	40	44	64	72
(I) RG	M	64	15	15	20	50	50	50	26	72	80
(I) PF	M	34	20	10	15	75	45	20	8	32	64
(I) TW	M	40	30	30	40	60	60	45	40	44	82
(I) HW	M	59	30	25	25	40	45	50	32	68	76
(I) JR	M	75	25	20	35	45	65	55	38	40	44
(II) JF	M	64	20	15	10	40	70	70	12	76	72
(II) VS	M	48	20	10	15	40	75	60	15	72	68
(II) WT	M	58	5	5	5	50	70	55	10	60	60
(I) RR	M	53	5	5	15	35	55	40	22	52	80
(I) DR	F	69	20	20	40	60	70	65	35	56	80
(II) TD	M	59	50	45	55	60	65	75	54	82	84

Appendix B

Order of Presentation of Lists and Conditions

TABLE 9

ORDER OF PRESENTATION OF LISTS AND CONDITIONS

	Subject Number											
	1	2	3	4	5	6	7	8	9	10	11	12
Phase I	1-2a	2-3a	5-4a	1-4b	2-3b	5-2b	1-3c	2-2c	5-4c	1-4d	2-2d	5-3d
Conditions	2-3a	5-4a	1-2b	2-2c	5-4b	1-3b	2-4c	5-3c	1-2d	2-2a	5-3d	1-4d
and Lists	5-4a	1-2b	2-3b	5-3c	1-2c	2-4b	5-2d	1-4c	2-3d	5-3a	1-4d	2-2a
	9-2b	6-3b	8-4b	6-4c	1-3c	5-2c	3-3d	2-2d	4-4d	7-4a	9-2a	6-3a
	4-3b	8-4b	4-2c	9-2d	3-4c	2-3c	6-4d	7-3d	1-2a	5-2b	8-3a	9-4a
	3-4b	5-2c	3-3c	8-3d	2-2d	7-4c	9-2a	6-4d	5-3a	8-3b	3-4a	4-2b
Phase II	7-2c	9-3c	7-4c	5-4d	6-3d	4-2d	8-3a	3-2a	9-4a	2-4b	4-2b	1-3b
Conditions	6-3c	2-4c	1-2d	7-2a	4-4d	9-3d	5-4a	8-3a	3-2b	1-2c	6-3b	2-4b
and Lists	5-4c	7-2d	2-3d	4-3a	9-2a	3-4d	1-2b	5-4a	6-3b	9-3c	7-4b	8-2c
	8-2d	1-3d	9-4d	3-4a	7-3a	6-2a	2-3b	4-2b	2-4b	4-4c	5-2c	3-3c
	1-3d	4-4d	6-2a	2-2b	5-4a	8-3c	7-4b	1-3b	8-2c	3-2d	2-3c	5-4c
	2-4d	3-2a	5-3a	1-3b	8-2b	1-4a	4-2c	9-4b	7-3c	6-3d	1-4c	7-2d

	No.	Condition	No.	Condition	No.	Condition
	1	LP	4	HP_3	7	BC_2
KEY	2	HP_1	5	HP_4	8	BC_3
	3	HP_2	6	BC_1	9	BC_4

Appendix C

Raw Data for Normal and Hearing-Impaired
Subjects in Phases I and II

TABLE 10

PHASE I RAW DATA FOR NORMAL AND HEARING-IMPAIRED SUBJECTS

Normals			Hearing-Impaired		
LP	HP_1	HP_4	LP	HP_1	HP_4
24	12	64	32	6	12
32	12	86	22	8	70
40	24	78	16	24	70
48	24	70	30	16	66
20	14	84	28	10	60
26	34	78	36	12	62
40	28	64	40	10	42
24	32	68	42	14	36
28	22	80	38	14	50
28	22	80	48	20	62
18	22	74	32	14	52
48	14	64	46	18	46

TABLE 11

RAW SCORES FOR NORMAL-HEARING SUBJECTS

Subject No.	Condition								
	L	H_1	H_2	H_3	H_4	BC_1	BC_2	BC_3	BC_4
1	42	28	56	36	76	80	84	86	98
2	48	54	68	94	76	82	90	96	96
3	42	26	46	72	94	88	98	98	100
4	52	56	84	76	94	96	94	92	100
5	20	18	68	84	86	52	64	92	92
6	46	36	68	80	82	84	94	94	94
7	48	20	52	80	86	88	98	96	94
8	30	44	70	80	92	76	86	90	96
9	26	40	60	74	82	76	96	96	100
10	30	22	68	90	78	78	80	92	100
11	24	22	68	74	86	88	86	96	86
12	54	20	58	72	78	74	88	90	92

TABLE 12

RAW SCORES FOR HEARING-IMPAIRED SUBJECTS

Subject	Condition								
	L	H_1	H_2	H_3	H_4	BC_1	BC_2	BC_3	BC_4
1	52	40	32	22	22	68	60	48	36
2	42	50	20	80	68	76	80	88	98
3	18	30	46	66	78	66	84	86	92
4	40	20	54	60	62	68	78	86	88
5	36	22	38	54	68	64	76	80	86
6	44	20	44	68	70	58	72	88	96
7	46	18	24	40	46	68	74	78	66
8	48	18	28	48	44	66	70	78	68
9	42	22	28	32	52	60	72	74	64
10	52	22	38	48	66	70	78	88	96
11	42	20	26	38	58	66	78	84	92
12	50	20	46	60	48	64	74	90	84

Appendix D

Statistical Analyses

TABLE 13

F-SCORES FROM THE ORTHOGONAL POLYNOMIAL ANALYSIS OF THE PERFORMANCE OF NORMAL AND HEARING-IMPAIRED SUBJECTS AND SUBGROUPS I AND II ON SINGLE BAND AND BAND-COMBINATION CONDITIONS

	F SCORE		
	Linear	Quadratic	Cubic
NORMALS			
High-Pass Conditions	163.52 **	15.97 **	1.87
HEARING-IMPAIRED			
High-Pass Conditions	54.85 **	<1	<1
NORMALS			
Band-Combination Conditions	43.64 **	2.5	<1
HEARING-IMPAIRED			
Band-Combination Conditions	19.34 **	3.25	<1
SUBGROUP I			
High-Pass Conditions	59.19 **	<1	<1
SUBGROUP II			
High-Pass Conditions	7.44 **	<1	<1
SUBGROUP I			
Band-Combination Conditions	173.21 **	1.07	<1
SUBGROUP II			
Band-Combination Conditions	<1	3.10	<1

* F significant at the .05 level
** F significant at the .005 level

TABLE 14

HIGH-PASS CONDITIONS FOR NORMAL-HEARING SUBJECTS

Subject	Filtering Condition HP_1	HP_2	HP_3	HP_4	Subject Totals
1	28	56	36	76	196
2	54	68	94	76	292
3	26	46	72	94	238
4	56	84	76	94	310
5	18	68	84	86	256
6	36	68	80	82	266
7	20	52	80	86	238
8	44	70	80	92	286
9	40	60	74	82	256
10	22	68	90	78	258
11	22	68	74	86	250
12	20	58	72	78	228
Treatment Totals	386	766	912	1010	3074

Effect	Filtering Condition and Discrimination Scores HP_1 386	HP_2 766	HP_3 912	HP_4 1010	Q	Kr	SS	F
Linear	-3	-1	+1	+3	2018	20(12)	16968.02	163.52
Quadratic	+1	-1	-1	+1	282	4(12)	1656.75	15.97
Cubic	-1	+3	-3	+1	226	20(12)	21.57	<1

Source	df	Analysis of Variance ss	ms
Subjects	11	2,570.92	233.72
Filtering	3	18,752.25	6,250.75
Error	32	3,320.75	103.77
Total	46	24,643.92	

TABLE 15

HIGH-PASS CONDITIONS FOR HEARING-IMPAIRED SUBJECTS

Subject	Filtering Condition HP_1	HP_2	HP_3	HP_4	Subject Totals
1	40	32	22	22	116
2	50	20	80	68	218
3	30	46	66	78	220
4	20	54	60	62	196
5	22	38	54	68	182
6	20	44	68	70	202
7	18	24	40	46	128
8	18	28	48	44	138
9	22	28	32	52	134
10	22	38	48	66	174
11	20	26	38	58	142
12	20	46	60	48	174
Treatment Totals	302	424	616	682	2024

Effect	Filtering Condition and Discrimination Scores HP_1 302	HP_2 424	HP_3 616	HP_4 682	Q	Kr	SS	F
Linear	−3	−1	+1	+3	1332	20(12)	7392.60	54.85
Quadratic	+1	−1	−1	+1	−56	4(12)	65.33	<1
Cubic	−1	+3	−3	+1	−196	20(12)	160.07	1.19

Analysis of Variance

Source	df	ss	ms
Subjects	11	3,635.67	330.52
Filtering	3	7,618.00	2,539.33
Error	32	4,313.00	134.78
Total	46	15,566.67	

TABLE 16

BAND-COMBINATION CONDITIONS FOR NORMAL-HEARING SUBJECTS

Subject	Filtering Condition BC_1	BC_2	BC_3	BC_4	Subject Totals
1	80	84	86	98	348
2	82	90	96	96	364
3	88	98	98	100	384
4	96	94	92	100	382
5	52	64	92	92	300
6	84	94	94	94	366
7	88	98	96	94	376
8	76	86	90	96	348
9	76	96	96	100	368
10	78	80	92	100	350
11	88	86	96	86	356
12	74	88	90	92	344
Treatment Totals	962	1058	1118	1148	4286
Means	80.16	88.16	93.17	95.67	

Effect	Filtering Condition and Discrimination Scores BC_1 962	BC_2 1058	BC_3 1118	BC_4 1148	Q	Kr	SS	F
Linear	−3	−1	+1	+3	618	20(12)	1591.00	43.64
Quadratic	+1	−1	−1	+1	−66	4(12)	90.75	2.50
Cubic	−1	+3	−3	+1	6	20(12)	.15	<1

Source	df	Analysis of Variance ss	ms
Subjects	11	1,499.00	136.27
Filtering	3	1,682.25	560.75
Error	32	1,166.75	36.46
Total	46	4,348.00	

TABLE 17

BAND-COMBINATION CONDITIONS FOR HEARING-IMPAIRED SUBJECTS

Subject	Filtering Condition BC_1	BC_2	BC_3	BC_4	Subject Totals
1	68	60	48	36	212
2	76	80	88	98	342
3	66	84	86	92	328
4	68	78	86	88	320
5	64	76	80	86	306
6	58	72	88	96	314
7	68	74	78	66	286
8	66	70	78	68	282
9	60	72	74	64	270
10	70	78	88	96	332
11	66	78	84	92	320
12	64	74	90	84	312
Treatment Totals	794	896	968	996	3624
Means	66.17	74.67	80.67	80.50	

Effect	Filtering Condition and Discrimination Scores BC_1 794	BC_2 896	BC_3 968	BC_4 956	Q	Kr	SS	F
Linear	-3	-1	+1	+3	588	20(12)	1440.60	19.34
Quadratic	+1	-1	-1	+1	104	4(12)	225.30	3.25
Cubic	-1	+3	-3	+1	44	20(12)	8.06	.11

Source	Analysis of Variance df	ss	ms
Subjects	11	3,466	315.09
Filtering	3	1,674	558.00
Error	32	2,384	74.50
Total	46	7,524	

TABLE 18

HIGH-PASS CONDITIONS FOR SUBGROUP I

Subject	Filtering Condition HP_1	HP_2	HP_3	HP_4	Subject Totals
2	50	20	80	68	218
3	30	46	66	78	220
4	20	54	60	62	196
5	22	38	54	68	182
6	20	44	68	70	202
10	22	38	48	66	174
11	20	26	38	58	142
Treatment Totals	184	266	414	470	1334

Effect	Filtering Condition and Discrimination Scores HP_1 184	HP_2 266	HP_3 414	HP_4 470	Q	Kr	SS	F
Linear	−3	−1	+1	+3	1006	20(7)	7228.80	59.19
Quadratic	+1	−1	−1	+1	26	4(7)	24.14	<1
Cubic	−1	+3	−3	+1	158	20(7)	178.31	1.46

Source	df	Analysis of Variance ss	ms
Subjects	6	1,121.43	186.91
Filtering	3	7,431.29	2,477.10
Error	15	1,831.71	122.11
Total	26	10,384.43	

TABLE 19

HIGH-PASS CONDITIONS FOR SUBGROUP II

Subject	Filtering Condition HP_1	HP_2	HP_3	HP_4	Subject Totals
1	40	32	22	22	116
7	18	24	40	46	128
8	18	28	48	44	138
9	22	28	32	52	134
12	20	46	60	48	174
Treatment Totals	118	158	202	212	690

Effect	Filtering Condition and Discrimination Scores HP_1 118	HP_2 158	HP_3 202	HP_4 212	Q	Kr	SS	F
Linear	−3	−1	+1	+3	326	20(5)	1062.76	7.44
Quadratic	+1	−1	−1	+1	−30	4(5)	45.00	<1
Cubic	−1	+3	−3	+1	−38	20(5)	14.44	<1

Source	df	Analysis of Variance ss	ms
Subjects	4	474	118.50
Filtering	3	1,122	374.00
Error	11	1,571	142.80
Total	18	3,167	

TABLE 20

BAND-COMBINATION CONDITION FOR SUBGROUP I

Subject	Filtering Condition BC_1	BC_2	BC_3	BC_4	Subject Totals
2	76	80	88	98	342
3	66	84	86	92	328
4	68	78	86	88	320
5	64	76	80	86	306
6	58	72	88	96	314
10	70	78	88	96	332
11	66	78	84	92	320
Treatment Totals	468	546	600	648	2262

Effect	Filtering Condition and Discrimination Scores BC_1 468	BC_2 546	BC_3 600	BC_4 648	Q	Kr	SS	F
Linear	−3	−1	+1	+3	594	20(7)	2520.26	173.21
Quadratic	+1	−1	−1	+1	30	4(7)		1.07
Cubic	−1	+3	−3	+1	18	20(7)	2.31	<1

Source	df	Analysis of Variance ss	ms
Subjects	6	213.71	35.62
Filtering	3	2,554.71	851.57
Error	15	218.29	14.55
Total	26	2,986.71	

TABLE 21

BAND-COMBINATION CONDITIONS FOR SUBGROUP II

Subject	Filtering Condition BC_1	BC_2	BC_3	BC_4	Subject Totals
1	68	60	48	36	212
7	68	74	78	66	286
8	66	70	78	68	282
9	60	72	74	64	270
12	64	74	90	84	312
Treatment Totals	326	350	368	318	1362
Means	65.2	70.0	73.6	63.6	

Effect	Filtering Condition and Discrimination Scores BC_1 326	BC_2 350	BC_3 368	BC_4 318	Q	Kr	SS	F
Linear	−3	−1	+1	+3	6	20(5)	.36	<1
Quadratic	+1	−1	−1	+1	74	4(5)	273.80	3.097
Cubic	−1	+3	−3	+1	62	20(5)	54.76	<1

Source	df	Analysis of Variance ss	ms
Subjects	4	1,374.8	343.7
Filtering	3	312.6	104.2
Error	11	972.4	88.4
Total	18	2,659.8	