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Differential Effects of Low-Frequency Filtering of Speech on the Discriminatory Facility of Sensorineural Hypacusis

David Jenkins

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DIFFERENTIAL EFFECTS OF LOW-FREQUENCY FILTERING OF SPEECH ON THE DISCRIMINATORY FACILITY OF SENSORINEURAL HYPACUSIS

by

David Jenkins

A thesis submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE in

Communicative Disorders
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ABSTRACT

Differential Effects of Low-Frequency Filtering of Speech on the Discriminatory Facility of Sensorineural Hypacusis

by

David Jenkins, Master of Science

Utah State University, 1974

Major Professor: Dr. Steven H. Viehweg
Department: Communicative Disorders

A long-standing controversy concerning the pros and cons of selective amplification for the sensorineural hypacusic has been and is now being waged. There exists clinical evidence to the effect that some cases with high-frequency sensorineural hearing loss can receive benefit through selective amplification.

The purpose of this study was to examine several aspects of the speech signal that could be affecting intelligibility when speech is presented at high-intensity levels.
CHAPTER I

INTRODUCTION

The individual with high-frequency sensorineural hearing impairment often demonstrates the following results during routine audiometric testing: (a) relatively normal sensitivity to pure tones in the lower frequencies with a progressive reduction in pure tone sensitivity in the higher frequencies and (b) reduction in discriminatory capacity for speech as demonstrated by impaired speech discrimination scores. The fact that a major portion of the information of speech is carried by the high-frequency, low-intensity components of the speech signal could be an important consideration in understanding the reason for the sensorineural hypacusis’s reduced speech intelligibility. If an individual has a high-frequency hearing loss, the degree to which he can distinguish the low-energy, high-frequency consonants of speech may be significantly affected.

From the traditional point of view, the individual with high-frequency sensorineural hearing loss is capable of receiving but little benefit from mechanical amplification. A hearing aid with a flat frequency response may be inappropriate as an amplifying system for high-frequency sensorineural hypacusics for two reasons. First, when high-frequency sounds are amplified in accordance with the
degree of high-frequency hearing loss the lower frequencies are also amplified to the same degree. The result may be a speech signal that is subjectively too loud and, therefore, sufficiently annoying to the subject to warrant its discard. A second possible reason for the lack of success with hearing aids with a flat frequency response for persons with high-frequency sensorineural hypacusis might relate to a masking effect of the higher frequency components of speech by the more intense lower frequency components of speech. Since the higher frequencies contribute most to speech intelligibility, the speech signal would be negatively affected by an interfering masking component in these important frequencies.

Fletcher (1953) and Wegel and Lane (1924) have described a masking effect produced by one pure tone on another pure tone higher in frequency and have termed the effect spread of masking. The spread-of-masking phenomenon has been demonstrated in the normal ear and to a more pronounced degree in the sensorineural hypacusis (Jerger, Tillman, and Peterson, 1960; Rittmanic, 1962). French and Steinberg (1947, p. 90) described speech as "... a succession of sounds varying rapidly from instant to instant in intensity and frequency." When speech is analyzed over a long period of time, it may be seen that the integrated speech spectrum is characterized by greater energy in the low frequencies (French and Steinberg, 1947; Miller, 1947). Thus, in one sense speech may be considered as a
low-frequency noise. The vowel sounds of speech are, for the most part, characterized by a preponderance of energy in the frequency region below 1000 Hertz (Hz) (Denes and Pinson, 1963; French and Steinberg, 1947; Fletcher, 1953). Since the vowel sounds are relatively less important to the intelligibility of speech than are the higher frequency consonant sounds, it could be reasoned that amplification of vowel sounds might produce little additional information and might, in fact, produce a spread-of-masking effect on the higher frequency consonant sounds which are so vital to speech intelligibility, thus causing speech intelligibility to decrease. If these low-frequency sounds could be attenuated and the high-frequency sounds amplified, the spread-of-masking effect could possibly be reduced significantly with the sacrifice of relatively little intelligence carried in the low-frequency vowel sounds.

Much controversy has arisen regarding the benefits of selective amplification whereby the hearing aid is selected on the basis of a relationship between the hearing aid frequency characteristics and the patient’s audiogram. Menzel (1964) reported on two cases in which scores improved markedly from the fitting of a sloping 30 dB per octave hearing loss with a hearing aid having a rising frequency response of 15 dB per octave. Possibly the reduction in low-frequency energy alleviated an interfering spread-of-masking effect in the higher frequencies. Jeffers (1962) tested a group of seven high-
frequency sensorineural subjects with hearing aids which selectively amplified the higher tones and found that discrimination scores were better than scores obtained under phones of two high-fidelity speech audiometers. Lewis and Plotkin (1963) noted improved discrimination scores when 15 subjects were fitted with hearing aids coupled with venter ear molds which served to filter acoustically the low frequencies of the speech signal. The articulation scores of these subjects improved 19 percent, indicating the adverse effects of the amplified low frequencies on speech intelligibility. The findings of the above investigators indicated that at least for some high-frequency sensorineural hypacusics, low-frequency components served to affect negatively speech intelligibility.

In following the above line of reasoning, Viehweg (1968) examined the effects of various speech and noise filtering conditions with high-frequency sensorineural hypacusics. The results demonstrated no significant improvement in discrimination scores when low-frequency energy was removed from the speech signal. Viehweg used the term self-masking in his dissertation to refer to the possibility of the spread-of-masking effect in the speech signal. In testing the hypothesis that self-masking was existent in the speech signal, Viehweg used subjects with high-frequency sensorineural hearing loss. Wide band noise was employed to lower each subject's discrimination score so that any changes in discrimination scores
due to the experimental conditions would be more readily observable. Self-masking was demonstrated to be not responsible for the improved phonemic discriminatory performance that some high-frequency sensorineural hypacusics experienced with selective amplification. The possibility was considered that the effects of self-masking might not have been readily observable because of the utilization of noise in the experiment for the purpose of reducing the discrimination scores of the experimental subjects. Although the noise was sharply filtered in many of the experimental conditions, noise in the 1000 Hz frequency region was present in all listening conditions. The present investigation was a partial replication and extension of Viehweg's work and employed as subjects high-frequency sensorineural hypacusics with low discrimination scores to eliminate the necessity of a wide band masking noise.

Specifically, the present study investigated the effect of self-masking (masking of high-frequency speech sounds by low-frequency speech sounds) on the discrimination scores of subjects suffering from high-frequency sensorineural hearing loss. The primary experimental hypothesis that guided the investigation stated that a significant improvement in the discrimination scores of the experimental subjects would be evidenced as a result of the filtering of low-frequency energy from the amplified speech signal. In the testing of this hypothesis monosyllabic words were administered to 20
subjects with high-frequency sensorineural hearing loss under four different test conditions. The first experimental condition involved no filtering and was used as a control or reference condition. The remaining three test conditions involved high-pass filtering of the speech signal at 600, 900, and 1200 Hz cutoff frequencies.

It was assumed that subjects who exhibited the greatest degree of spread of masking as demonstrated by pure tones would be the same subjects who would be most affected by self-masking. According to this line of reasoning a secondary or corollary hypothesis stated that a positive correlation would exist between the amount of spread of masking demonstrated with pure tones and the amount of improvement in discriminatory performance occurring as a result of the removal of low-frequency energy from the speech signal. In the testing of the corollary hypothesis a spread-of-masking index (SMI) was derived for each subject by introducing to the ear under test a narrow band noise centered at 250 Hz presented at 90 dB sound pressure level (SPL). A "masked" pure tone audiogram was obtained in the presence of the narrow band noise and compared to a pure tone audiogram obtained in the absence of noise. The difference between these two thresholds at each octave frequency above 250 Hz was averaged and this value was designated as the SMI. The SMI for each subject was compared with the discrimination scores so that any relationship between self-masking by speech and spread of masking by pure tones could be observed.
In summary, it is known that individuals with high-frequency sensorineural hearing loss are characteristically affected to a greater extent by spread of masking at high intensities than are conductive loss or normal hearing populations. The hypothesis of the present investigation examined the possible relationship between spread of masking and reduced discrimination scores which also characterize high-frequency sensorineural hypacusis. It was anticipated that if the more intense but less contributory lower frequencies of speech were removed, the effects of self-masking would also be reduced, resulting in an improvement in discrimination. In the next chapter the literature which suggested that the hypothesis was a tenable one is reviewed in detail.
CHAPTER II

REVIEW OF RELATED LITERATURE

Individuals with high-frequency sensorineural hearing impairment often experience difficulty in communicating in everyday situations because of a lack of ability to understand speech. Since a major portion of the information of speech is carried in the higher frequencies, it is assumed that the discrimination ability of the sensorineural hypacusis is impaired, at least in part, because of reduced sensitivity for high-frequency elements of speech.

Through selective amplification by a hearing instrument, many high-frequency loss cases have received significant help and, in fact, have demonstrated improvement in discrimination scores. A substantial amount of information available regarding the issue of selective amplification has demonstrated that when low-frequency speech components are reduced in intensity and the high frequencies are amplified through a hearing aid, there is often significant improvement in the sensorineural hypacusis's discrimination score over that obtained with a hearing aid having a flat frequency response. A reduction in self-masking, resulting from the reduction of intensity of low-frequency speech components, could be a variable operating to produce the increased discriminatory facility. Therefore, the
experimental hypothesis of the present investigation stated that when
the lower frequency speech sounds are presented in unamplified form
and the higher frequency sounds are amplified and presented to
subjects with high-frequency hearing loss, the result would be an
improvement in discrimination ability as a consequence of decreased
self-masking.

The present chapter discusses specifically those factors which
made the above hypothesis a reasonable one. A thorough examina-
tion of the available literature pertinent to the development of the
hypothesis is reviewed under the following topics: (a) factors govern­
ing the intelligibility of speech, (b) effects of the spread-of-masking
phenomenon, and (c) clinical research regarding selective amplifica­
tion for high-frequency sensorineural impairment.

Factors Governing the Intelligibility of Speech

When two or more pure tones of different frequency and
intensity are combined, a waveform is produced which is different
from any of the component pure tone waveforms (Denes and Pinson,
1963; Stevens and House, 1963; Stevens and Davis, 1938). The
sounds of speech are in fact a mixture of individual pure tones which
have combined in different phase relationships to produce the sound
perceived as voice (Victoreen, 1960; Stevens and Davis, 1938). In
the following section, factors which produce variability in speech intelligibility will be discussed.

"Speech consists of a succession of sounds varying rapidly from instant to instant in intensity and frequency" (French and Steinberg, 1947, p. 90). "The intelligibility of the speech signal depends on its spectral characteristics and the level of interfering noise in which it is immersed" (Black, 1952, p. 412).

One approach in examining the spectral characteristics of speech is through the method involved in obtaining the "long-term average speech spectrum" (Dunn and White, 1940). The long-term average speech spectrum is determined by taking intensity measurements from conversational speech in a series of discrete frequency bands and plotting the average spectral values graphically. The graphical representation of the long-term average speech spectrum shown in Figure 1 emphasizes the fact that the greatest amount of energy in the speech signal lies in the lower frequencies. Denes and Pinson (1963) reported that the range of the most intense frequencies is between 100 and 600 Hz. Fletcher (1953) and French and Steinberg (1947) stated that more than one third of the power of the human voice exists in the frequency range between 250 and 500 Hz. The overall intensity level of conversational speech ranges from 65 dB SPL to 75 dB SPL (French and Steinberg, 1947; Kryter, 1956; Denes and Pinson, 1963).
Figure 1. Idealized long-term average speech spectrum at one meter from the lips in a sound field free from reflection (French and Steinberg, 1947, p. 94).
The frequency characteristics of each individual speech sound or phoneme are also of interest when considering the acoustical characteristics of speech. Traditionally, the speech sounds are classified as either vowels or consonants. The vowels of speech are voiced and relatively more sustained. When the shape and movement of the articulators are changed, various cavity and tube resonances are established which reinforce certain frequencies and subdue others. These reinforced regions of resonance are known as formant frequencies. Each vowel sound shown in Table 1 has a characteristic energy pattern or formant band relationship. Most of the acoustical energy of these vowels is in the lower frequencies and, therefore, the vowels are essentially low-frequency sounds (Denes and Pinson, 1963; Saltzman, 1949).

Through experiments with speech it has been found that formants below 250 Hz contribute little to vowel recognition (Saltzman, 1949). Denes and Pinson (1963, p. 116) stated, "The energy (for speech) is the greatest in the 100 to 600 Hz region which includes both the fundamental component of the speech wave and the first formant." However, the formants which contribute the most to vowel recognition are believed to be in the 1500 to 2500 Hz frequency range (Castle, 1963). Table 1 shows that for the most part the second and third formants, $F_2$ and $F_3$, lie within this latter range. These higher frequency elements supposedly contribute relatively more to vowel
Table 1. Median frequencies of vowel formants in Hz and median amplitudes of vowel formants in dB (Holbrook and Fairbanks, 1962, p. 42)

<table>
<thead>
<tr>
<th>Vowel</th>
<th>F₀</th>
<th>F₁</th>
<th>F₂</th>
<th>F₃</th>
<th>A₀</th>
<th>A₁</th>
<th>A₂</th>
<th>A₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>/i/</td>
<td>120</td>
<td>272</td>
<td>2312</td>
<td>2940</td>
<td>40</td>
<td>41</td>
<td>20</td>
<td>18</td>
</tr>
<tr>
<td>/I/</td>
<td>120</td>
<td>422</td>
<td>2025</td>
<td>2710</td>
<td>40</td>
<td>40</td>
<td>25</td>
<td>22</td>
</tr>
<tr>
<td>/ɛ/</td>
<td>125</td>
<td>520</td>
<td>1425</td>
<td>2610</td>
<td>40</td>
<td>40</td>
<td>26</td>
<td>23</td>
</tr>
<tr>
<td>/æ/</td>
<td>112</td>
<td>592</td>
<td>1955</td>
<td>2615</td>
<td>38</td>
<td>37</td>
<td>28</td>
<td>24</td>
</tr>
<tr>
<td>/a/</td>
<td>125</td>
<td>752</td>
<td>1245</td>
<td>2500</td>
<td>38</td>
<td>38</td>
<td>30</td>
<td>16</td>
</tr>
<tr>
<td>/ɔ/</td>
<td>135</td>
<td>630</td>
<td>902</td>
<td>2580</td>
<td>36</td>
<td>40</td>
<td>33</td>
<td>12</td>
</tr>
<tr>
<td>/U/</td>
<td>130</td>
<td>465</td>
<td>1192</td>
<td>2385</td>
<td>39</td>
<td>42</td>
<td>23</td>
<td>14</td>
</tr>
<tr>
<td>/u/</td>
<td>135</td>
<td>342</td>
<td>940</td>
<td>2302</td>
<td>40</td>
<td>41</td>
<td>20</td>
<td>8</td>
</tr>
<tr>
<td>/ʌ/</td>
<td>120</td>
<td>630</td>
<td>1322</td>
<td>2600</td>
<td>38</td>
<td>41</td>
<td>26</td>
<td>16</td>
</tr>
<tr>
<td>/ʃ/</td>
<td>125</td>
<td>475</td>
<td>1310</td>
<td>1650</td>
<td>38</td>
<td>41</td>
<td>26</td>
<td>20</td>
</tr>
</tbody>
</table>
intelligibility and also aid in the identification of the consonant which precedes or follows the vowel. These cues derive from the relative position of \( F_2 \) and \( F_3 \) as well as from the direction of the \( F_2 \) and \( F_3 \) transition (Delattre, Liberman, and Cooper, 1955; Denes and Pinson, 1963; Stevens and Davis, 1938). Thus, it can be suggested that removal or filtering of low-frequency elements from vowel sounds may be accomplished without significant sacrifice to vowel intelligibility.

The consonant sounds contain acoustic energy spread over a wide range of frequencies and are not characterized by specific formant frequencies. Table 2 illustrates that most of the power of the consonants appears above 1000 Hz. Miller (1951) and Hirsh (1952) agreed that the consonants are represented in the higher frequencies and that they are responsible for a major portion of the intelligibility carried by English words.

Fletcher (1929) found that when speech was high-pass filtered at 500 Hz, 60 percent of the energy was deleted with only a concomitant 2 percent decrease in discrimination. Conversely, if the filter was set to low-pass all speech frequencies below 1500 Hz, only 10 percent of the acoustic energy was removed but with a 35 percent sacrifice of speech intelligibility. These results indicated that the high frequencies carry a majority of the intelligibility of the speech signal and that the low-frequency speech sounds carry the majority
Table 2. Frequency range and regions of resonance at which the majority of acoustical energy exists for consonant sounds (Saltzman, 1949, p. 211)

<table>
<thead>
<tr>
<th>Consonant</th>
<th>Most energy at:</th>
<th>Other regions of resonance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Low</td>
</tr>
<tr>
<td>b</td>
<td>1500-2000</td>
<td>700</td>
</tr>
<tr>
<td>d</td>
<td>1500-3000</td>
<td>500</td>
</tr>
<tr>
<td>f</td>
<td>1500-3500</td>
<td>500</td>
</tr>
<tr>
<td>g</td>
<td>1500-3000</td>
<td>550</td>
</tr>
<tr>
<td>h</td>
<td>600-2000</td>
<td>500</td>
</tr>
<tr>
<td>j</td>
<td>1000-3000</td>
<td>450</td>
</tr>
<tr>
<td>k</td>
<td>2500-3000</td>
<td>1200</td>
</tr>
<tr>
<td>i</td>
<td>500-1000</td>
<td>250</td>
</tr>
<tr>
<td>m</td>
<td>500-1500</td>
<td>250</td>
</tr>
<tr>
<td>n</td>
<td>650-2000</td>
<td>200</td>
</tr>
<tr>
<td>p</td>
<td>1500-3000</td>
<td>900</td>
</tr>
<tr>
<td>r</td>
<td>500-1500</td>
<td></td>
</tr>
<tr>
<td>s</td>
<td>3500-6000</td>
<td>500</td>
</tr>
<tr>
<td>t</td>
<td>1000-4000</td>
<td>900</td>
</tr>
<tr>
<td>v</td>
<td>100-3000</td>
<td>600</td>
</tr>
<tr>
<td>w</td>
<td>500-1250</td>
<td></td>
</tr>
<tr>
<td>j</td>
<td>500-1500</td>
<td></td>
</tr>
<tr>
<td>z</td>
<td>500-6000</td>
<td>400</td>
</tr>
<tr>
<td>ch</td>
<td>1000-3000</td>
<td>500</td>
</tr>
<tr>
<td>ng</td>
<td>500-1500</td>
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</tr>
<tr>
<td>sh</td>
<td>1000-2500</td>
<td>450</td>
</tr>
<tr>
<td>th</td>
<td>1500-3200</td>
<td>600</td>
</tr>
</tbody>
</table>
of the energy of speech. Other data also suggest that a relatively
greater amount of information is carried by frequencies above 1000
Hz. For example, a computational procedure called the articulation
index (AI) involved the selection of 20 frequency bandwidths between
200 and 6100 Hz, each of which contribute equally to speech percep-
tion. The importance of French and Steinberg's (1947) data to the
present study is to be found in the location of the 20 equally contrib-
uting bands on the speech spectrum. Only six of the 20 equally
contributing bandwidths are located in the frequency region below
1000 Hz. This value indicates that more than two thirds of the
information in the speech spectrum is carried by frequencies above
1000 Hz.

Pollack (1948) presented phonetically balanced (PB) 50-word
lists to normal listeners in background noise. By developing articu-
lation functions for both low-pass and high-pass filtering conditions
he was able to make certain inferences from the configuration of the
curves. It was noted that the high-pass filtering conditions produced
a rather sharp slope as additional frequencies were added. The
articulation function for the low-pass filtering conditions was more
gradual. These results indicated that the addition of frequencies at
the high-frequency end of the spectrum produced a greater effect than
the addition of an equal number of frequencies at the low-frequency
end of the spectrum.
In reviewing the above research it becomes evident that the low-frequency vowel sounds contain more acoustic energy than the consonant sounds, but low-frequency vowel elements are less critical to the understanding of speech than are the higher frequency consonant sounds. Since most of the consonantal energy lies above 1000 Hz, it may be reasoned that removal of low frequencies from the speech signal should not interfere significantly with consonant recognition. Further, by filtering out low-frequency components from the speech signal, discriminatory facility could possibly be enhanced if the effects of spread of masking are reduced by the operation. The purpose of the next section is to review the concept of spread of masking more thoroughly in regard to its effects on pure tones and its possible deleterious effects on speech discrimination.

**Effects of the Spread-of-Masking Phenomenon**

"Masking is defined as the number of decibels by which a listener's threshold of audibility for a given tone is raised by the presence of another sound" (Stevens and Davis, 1938, p. 453).

Masking can be accomplished by either pure tones or noise bands. The speech signal is, in purely physical terms, a low-frequency noise (Steinberg, 1929; Viehweg, 1968; Denes and Pinson, 1963). There are two types of masking: interband masking and extraband masking. Interband masking refers to the direct masking
of sounds which lie within the frequency band limits of the interfering
noise. Extraband masking is evidenced by the masking of tones or
signals which lie above the frequency limits of the masker (spread of
masking) or below the frequency limits of the masker (remote mask­
ing). The objective of the present section is to review the available
research which specifically relates to spread of masking and its
effects on the normal and pathological listener.

In a classical paper presented by Wegel and Lane (1924), the
amount of masking produced by one pure tone on another was investi­
gated. Primary or masking tones were presented to normal hearing
subjects at frequencies from 200 to 3500 Hz, and pure tone thresholds
were established for frequencies in the range from 150 to 5000 Hz.
The intensity of the masking tone was presented at increasing values,
and thresholds were plotted at each of a number of frequencies in the
presence of the masking tone. The results indicated that for tones
below the masking tone there was very little shift in threshold at
either low or high masker intensities. Above the primary or mask­
ing tone, frequencies under test were negligibly affected at low
masker intensities but demonstrated a significant threshold shift at
increased primary tone intensities. Also, it was observed that the
closer the tones lay together in frequency, the greater the masking.

Wegel and Lane, in referring to the spread-of-masking
phenomenon, stated:
At intensities considerably above minimum audibility, there is no longer a linear relationship between the sound pressure and the response of the ear. Data is given showing combinational tones resulting from this non-linearity when two tones are simultaneously introduced in the ear. The presence also of subjective overtones in a loud tone accounts for the large amount of masking of tones higher than itself by a loud masking tone. (Wegel and Lane, 1924, p. 266)

In regard to the above study by Wegel and Lane, Egan and Hake stated:

The masking audiogram of a pure tone is complicated by phenomena that arise from the interaction of the test tone with the masking stimulus. The production of beats and difference tones results in a masking audiogram that does not represent the pattern of activity in the cochlea or nerve due to a simple masking stimulus. (Egan and Hake, 1950, p. 622)

Egan and Hake (1950) performed a similar study to that of Wegel and Lane, but in addition to using a pure tone masker, Egan and Hake employed a narrow band of noise in determining masked pure tone thresholds. This was accomplished for the purpose of alleviating the effects produced by beats and difference tones at high intensities when a pure tone masker was used. Masking audiograms were taken under two conditions. The first utilized a 400 Hz pure tone as a masking stimulus. The second masking stimulus was a narrow band of noise with a center frequency of 410 Hz. The results supported the findings of Wegel and Lane in demonstrating increased masking for frequencies above the masking stimulus under both testing conditions at high intensities. However, in comparing the two
experimental results, the researchers found that the masked thresh-old curve for the condition involving noise as the masker was more symmetrical on either side of the masking stimulus than was the curve utilizing the pure tone as a masking stimulus. These results indicated that spread of masking existed in both pure tone and noise band masking. Since, from a physical standpoint, speech is considered to be a low-frequency noise, it may be reasoned that the effects of spread of masking may be existent in the speech signal.

Spread of masking to this point has been shown to be characteristic of the normal ear. The masked audiogram of the sensorineural hypacusis depicts a spread-of-masking effect that is not predictable from the data secured from the masked audiograms of normal subjects. Jerger, Tillman, and Peterson (1960) explored spread of masking in a detailed experiment involving three different octave bands of thermal noise as maskers in obtaining masked pure tone threshold audiograms from both normal subjects and subjects having sensorineural hearing loss. Two effective masking levels were employed. The effective level of masking for each subject was determined by subtracting the threshold in quiet from the level per cycle of the noise and adding the critical bandwidth in dB. The first effective level was 10 dB and the second was a 30 dB effective level. The results when using the 10 dB effective level showed no differences in the masked audiogram either above or below the noise bands for
either group. However, when the 30 dB effective level was used, spread and remote masking were both demonstrated, but the individuals with sensorineural impairment demonstrated more masking both above and below the noise band than did the normal hearing group. The 30 dB effective level corresponds to a mean overall level of 87 dB SPL. Therefore, the results indicated that the effect of spread of masking was in evidence at a much lower intensity for the sensorineural hypacusis than for normal hearing individuals who demonstrated masking effects at an overall intensity level of 100 dB SPL.

Rittmanic (1962) performed a similar study to that of Jerger, Tillman, and Peterson (1960). Bands of noise with center frequencies at 250, 500, 1000, 2000, and 4000 Hz were employed as masking stimuli and were administered at 100 dB SPL to 40 subjects arranged in three test groups. The test groups were composed of normals, plugged normals, and sensorineurals. Rittmanic reported that subjects with sensorineural loss experienced abnormal spread of masking when compared to the normal and plugged-normal groups.

Ruhm (1959) tested the discrimination of 20 normal hearing subjects and 20 subjects with sensorineural hearing impairment at a sensation level of 10 dB (re SRT [speech reception threshold]) and again at 120 dB SPL. Monosyllabic word lists were presented in unfiltered form and in a condition involving high-pass filtering at
1200 Hz. Other conditions were constructed by the inclusion of white noise that had been low-pass filtered at 600 Hz and presented at 50, 80, and 110 dB SPL. The results showed that the discrimination scores of sensorineural hearing impaired subjects suffered more from the effects of low-frequency noise than did the discrimination scores of the normal subjects.

Harbert and Young (1965) conducted a study concerning the effects of spread of masking on normal listeners and on conductive and sensorineural hearing impaired subjects. A Bekesy sweep frequency audiogram was obtained with pulsed tone for each subject, and the effects of different intensities of narrow band noise on the frequencies above and below the narrow band masker were observed for each group. The results showed that spread of masking was less evident in the conductively impaired and normal hearing groups than in subjects having sensorineural hearing loss. Thus, spread of masking was found to be operative to a greater degree in individuals with sensorineural loss than for the conductively impaired or normal hearers.

The research reviewed in this section substantially supported the tenability of the experimental hypothesis of the present study. The hypothesis under test in this study asked the question, Do low frequencies of speech mask high frequencies of speech in such a way that discrimination scores are adversely affected? The studies
reported above showed definitely that, though spread of masking is characteristic of all hearing individuals, the individual with sensorineural impairment demonstrates spread-of-masking effects which are greater than the effects demonstrated in cases of normal or conductively impaired hearing. The final section of the present chapter will review some clinical data which indicate that improved speech discrimination scores can be obtained by reducing the intensity of low-frequency speech components. It seems reasonable to assume that such improvements may be due to decreased masking of high-frequency speech elements by low-frequency speech elements (self-masking).

**Clinical Research Regarding Selective Amplification for High-Frequency Sensorineural Impairment**

Bunch (1943) reported that four of his patients demonstrating high-frequency sensorineural losses were successfully fitted with hearing aids that amplified the high frequencies and suppressed the low frequencies of speech. Although discrimination scores and empirical data from these individuals were not given, Bunch (1943, p. 20) postulated that the reason many clients demonstrating this type of hearing loss experienced little success with hearing instruments was that "the low tones of the voice are heard so well and the high tones so poorly that the loud low tones tend to mask or drown out the high ones."
Menzel (1964) reported two examples of improvement in the discrimination scores of two of his high-frequency loss patients through the use of hearing aids with a rising frequency response. One patient evidenced an unaided discrimination score of 32 percent for the right ear and 38 percent for the left ear. When tested while wearing the hearing aid in sound field, this patient had a discrimination score that was improved to 80 percent. The second patient had an unaided discrimination score of 44 percent for each ear. When a hearing aid with a rising frequency response was worn and the test was repeated, this individual's discrimination score improved to 84 percent. Both patients achieved a significant improvement in discrimination scores through the use of a hearing aid that did not effectively amplify the lower tones of speech but did amplify the higher frequencies of speech. Since the audiograms of these patients indicated a loss of sensitivity for pure tones in the higher frequencies, it is possible that the relatively slight amplification in the low frequencies prevented the effects of spread of masking to the higher frequencies.

Jeffers (1962, 1964) found that discrimination scores for high-frequency sensorineural hypacusics obtained with a high-fidelity speech audiometer were not as high as when sensorineural subjects with high-frequency loss were fitted with hearing aids that provided relatively little amplification in the frequencies below 1000 Hz. It
could be postulated from Jeffer's reports that since the high-fidelity instrument was amplifying all frequencies equally it was causing a self-masking effect such that high frequencies of the speech signal were partially masked by low frequencies of the speech signal.

Lewis and Plotkin (1963) obtained discrimination scores from 15 subjects with high-frequency sensorineural hearing loss in three conditions. An unaided discrimination score was first obtained and was compared with two different aided discrimination scores. The first aided score was obtained with a hearing aid coupled to an unvented earmold. A second aided score was obtained with an acoustic modifier or vented earmold. The vent(s) refers to one or two hole(s) in the mold through which low frequencies from the hearing aid receiver can escape to the atmosphere. The vents have the acoustical property of allowing the tones with longer wave lengths (lower frequency sounds) to pass from the mold into the atmosphere. The higher frequency sounds do not escape. This device theoretically serves the same general function as a hearing aid with a high-frequency response. When fitted with a vented earmold, patients whose discrimination scores were lower than 70 percent experienced a 19 percent increase in the articulation score over the unaided score. Lewis and Plotkin's data are shown in Table 3.

In considering the research concerning improved discrimination scores in high-frequency sensorineural hypacusics when a hearing
Table 3. Results of an experiment on 15 subjects with high-frequency sensorineural hearing loss (Lewis and Plotkin, 1963)<sup>a</sup>

<table>
<thead>
<tr>
<th>Total</th>
<th>Group</th>
<th>N=15</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SRT&lt;sup&gt;b&lt;/sup&gt;</td>
<td>PB&lt;sup&gt;c&lt;/sup&gt; percentage</td>
</tr>
<tr>
<td>Unaided</td>
<td>24</td>
<td>65</td>
</tr>
<tr>
<td>Standard mold</td>
<td>5</td>
<td>62</td>
</tr>
<tr>
<td>Vented mold</td>
<td>6</td>
<td>75</td>
</tr>
<tr>
<td>PB scores</td>
<td>Over 70 percent</td>
<td>N=7</td>
</tr>
<tr>
<td>Unaided</td>
<td>29</td>
<td>77</td>
</tr>
<tr>
<td>Standard mold</td>
<td>5</td>
<td>64</td>
</tr>
<tr>
<td>Vented mold</td>
<td>6</td>
<td>75</td>
</tr>
<tr>
<td>PB scores</td>
<td>Under 70 percent</td>
<td>N=8</td>
</tr>
<tr>
<td>Unaided</td>
<td>18</td>
<td>56</td>
</tr>
<tr>
<td>Standard mold</td>
<td>4</td>
<td>60</td>
</tr>
<tr>
<td>Vented mold</td>
<td>6</td>
<td>75</td>
</tr>
</tbody>
</table>

<sup>a</sup>Mean speech reception thresholds and discrimination scores were obtained under unaided conditions and under conditions whereby each subject wore a standard and a vented mold.

<sup>b</sup>Speech reception threshold.

<sup>c</sup>Phonetically balanced.
instrument is provided which amplifies the high frequencies more than the low frequencies of speech, two logical possibilities present themselves. First, the frequency characteristic of the hearing instrument produces the amplification in the area of speech spectrum in which the patient with sensorineural impairment has the greatest loss. Secondly, the attenuation of the lower frequencies reduces the possibility of the effects of self-masking and allows the high-frequency speech components to reach the hearing mechanism in a more clear and distinct fashion so that the patient can function in a communicative situation with less interference.

The Present Investigation

In the present chapter it has been shown that in normal conversational speech the low frequencies below 1000 Hz contain the majority of the acoustical power of speech. These low frequencies are represented by the vowel sounds of speech which have been demonstrated to carry a lesser amount of speech intelligibility. The consonants consist of high-frequency, low-intensity speech sounds which are the most critical components in the understanding of speech. The spread-of-masking phenomenon has been shown to be operative in pure tone testing and this finding suggests the possibility that the speech signal may also produce a masking effect on itself (self-masking), especially in cases with high-frequency sensorineural
hearing loss where spread of masking is exaggerated. If this reasoning is valid, the removal of low frequencies from an amplified speech signal should partially negate the effects of self-masking without sacrificing an important portion of the intelligibility of speech.

From the above reasoning the hypothesis of the present study was developed. Specifically, the primary experimental hypothesis stated that when the low-frequency speech sounds are eliminated from the amplification process, the phenomenon of self-masking will be negated. This will be evidenced by the resultant improvement in the discriminatory facility of the experimental subjects with high-frequency sensorineural hearing loss. A corollary hypothesis stated that individuals who evidence the greatest amount of spread of masking for pure tones will be the same individuals who experience the greatest improvement in the discrimination score subsequent to the removal of low-frequency energy from the speech signal.

The method employed in testing the primary hypothesis involved discrimination testing under four experimental conditions. The speech signal was presented in one unfiltered condition and in three conditions involving high-pass filtering at three different cutoff frequencies. In testing the corollary hypothesis, a masked audio-gram was obtained for each subject and a spread-of-masking index was computed from the results. This value was then correlated with
the difference in discrimination score for the unfiltered condition and the score in each of the high-pass experimental conditions. It was reasoned that a high positive correlation would lend support to the postulate that spread of masking demonstrated by pure tones could be indicative of self-masking by speech. The specific methods and procedures followed in testing the above hypotheses are more completely detailed in Chapter III.
CHAPTER III

METHODOLOGY

Procedures and Instrumentation

The purpose of the present investigation was to examine the effects of self-masking (masking of high-frequency speech sounds by low-frequency speech sounds) on the discrimination scores of subjects suffering from high-frequency sensorineural loss. It was hypothesized that removal of low-frequency energy from an amplified speech signal would cause the discrimination scores of the experimental subjects to improve.

In the testing of the hypothesis, each subject received a speech discrimination test under each of four different experimental conditions. The first experimental condition was an unfiltered presentation of the speech material, the score from which served as a base or reference against which discrimination scores from the other experimental conditions were measured. The three testing conditions involved the presentation of high-pass filtered word lists at 600, 900, and 1200 Hz cutoff frequencies. The filter was used for the purpose of removing successively greater portions of low-frequency speech energy. This filtering at 600, 900, and 1200 Hz progressively
reduced the overall level of the speech signal, but the level per cycle remained the same for the unfiltered portion of the speech signal for all filtering conditions. The reason for the selection of the indicated cutoff frequencies will be more fully discussed in a later section of this chapter.

A corollary hypothesis stated that individuals demonstrating a greater amount of spread of masking for pure tones would be the same individuals who experienced the greatest improvement in the discrimination score following the removal of low-frequency energy from the speech signal.

In the testing of the corollary hypothesis, a masked audiogram was developed for each subject. Pure tone audiometric thresholds were obtained from the subject’s test ear at frequencies from 500 to 8000 Hz while presenting to the same ear a narrow band of noise with a center frequency at 250 Hz and at an intensity level of 90 dB SPL. The masked audiogram was then compared to the subject’s audiometric thresholds obtained in the absence of the narrow band masking noise. The decibel differences between the masked audiogram and the pure tone thresholds taken in quiet for the octave frequencies from 500 to 8000 Hz were totaled and divided by five. The result is referred to as the spread-of-masking index (SMI). Each subject’s SMI was correlated with the difference between the discrimination score under Condition 1 and that of each of the three filtering conditions. It was reasoned that a high positive correlation would indicate
a positive relationship between the degree of spread of masking by pure tones and the degree to which self-masking was operative in the speech signal.

**Experimental Subjects**

For testing the hypothesis, 20 subjects with high-frequency sensorineural hearing loss were selected. The age range of the subjects was from 20 to 71 years, with a mean age of 42.7 years and a standard deviation of 19.5 years. Eight subjects were in the 20 to 24 year age range, nine subjects were in the age range of 60 to 71 years, and the remaining three subjects were in their mid-forties.

The high-frequency sensorineural hypacusics selected demonstrated a pure tone audiometric configuration that sloped downward above 500 Hz or 1000 Hz at the rate of between 10 and 30 dB per octave. A slope greater than 30 dB per octave above 500 or 1000 Hz was believed to be too steep to meet the criteria for the study. It was reasoned that a slope exceeding 30 dB per octave would make some of the higher frequencies totally inaudible. Since it was the purpose of the present investigation to examine the masking effects of low-frequency speech sounds on the high-frequency sounds of speech, it was necessary that the high-frequency sounds be in a range such that amplification would place them in a range where they could contribute to speech intelligibility.
A second criterion stated that each subject's discrimination score, obtained under the same conditions to be used in the investigation, could not be higher than 80 percent. There were two reasons for the second criterion. First, it was believed that it would be difficult to demonstrate any improvement in discriminatory performance as a result of high-pass filtering of the speech signal in subjects who obtained a higher score than 80 percent. Quite obviously, in order to show an improvement there must necessarily be room provided to show improvement. Furthermore, it was desirable to select a group of subjects representative of patients who are "problem cases" for hearing aid fitting. Patients with a sloping loss above 500 or 1000 Hz and who have poor discrimination scores are, indeed, problem cases as hearing aid candidates.

The third criterion required that each subject have a sensorineural hearing loss as opposed to a conductive or mixed loss. Therefore, prospective subjects with air-bone gaps of 15 dB or more between 250 and 4000 Hz were eliminated from the study.

Each subject's air conduction thresholds were bilaterally symmetrical such that the two ears were within 10 dB of each other at 250, 500, 1000, 2000, and 4000 Hz. Therefore, the ear selected for testing depended on the following criteria. First, the bone conduction thresholds for the test ear were either the same as or more sensitive to bone conducted tones than the ear not under test for all but three
experimental subjects. The exceptions were never more than 10 dB. Second, the ear with the discrimination falling in the 50 to 80 percent range was considered the best selection. If the discrimination score from an ear fell below 50 percent or above 80 percent, the ear was not considered for testing. The reasons for the 80 percent criterion have been previously mentioned. The 50 percent cutoff score was used in the attempt to maintain some semblance of homogeneity with respect to discriminatory capacity. The mean discrimination score was 69.7 percent and the standard deviation was 7.44 percent.

The mean audiogram for the experimental group is shown in Figure 2. Four cases gave no response to pure tone testing at 8000 Hz. All other subjects met the criteria for subject selection mentioned above. From Figure 2 it can be seen that the mean audiogram was within the 10 to 30 dB limits of slope between each octave tested above 500 Hz.

Because of an oversight on the part of the experimenter, spondee words were not recorded on the test tape. For this reason speech reception thresholds were obtained by monitored live voice through a speech audiometer (Grason and Stadler Model 162) terminated in an earphone (Telephonics Model TDH-39-10Z). The SRT was defined as that hearing level at which the subject responded correctly to three of six spondee words presented. When the SRT of each individual was compared to the pure tone average of 500, 1000,
Figure 2. Mean pure tone audiogram for 20 high-frequency sensorineural hypacusics making up the study sample.
and 2000 Hz for each individual, the mean discrepancy was 4 dB with the SRT being poorer. This 4 dB discrepancy could possibly be due to the reduced discriminatory function of the experimental subjects. The mean SRT was 41 dB with a standard deviation of 9.44 dB, while the mean pure tone average was 45 dB.

**Test Materials**

**Selection of materials**

Phonetically balanced monosyllabic word lists were selected for testing the discrimination ability of subjects in the four experimental conditions. There were several available lists, but those lists developed by Tillman and Carhart (1966) in the Northwestern University Auditory Research Laboratories and referred to as Northwestern University Auditory Test No. 6 (NU-6) were considered the most appropriate for the present study for the following reasons. First, NU-6 is comprised of four different lists with a very high degree of interlist equivalency. In the present study the writer recorded the NU-6 lists for presentation to the subjects to be tested. Although a check was not made to determine interlist equivalency, there was little reason to expect poor interlist equivalency since the writer took precautions to record the lists in a precise manner (to be discussed later in the chapter). Secondly, the difficulty of the word lists was an important consideration. That is, it was reasoned that the lists
used should be sufficiently difficult to tax discriminatory facility so that 100 percent correct responses could not be achieved by the test subjects. Such a circumstance would eliminate the possibility of an improvement in discrimination scores as a consequence of filtering the lists. On the other hand, it was reasoned that the word lists used should not be so difficult that any possible improvement in discrimination would be negated by the difficulty of the lists. As recorded by Tillman at Northwestern University, the slope of the articulation function of the NU-6 word lists is a 6 percent per dB increase in intensity on the linear portion of the curve (Tillman and Carhart, 1966). It should be mentioned that the word lists recorded by Tillman were not available, and the writer was obliged to tape-record the NU-6 lists for use in the present study. The investigator's presentation of the test materials could possibly have changed the articulation function slope, but it was assumed, as mentioned above, that the lists as recorded and used in the present study closely approximated the NU-6 lists as recorded by Tillman.

Since a portion of the thesis involved an investigation of any existing correlation or relationship between spread of masking by pure tones and self-masking by speech, it was necessary to obtain a measure of spread of masking so that comparisons could be made between the amount of spread of masking and the amount of improvement in the discrimination score resulting from the filtering of low
frequencies from the speech signal. For this reason a "masked" audiogram was constructed for each individual. A narrow band of noise with a center frequency at 250 Hz was presented at 90 dB SPL and mixed with the octave frequency pure tones. The noise and pure tone test signals were fed to the same earphone. Figure 3 is a block diagram of instrumentation employed in obtaining the masked audiogram. The narrow band noise was presented through a narrow band masker (Beltone Model NB102). The signals from the masker and audiometer were mixed and fed into the sound-treated booth (Industrial Acoustical Corporation Model 1603) where the subject was seated. The signals were terminated in the same earphone. Pure tone thresholds were obtained at octave frequencies from 500 to 8000 Hz in the presence of the noise. A 90 dB SPL narrow band masking stimulus was used since it had been shown to produce a greater spread-of-masking effect in sensorineural hypacusics than in individuals with conductive or mixed loss (Rittmanic, 1962).

Preparation of materials

A cardioid dynamic microphone and cathode follower (Turner Model 500), a tape recorder (Uher Model 4400), and magnetic recording tape (Scotch Type 1400) were used in recording the four NU-6 lists for use in the present study. The frequency response of the tape recorder and magnetic recording tape was checked prior to the recording of the lists. A beat frequency oscillator (Bruel and
Figure 3. Instrumentation used in obtaining masked audiograms of subjects for the purpose of demonstrating spread of masking.
Kjaer Type 1022) provided a flat sweep frequency signal from 20 to 20,000 Hz. This signal was recorded on the tape and played back through a graphic level recorder (Bruel and Kjaer Type 2305) from which a graphic write-out of the frequency response characteristics of the recorder and tape was obtained. From Figure 4 it is apparent that the frequency response of the recorder and associated tape did not deviate more than 3 dB between the frequencies of 150 and 10,000 Hz.

Following the above-described step, the NU-6 lists were recorded on the magnetic tape at a recording speed of 15 inches per second (ips). This recording speed was the fastest speed of which the tape recorder was capable and gave the best recording fidelity to the speech signal that could be obtained. Figure 5 schematically shows the apparatus used in recording the NU-6 lists. The cathode follower served as an amplifier for the signal from the dynamic microphone and fed the amplified signal to the tape recorder. The signal was then transferred to the external input of the speech audiometer so that a constant recording level could be monitored by observation of the VU meter.

During the recording the microphone and cathode follower were located in a double-walled, sound-treated test booth. The tape recorder and speech audiometer were located in the control room. With this arrangement, less ambient noise was recorded on the
Figure 4. Frequency response of the magnetic recording tape and tape recorder used in presenting experimental material to the subjects of the present study.
Figure 5. Instrumentation employed in the recording of NU-6 monosyllabic test materials for the present study.
tape than would have been the case had all of the equipment been placed in the same room.

The NU-6 words were recorded by the investigator, with each test word preceded by the carrier phrase "Say the word." The final word of the carrier phrase was monitored by the speaker to peak at zero on the VU meter. The test word followed the carrier phrase as it would in natural, connected discourse with no attempt being made to peak the test item at a predetermined level. Figure 6 is a sample illustration of the relationship between the final word of the carrier phrase and the test item. The carrier phrase peaks were all constant within plus or minus 2 dB for all four NU-6 word lists.

The signal-to-noise ratio of the speech material can also be observed in Figure 6. It is evident that the signal-to-noise ratio was approximately 27 dB. At a 27 dB signal-to-noise ratio, speech intelligibility should be at a maximum (French and Steinberg, 1947). The relationship between the carrier phrase peaks, test words, and noise level remained stable throughout the recording of the test materials.

All four NU-6 lists were recorded on one track of the tape at a recording speed of 15ips. Each list was identified on the tape for the purpose of facilitating randomization. That is, each list was presented at each of the four positions in the test sequence five times. List 1 was presented first to five of the 20 subjects, second to five
Figure 6. Intensity relationship between carrier phrases, test words, and the noise level contained on the recording tape bearing experimental speech materials.
of the subjects, third to five of the subjects, and fourth to the last five subjects. Presentation of lists 2, 3, and 4 was randomized in the same way.

A 1000 Hz calibration tone was recorded at the beginning of the tape at a voltage level equal to the peaks of the carrier phrase. This was done so that the VU meter of the speech audiometer could be correctly referenced to zero for proper calibration of the intensity of test materials.

A sweep frequency signal between 20 and 20,000 Hz was also recorded on the tape so that the frequency response of the magnetic tape and tape recorder system could be monitored at each testing session. At no time did the frequency response vary between testing sessions.

Apparatus used in presentation of test materials

Figure 7 is a block diagram of the instrumentation used in presenting the test materials to experimental subjects. The Channel 1 output of the tape recorder fed the recorded speech material directly to the frequency filter (Allison Model 1-AB) which was set to high-pass filter at each of the appropriate experimental conditions. The output from the filter was led to the Channel 1 external input of a speech audiometer (Grason and Stadler Model 162). Since the output impedance of the tape recorder was low
Figure 7. Instrumentation used in the presentation of the experimental test materials to the subjects of the present study.
(6 ohms) and the filtering system had an input impedance of 600 ohms, an impedance match was necessary. Therefore, a 600 ohm series resistor was connected between the tape recorder and the frequency filter. The input impedance of the speech audiometer was 330 megohms, which was much higher than the 600 ohm output impedance of the frequency filter. Therefore, a 600 ohm resistor was connected in parallel between the speech audiometer and frequency filter to achieve an impedance match and a maximum power transfer. It should be mentioned at this point that the investigator did not foresee the possibility of an insertion loss when the filter was switched from the "off" position in obtaining unfiltered discrimination scores to the "on" position in obtaining discrimination scores under the three filtering conditions. Upon measuring the insertion loss subsequent to the termination of the study, it was found that 3 dB was lost when the filter was operative. Therefore, the level per cycle of the unfiltered portion of the speech signal in the three filtering conditions was 3 dB less than the level per cycle of the speech signal in the test condition involving no filtering.

The speech audiometer served as a switching and control device. The intensity of the speech signal was controlled with the speech audiometer and served to switch the speech signal to the appropriate earphone for the individual being tested in the sound-treated audiometric booth. The tape recorder, frequency filter, and
speech audiometer were all located outside the test booth in the control room and the earphone and experimental listener were located inside the test booth.

Each stimulus word was repeated by the experimental subject into a microphone in the test booth. The microphone fed the subject’s response to a tape recorder outside the sound-treated test booth. This procedure was utilized so that the experimenter would not be forced to make an immediate and arbitrary decision concerning the correctness of the subject’s response.

The actual characteristics of the filter were important because it was necessary to know what portion of the speech signal was arriving at the subject’s ear. In measuring the portion of the speech signal being transferred to the earphone at each of the high-pass frequency cutoffs, a voltmeter was connected across the output of the filter. A pure tone signal generator introduced a signal to the filter at the particular cutoff frequency being measured and the output from the filter was measured by the voltmeter. The signal generator was then set at one octave below the cutoff frequency and the level at the output was again measured. These two voltage values were then inserted into the decibel voltage formula and the difference was computed. It was found that the filtering system attenuated a pure tone signal at the rate of approximately 30 dB per octave for each of the high-pass filtering conditions (600, 900, and 1200 Hz).
The insertion loss when the filter was switched into the circuit from the unfiltered condition to the filtering conditions was found to be three decibels.

**Experimental Listening Conditions**

As mentioned previously, four experimental listening conditions were employed in testing for the existence of self-masking and its effects on the discriminatory capacity of high-frequency sensorineural hypacusics. The four listening conditions were as follows: (a) no filtering, (b) high-pass filtering at 600 Hz, (c) high-pass filtering at 900 Hz, and (d) high-pass filtering at 1200 Hz.

The unfiltered speech material was presented to each subject at a 40 dB sensation level (SL) re the SRT. Since the mean SRT for the subjects of the experiment was 41 dB, the result would be a mean presentation level of 81 dB hearing level or a mean presentation level of approximately 101 dB SPL. This intensity level was thought to be sufficiently high to produce the effects of self-masking. Research was discussed in Chapter II which involved spread of masking from pure tones and narrow band noise. This research indicated that the effects of spread of masking are pronounced above approximately 80 dB SPL (Egan and Hake, 1950; Wegel and Lane, 1924; Rittmanic, 1962; Jerger, Tillman, and Peterson, 1960).
After the presentation of each 50-word list, the frequency filter was switched to the appropriate cutoff frequency under test. There was no manual adjustment of either the hearing level dial or the calibration dial on the speech audiometer to accommodate the reduction in overall intensity, and with the exception of the 3 dB insertion loss when the filter was in operation, the level per cycle remained constant for frequencies not affected by the filter.

Rationale for Selection of Cutoff Frequencies

The rationale behind the selection of the three high-pass filtering conditions (600, 900, and 1200 Hz) was as follows: In normal conversational speech, the frequencies below 1000 Hz contain the major portion of the acoustical power of speech. These low frequencies carry much less speech intelligibility than do the higher frequencies of speech above 1000 Hz (French and Steinberg, 1947; Fletcher, 1929; Miller, 1951; Hirsh, 1952). As noted in Chapter II, Denes and Pinson (1963) stated that the frequency range of the greatest intensity of speech is between 100 and 600 Hz. French and Steinberg (1947) stated that more than one third of the power of the human voice exists in the frequency range of 250 to 500 Hz. Fletcher (1929) found that when speech was high-pass filtered at 500 Hz, 60 percent of the energy was extricated with only 2 percent decrease in discrimination. Since the present thesis involved testing for
evidence of self-masking with sensorineural hypacusics, it was hypothesized that if the frequencies of the speech signal below 600 Hz were filtered, a substantial amount of the acoustical power would be deleted with a subsequent decrease in self-masking and an improvement in the discrimination score between the no filtering test condition and the test condition in which high-pass filtering was accomplished at 600 Hz. Castle (1963) stated that vowel recognition is most dependent on the 1500 to 2500 Hz frequency range, which includes most of the second and third formants of English vowels. It has also been found that the majority of consonantal power appears above 1000 Hz (Miller, 1951; Hirsh, 1952). Since consonants are the most vital sounds to speech intelligibility, it was decided that a test condition should be included which would pass a major portion of the power of the consonant sounds and reject a major portion of the power of the vowel sounds. Therefore, the experimental condition of 1200 Hz was chosen. The cutoff frequency of 900 Hz was employed as a test condition for the purpose of observing a progressive improvement of discrimination scores should self-masking be operative. The experimental condition of no filtering was used as a control for two purposes: (a) to test for improvement in discriminatory capacity resulting from filtering of the speech signal and (b) to correlate the spread-of-masking index derived from the masked audiogram with
the differences between discrimination scores under each filtering condition and the control (no filtering) condition.

Summary

The present investigation was based on the supposed existence of a masking component produced by the lower frequencies of the speech spectrum on the higher frequencies of the speech spectrum in an amplified speech signal such that discriminatory facility of sensorineural hypacusics with high-frequency hearing impairment is significantly reduced. In testing the hypothesis it was reasoned that if the lower frequencies could be removed from the speech signal, the masking effect would be reduced and discriminatory performance for these individuals would be improved.

Twenty sensorineural hypacusics demonstrating a sloping audiometric configuration of 10 to 30 dB per octave above 500 Hz or 1000 Hz were used in testing this hypothesis. Discrimination scores of acceptable subjects, as measured by routine speech tests, ranged between 50 and 80 percent.

In testing the hypothesis, four experimental conditions were used. Three of the listening conditions involved the removal of low-frequency energy. Specifically, cutoff frequencies of 600, 900, and 1200 Hz were employed. In accomplishing the filtering, the low-frequency components of speech were removed without a reduction in
the level per cycle of the more important speech sounds above the
cutoff frequencies. It was thought that high-pass filtering would
improve discrimination scores if self-masking was indeed exerting a
deleterious effect on the score obtained in the listening condition
employing no filtering.

The preparation of experimental test materials involved the
recording of four 50-word NU-6 lists on magnetic recording tape.
In the presentation of materials to experimental subjects the taped
lists were fed through an electronic filter to the external input of a
speech audiometer which, in turn, introduced the recorded material
to the test ear of each subject seated in a sound-treated audiometric
test booth. The audiometer served to direct the recorded lists to the
appropriate ear and also to adjust the intensity to the proper level for
each subject (40 dB SPL re SRT).

The occurrence of the test lists in the test sequence was
counterbalanced such that each list occurred in each position an
equal number of times. Any error due to possible list differences
was reduced by counterbalancing the order of presentation of the test
lists.

In Chapter IV the results obtained from the procedures
described in the preceding pages are presented.
For the purpose of testing for statistical significance, the null hypothesis in this investigation stated there would be no significant change in the discriminatory performance of subjects at high signal levels when levels of low-frequency speech elements were eliminated.

In testing the above hypothesis the speech signal was high-pass filtered at three different cutoff frequencies. The changes in the subject’s discrimination scores were observed under the conditions involving filtering by comparison with the score observed under the condition involving no filtering. It was reasoned that if discrimination scores obtained under the high-pass filtering conditions demonstrated significant improvement over the score obtained with no filtering then the null hypothesis would be rejected. On the other hand, if no significant change in the discrimination scores occurred, or if the results showed decreased discriminatory performance as a consequence of high-pass filtering of the speech signal, the null hypothesis would be accepted.

The data to be reported in the following pages resulted from the testing of 20 sensorineural hypacusics with high-frequency hearing loss under four experimental conditions. In Condition 1 a list of
50 unfiltered monosyllabic words was presented via an earphone to each individual subject while seated in a sound-treated booth. The unfiltered condition was employed as a reference for the purpose of comparing the subject's performance under three high-pass filtering conditions. Under listening Condition 2, the speech signal was high-pass filtered at a cutoff frequency of 600 Hz. Under listening conditions 3 and 4 the speech signal was high-pass filtered at 900 and 1200 Hz, respectively. It was reasoned that if self-masking in fact exists such that low-frequency speech components mask high-frequency speech components, and if high-pass filtering as described above does not significantly alter the intelligibility of the speech signal, then progressive improvement in the discrimination score should result in moving from listening Condition 1 to listening Condition 4.

**Experimental Findings**

The raw discrimination score data, together with the mean and standard deviation of each of the four listening conditions, are presented in the Appendix as Table 9. As is evident, the means were fairly close, the range being from 67.5 percent in Condition 4 (speech high-pass filtered at 1200 Hz) to 72 percent in Condition 2 (speech high-pass filtered at 600 Hz). The standard deviations ranged between 6.5 and 9.4 percent and indicated relatively little dispersion in scoring among the 20 subjects.
In statistically testing for significant differences between means for the four listening conditions, a one-way analysis of variance for repeated measures was employed. The data relative to the analysis are shown in Table 4. There were no significant differences between means for the four listening conditions at the .05 level of confidence. Thus, the null hypothesis was not rejected. It appears that under the conditions of the present investigation, self-masking does not exist to a sufficient magnitude to render improved discriminatory performance by its removal through high-pass filtering of the speech signal.

In summary, the null hypothesis cannot be rejected. Self-masking cannot satisfactorily explain the findings of clinical research which has demonstrated increased discrimination facility for sensorineural hypacusics when low-frequency components of an amplified speech signal have been attenuated by a wearable hearing aid.

A corollary hypothesis of the present study stated that there would be no positive relationship between the degree of spread of masking by pure tones and self-masking in the speech signal. As explained in Chapter III, a masked audiogram was obtained for each subject for frequencies from 500 through 8000 Hz. An SMI was then computed by totaling the masked threshold values at each of the five discrete frequencies and dividing by five. The SMI was then correlated with the mean difference in discrimination scores.
Table 4. One-way analysis of variance with repeated measurements, testing for a significant difference between the mean discrimination scores for the four experimental conditions

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Sum of squares</th>
<th>Degrees of freedom</th>
<th>Mean square</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between subjects</td>
<td>609</td>
<td>19</td>
<td></td>
<td>Observed F = .952</td>
</tr>
<tr>
<td>Within subjects</td>
<td>4543</td>
<td>60</td>
<td></td>
<td>Needed F = 2.75</td>
</tr>
<tr>
<td>Treatments</td>
<td>217</td>
<td>3</td>
<td>72.3</td>
<td></td>
</tr>
<tr>
<td>Residual</td>
<td>4326</td>
<td>57</td>
<td>75.89</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>5152</td>
<td>79</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

between conditions 1 and 2, 1 and 3, and 1 and 4. The Pearson product moment correlation coefficient procedure utilized in this step produced the results shown in Table 5. An $r = .56$ was computed for the difference score of conditions 1 and 2 and the SMI. This indicated that 31.36 percent of the total variation of the SMI can be explained by the regression of the difference score of conditions 1 and 2 with the SMI. Although the coefficient was not high between the magnitude of the SMI and the magnitude of the difference score from conditions 1 and 2, the coefficient was positive and suggested that individuals with the greatest spread of masking as reflected by
Table 5. Pearson product moment correlation coefficient applied to each subject's difference score and the spread of masking index

<table>
<thead>
<tr>
<th>Source</th>
<th>$\bar{x}$</th>
<th>$\bar{y}$</th>
<th>Sx</th>
<th>Sy</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition 1 vs.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condition 2</td>
<td>2</td>
<td>21</td>
<td>4.9</td>
<td>5.46</td>
<td>.56</td>
</tr>
<tr>
<td>Condition 1 vs.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condition 3</td>
<td>1.8</td>
<td>21</td>
<td>6.48</td>
<td>5.46</td>
<td>.40</td>
</tr>
<tr>
<td>Condition 1 vs.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condition 4</td>
<td>-3</td>
<td>21</td>
<td>10.39</td>
<td>5.46</td>
<td>.55</td>
</tr>
</tbody>
</table>

Key: $\bar{x}$ = Mean difference score  
$\bar{y}$ = Mean SMI  
Sx = Standard deviation of difference scores  
Sy = Standard deviation of SMIs  
r = Pearson product moment correlation coefficient

the SMI were the same individuals who experienced the greatest improvement (although small) as a consequence of the removal of speech energy below 600 Hz.

In performing the same operation with the difference scores from conditions 1 and 3, a positive correlation coefficient of .40 was found. This result also suggests that some variable existing in the speech signal was partially responsible for the relationship between spread of masking by pure tones and changes in the discrimination scores between conditions 1 and 3. The variable could possibly be a decrease in self-masking as a consequence of the removal of energy from the speech signal below 900 Hz.
The last correlation was performed on the difference score from conditions 1 and 4 and the SMI. The result revealed a positive correlation coefficient of .55. Approximately 30 percent of the total variation can be accounted for by this coefficient. The mean score was lower (poorer) in Condition 4 than in Condition 1, indicating that discriminatory performance decreased as a consequence of the filtering of the speech signal. Nevertheless, the correlation coefficient indicated that, by and large, individuals with the largest SMI were the individuals with the smallest decrement in discriminatory performance resulting from the filtering of the speech signal. This fact supports the possibility of a relationship between spread of masking by pure tones and self-masking by speech.

Two counteracting influences appear to be revealed by the data. First, it appears that high-pass filtering reduces low-frequency speech information to some degree and has a detrimental influence on discriminatory performance. Secondly, the correlation coefficients between the SMI and the discrimination difference scores seem to suggest that self-masking was reduced by the experimental operations such that discrimination scores were not as adversely affected as would have been the case had self-masking not been present. Stated differently, the results seem to indicate that self-masking is operative in the speech signal but that the effects of high-pass filtering remove from the signal a sufficient amount of useful information to
negate the positive benefits to intelligibility produced by a reduction in self-masking.

In summary, it can be seen from the results of the data obtained from the testing of the corollary hypothesis that there does exist a positive correlation between spread of masking as reflected by the SMI and the difference scores between Condition 1 and the three high-pass filtering conditions.

In the following section the concept of the articulation index will be introduced. The purpose of this step is to explain more fully and discuss the experimental findings of the present study.

The Articulation Index

Development of the index

The articulation index (AI) was developed at the Bell Telephone Laboratories. The purpose of the research regarding the AI stemmed from the need for a method to evaluate or predict the efficiency of communication systems without using a group of human listeners under actual test conditions.

French and Steinberg (1947) were the originators of the concept of AI. A system was developed by these researchers whereby the acoustical energy of speech and noise produced by a communication system could be used in computing and predicting the intelligibility of speech presented through the system. More specifically, the AI is a
theory of speech intelligibility based on the idea that through a knowledge of the acoustic energy of speech and of extraneous noise in each of a number of frequency bands which reach the ear, it is possible to predict the articulation score. The energy of the speech signal and its spectral range were compared with the level of competing noise and a predicted intelligibility score was derived. Since the present study and the AI were both concerned with the intelligibility of speech as it relates to the spectral characteristics of the speech signal, the degree to which the AI would predict the results of the present study could have important implications.

In developing the AI, French and Steinberg (1947) presented CVC (consonant-vowel-consonant) nonsense syllable materials to a group of normal hearing subjects. The syllables were presented under a series of high-pass and low-pass filter conditions and at different intensity levels. Articulation curves were graphed as a function of cutoff frequency and a family of curves was established for the high-pass filtering conditions. A second family of curves was established for the low-pass filtering conditions. From the above information, French and Steinberg were able to determine the frequency limits of 20 frequency bands between 200 and 6100 Hz, each of which contributed equally to speech intelligibility. From empirical data French and Steinberg established that if a 30 dB difference exists between the threshold of hearing in each of the 20
equally contributing frequency bands and the intensity of speech peaks in each band, the intelligibility by each band would be maximum. If the difference is less than 30 dB in any of the bands, the contribution to intelligibility of these bands will be proportionately reduced. An index between zero and unity was established for each bandwidth. In deriving the total articulation index, the 20 values from the 20 bandwidths are added and divided by 20.

French and Steinberg developed a conversion curve which would allow one to convert the obtained AI value to a predicted intelligibility score in percentage value. Since the intelligibility of different speech materials is not the same, other factors being equal, it was necessary to develop separate conversion curves for syllables, words, and sentences.

Kryter (1956) has indicated that certain weaknesses seem to exist in the AI as designed by French and Steinberg (1947) when noise is involved in the system. Kryter developed, within the method for determining the AI, procedures which help to alleviate the problems in the French and Steinberg procedure. Because it has been shown to be more precise, the present investigator selected the Kryter method utilizing 20 equally contributing bandwidths in the computation of the AI and a predicted discrimination score for each experimental condition. The procedure was accomplished for the purpose of observing the degree of discrepancy in discrimination
scores as predicted by the AI and as observed through the testing of the subjects.

**Method of computation**

In computing the AI by the Kryter method, Viehweg (1968) described the following specific steps:

First the spectrum level, i.e., the level-per-cycle, of the speech peaks reaching the listener's ear is plotted on a work sheet. This is accomplished by first algebraically adding together the frequency response characteristics of the system to be evaluated and the idealized speech spectrum found plotted on the work sheet of the Kryter publication. Following this step, the position of the idealized speech spectrum, as plotted by Kryter, is varied along a spectrum level continuum by an amount equal to the difference between the measured long-term RMS for the speech signal under consideration and 65 dB, the over-all long-term RMS sound-pressure-level (SPL) of the idealized speech spectrum plotted in the Kryter article. (Viehweg, 1968, p. 176)

The second step was described by Viehweg as follows:

The spectrum level of steady-state noise reaching the ear of the listener is plotted. If the band sensation level of the noise in any equally contributing band exceeds 80 dB, a correction factor is added to the SPL of the noise in that band. Procedures are also provided to allow for spread and remote masking of the noise spectrum. As would be expected, the magnitude of correction for spread-of-masking and remote masking from the noise is dependent upon the frequency response characteristics and the intensity of the noise. Again, the nature of the correction may be determined by reference to the tables in the Kryter article. (Viehweg, 1968, p. 177)

---

1The band sensation level of a noise is the difference in decibels between the measured SPL integrated over a frequency band and the threshold SPL of that band of noise in quiet.
In the third step, as described by Viehweg,

the difference in decibels between the spectrum level of
the speech peaks and that of the noise spectrum, or the
noise spectrum corrected for masking, whichever is
higher, is determined at the center frequency of each of
the 20 frequency bands indicated on the work sheet.
Differences greater than 30 dB are assigned a value of
30 and differences smaller than zero (spectrum level of
the noise more intense than the spectrum level of the
speech peaks) are assigned a value of zero. Whenever
the threshold-of-audibility curve on the work sheet
exceeds the noise spectrum, the threshold-of-audibility
curve is to be considered as the "minimum noise spec-
trum." (Viehweg, 1968, p. 178)

In explaining the final step of the Kryter method for determining the
AI, Viehweg stated:

Finally, the differences found in step three for each of the
20 bands are summed and the resultant total is divided by
600. This final value is the AI for the particular system
operating under the noise conditions and for the speech level
specified. (Viehweg, 1968, p. 178)

---

2 The threshold-of-audibility curve shown on the Kryter
work sheet, and which is to be considered as the "minimum
noise spectrum," was obtained in the following way. The
threshold-of-audibility was obtained for each of 20 equally
contributing bands. Following this step, the level-per-cycle
or spectrum level of the noise in each band, when at thresh-
old, was determined. These values are shown plotted on the
Kryter work sheet and the resulting curve is to be considered
as the "minimum noise spectrum."

The following steps were followed in obtaining AI values from
the four listening conditions of the present investigation. First, the
frequency response characteristics of the experimental system
including the magnetic tape, tape recorder, speech audiometer, and
earphones were added algebraically to the idealized speech spectrum.
The position of the frequency response curve along a spectrum level continuum was determined by taking the difference between the measured long-term RMS for the speech signal presented to the experimental subjects and the overall long-term RMS sound pressure level of the idealized speech spectrum of 65 dB. Specifically, in Condition 1 the speech was presented in unfiltered form at 40 dB sensation level (re each subject's SRT). For purposes of computation, a mean audiogram and mean SRT were determined. Added to the mean SRT of 41 dB was the 40 dB sensation level which resulted in the presentation of the unfiltered speech signal at an intensity level of 81 dB. The intensity level of 81 dB when converted to its equivalent SPL value is 101 dB. As stated, the overall long-term RMS level of 65 dB SPL corresponds to the idealized speech spectrum. Thus, the difference of 36 dB shifted the modified idealized speech spectrum to the position occupied as shown in Figure 8.

As stated previously, the second step involved the determination of the spectrum level of the noise components at each of the 20 equally contributing bands. It should be realized that the threshold-of-audibility curve shown on the Kryter work sheet may be considered as the minimum noise spectrum. In describing the minimum noise spectrum, Viehweg stated the following:

The threshold-of-audibility curve which is to be considered as the "minimum noise spectrum" is, in actuality, the threshold-of-audibility for narrow bands of noise expressed in terms of spectrum level or, i.e., level-per-
Mid-frequencies of 20 bands contributing equally to speech intelligibility with male voices

Figure 8. Long-term average spectrum (plotted 36 dB above that shown by Kryter [1956]) of speech peaks as modified by the frequency characteristics of recording apparatus used in the present study.
cycle. It is important to realize that the threshold-of-audibility curve, or, i.e., the 'minimum noise spectrum' used by Kryter was obtained using normal listeners. (Viehweg, 1968, p. 88)

The subjects in the present study had a high-frequency hearing loss, thus the minimum noise spectrum established by Kryter would not be applicable in the present instance. The situation was further complicated by the fact that the investigator did not foresee the necessity of obtaining thresholds from the experimental subjects for narrow bands of noise that corresponded to those used by Kryter. Therefore, a threshold-of-audibility curve for narrow bands of noise expressed in terms of spectrum level could not be established as a minimum noise spectrum for the subjects in the present study. A substitute procedure was necessitated, therefore, in determining a minimum noise spectrum that would give normal listeners the same threshold configuration as that obtained from the subject sample of the present investigation. In regard to the substitute procedure used in obtaining the minimum noise spectrum, Viehweg stated the following:

Through empirical measurements, Fletcher and Munson (1937), Fletcher (1940), and Hawkins and Stevens (1950) identified the difference in decibels across the frequency range between the power in pure tones and the power of broad band white noise expressed in terms of the level-per-cycle which is necessary to just mask these pure tones. For instance, the difference in decibels between a 1000 Hz tone and the level-per-cycle of broad band white noise when it is sufficiently intense to just mask the 1000 Hz tone is given as 18 dB. Fletcher (1940) and Hawkins and Stevens (1950) have postulated
that only that portion of the broad band of noise which is circumscribed around a given pure tone will serve to mask it. They postulated further that the total noise power required to just mask a pure tone will be equal to the power in the pure tone itself. As stated previously, we know from Hawkins and Stevens information that at 1000 Hz, the level-per-cycle of the masking noise is 18 dB below the masked threshold of the pure tone. Since 18 dB corresponds to a power ratio of 63 to one, the band of frequencies having a total power equal to that of the 1000 Hz tone would be 63 Hz wide. Thus, according to Fletcher and Hawkins and Stevens, 63 Hz is the width of the noise band around 1000 Hz which serves to mask it and this noise band is called the "critical band." Under the reasoning of Fletcher and Hawkins and Stevens, extending the bandwidth (while maintaining the level-per-cycle constant) will not shift the threshold further. It is apparent that the critical band, as defined by Fletcher and Munson and also by Hawkins and Stevens, can be expressed either in terms of Hz or in terms of dB. According to Hawkins and Stevens, the critical bandwidths of other specific frequencies, when expressed in terms of dB, are as follows: 18.5 dB at 125 Hz, 17.0 dB at 250 Hz, 17.0 at 500 Hz, 20.0 dB at 2000 Hz, 23.0 dB at 4000 Hz, and 26.0 at 6000 Hz.

With this information, it is possible to plot a noise spectrum which should theoretically give normal listeners the threshold configuration of the subject sample employed here (listeners with high-frequency sensorineural loss). As a first step, the mean pure tone (discrete frequency) thresholds of the subject sample were plotted in dB re 0.0002 microbar. Second, the decibel value of the critical band was subtracted from the threshold value of each test frequency in order to obtain the level-per-cycle values of noise at each test frequency which would give normal listeners a masked threshold configuration like the mean threshold configuration of the present subject sample as obtained in quiet. The level-per-cycle values obtained by subtracting the width of the critical band (in dB) from the threshold value in SPL at each test frequency were connected by a smoothed curve. The smoothed curve was then treated as the "minimum noise spectrum" rather than treating the spectrum level threshold-of- audibility, as obtained by Kryter from normal listeners, as the "minimum noise spectrum." (Viehweg, 1968, pp. 184-186)
The above procedure was performed on the subjects of the present study and the resultant smoothed curve which was used as the minimum noise spectrum is shown in Figure 9.

Figure 10 illustrates the relationship among the four experimental conditions and the minimum noise spectrum for each of the 20 equally contributing frequency bands in the Kryter method. By means of the above procedures, the differences in decibels between the peaks of the speech spectrum and the minimum noise spectrum at the center frequency of each of the 20 equally contributing bands were obtained. The values appear in Table 6. The values for each condition were added and the sum divided by 600. The values were referred to the transfer curve in the Kryter publication for the purpose of determining the predicted discrimination scores for each of the four experimental conditions. The AI values and the predicted discrimination scores appear in Table 7. The transfer curve for 1000 PB words in the Kryter article was selected in converting the AI values to predicted discrimination scores since the materials used in establishing this curve were similar to those of the present study. It is logical to assume that the transfer functions for the materials used in the present study and the materials used by Kryter's 1000-word list were very similar, but a definite statement to this effect cannot be made.
Mid-frequencies of 20 bands contributing equally to speech intelligibility with male voices.
Mid-frequencies of 20 bands contributing equally to speech intelligibility with male voices

Figure 10. Relationships among the four experimental conditions and the minimum noise spectrum used in the computation of the AI by the Kryter 20-band method.
Table 6. Differences in dB between the level per cycle of the speech peaks and the minimum noise spectrum for the 20 frequency bandwidths established by Kryter (1956) in computing the AI in the present investigation

<table>
<thead>
<tr>
<th>Band</th>
<th>Band limits in cycles</th>
<th>Level of speech peaks in dB</th>
<th>Level of minimum noise spectrum in dB</th>
<th>Difference in dB between speech peaks and minimum noise spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>200-300</td>
<td>88</td>
<td>32</td>
<td>56</td>
</tr>
<tr>
<td>2</td>
<td>330-430</td>
<td>89</td>
<td>27</td>
<td>62</td>
</tr>
<tr>
<td>3</td>
<td>430-560</td>
<td>85</td>
<td>26</td>
<td>49</td>
</tr>
<tr>
<td>4</td>
<td>560-700</td>
<td>82</td>
<td>24</td>
<td>58</td>
</tr>
<tr>
<td>5</td>
<td>700-840</td>
<td>80</td>
<td>25</td>
<td>55</td>
</tr>
<tr>
<td>6</td>
<td>840-1000</td>
<td>76</td>
<td>30</td>
<td>46</td>
</tr>
<tr>
<td>7</td>
<td>1000-1150</td>
<td>73</td>
<td>32</td>
<td>41</td>
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<tr>
<td>8</td>
<td>1150-1310</td>
<td>70</td>
<td>38</td>
<td>32</td>
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<tr>
<td>9</td>
<td>1310-1480</td>
<td>68</td>
<td>42</td>
<td>27</td>
</tr>
<tr>
<td>10</td>
<td>1480-1660</td>
<td>66</td>
<td>47</td>
<td>23</td>
</tr>
<tr>
<td>11</td>
<td>1660-1830</td>
<td>65</td>
<td>50</td>
<td>14</td>
</tr>
<tr>
<td>12</td>
<td>1830-2020</td>
<td>62</td>
<td>52</td>
<td>10</td>
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<tr>
<td>13</td>
<td>2020-2240</td>
<td>61</td>
<td>54</td>
<td>5</td>
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<tr>
<td>14</td>
<td>2240-2500</td>
<td>60</td>
<td>55</td>
<td>3</td>
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<td>15</td>
<td>2500-2820</td>
<td>58</td>
<td>58</td>
<td>0</td>
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<tr>
<td>16</td>
<td>2820-3200</td>
<td>60</td>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>17</td>
<td>3200-3650</td>
<td>62</td>
<td>62</td>
<td>0</td>
</tr>
<tr>
<td>18</td>
<td>3650-4250</td>
<td>60</td>
<td>65</td>
<td>-5</td>
</tr>
<tr>
<td>19</td>
<td>4250-5050</td>
<td>69</td>
<td>79</td>
<td>-10</td>
</tr>
<tr>
<td>20</td>
<td>5050-6100</td>
<td>62</td>
<td>75</td>
<td>-13</td>
</tr>
</tbody>
</table>
Table 7. Predicted mean discrimination scores for each experimental condition and the equivalent AI

<table>
<thead>
<tr>
<th>Test condition&lt;sup&gt;a&lt;/sup&gt;</th>
<th>AI value</th>
<th>Predicted discrimination scores in percentage value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.53</td>
<td>78</td>
</tr>
<tr>
<td>2</td>
<td>.51</td>
<td>75</td>
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<td>3</td>
<td>.44</td>
<td>63</td>
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<td>4</td>
<td>.32</td>
<td>42</td>
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</tbody>
</table>

<sup>a</sup>Condition 1, no filtering; Condition 2, high-pass filtering at 600 Hz; Condition 3, high-pass filtering at 900 Hz; Condition 4, high-pass filtering at 1200 Hz.

Presented in the following section is a comparison of discrimination score values predicted by the AI with observed discrimination scores obtained in the present research.

**Comparison of Obtained Discrimination Scores with Predicted Discrimination Scores**

Table 8 lists the observed discrimination score, predicted discrimination score, and the difference between observed and predicted scores for each of the four experimental listening conditions. It can be seen from Table 8 that for Condition 1 the predicted discrimination score was 9 percent higher than the observed score.
Table 8. Differences between mean observed and predicted discrimination scores for the four listening conditions

<table>
<thead>
<tr>
<th>Listening condition</th>
<th>Discrimination scores in percentage value</th>
<th>Difference between observed and predicted discrimination scores</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean observed</td>
<td>Predicted&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>1</td>
<td>69</td>
<td>78</td>
</tr>
<tr>
<td>2</td>
<td>72</td>
<td>75</td>
</tr>
<tr>
<td>3</td>
<td>71</td>
<td>63</td>
</tr>
<tr>
<td>4</td>
<td>67.5</td>
<td>42</td>
</tr>
</tbody>
</table>

<sup>a</sup>Predicted scores were obtained by computing AI values for each of the four listening conditions and then referring the AI value to the Kryter transfer curve.

In Condition 2, where a 600 Hz high-pass cutoff frequency was employed, the difference was only 3 percent, with the predicted score being the higher. In conditions 3 and 4 the trend changed such that the observed scores were higher than the predicted scores by 8 and 25 percent, respectively. In the absence of self-masking, one would expect the difference between the observed and predicted scores to remain constant across listening conditions. As is evident, a constant difference did not exist. In further analyzing the data in Table 8 it can be seen that the AI predicted a drop in discrimination of 3 percent as a consequence of removing energy below 600 Hz, a drop of 15 percent in removing speech energy below 900 Hz, and a
Drop of 36 percent in removing speech energy below 1200 Hz. No such decreases were observed when the subjects were tested. As stated earlier, observed discrimination scores were not significantly different. Thus, some factor must be responsible for the fact that observed discrimination scores did not decrease or become poorer as a consequence of removing low-frequency energy as predicted by the AI. The progressive elimination of the effects of self-masking resulting from filtering of the speech signal may be responsible for the fact that observed scores did not show a decrement.

**Summary**

The null hypothesis of the present investigation stated that there would be no change in discriminatory performance of individuals with high-frequency sensorineural loss when the speech signal was presented at high signal levels and low-frequency speech elements were eliminated.

A statistical test was conducted for significance between the mean scores for each of the experimental conditions, three of which involved high-pass filtering of the speech signal at 600, 900, and 1200 Hz frequency cutoffs and a fourth condition that involved the unfiltered speech signal. No differences were found between any of the means of the experimental conditions at the .05 level of significance. Thus, the null hypothesis was accepted. Self-masking as a
variable of the speech signal seems to be an unsatisfactory explanation of earlier research which demonstrated increased discriminatory facility for some sensorineural hypacusics when the low-frequency elements of the speech signal had been attenuated by a wearable hearing aid.

A corollary hypothesis of the present study stated that no significant positive relationship existed between the degree of spread of masking by pure tones and self-masking in the speech signal. In examining the corollary hypothesis a masked audiogram was obtained and a spread-of-masking index was computed for each experimental subject. The SMI was then correlated with the difference between discrimination scores obtained under the unfiltered experimental condition and each of the experimental conditions involving high-pass frequency filtering at 600, 900, and 1200 Hz. The results revealed a positive relationship between the SMI and the difference scores obtained from Condition 1 related to Condition 2, 3, and 4, respectively. More specifically, the results indicated that the greater the degree of spread of masking, the greater the individual's improvement in discrimination performance as low-pass speech components were filtered from the speech signal. Stated differently, the results suggested the possibility of a relationship between spread of masking by pure tones and self-masking by speech.
Since two different statistical measurements suggested opposing results, a third step utilizing the articulation index was employed in order to examine and explain more thoroughly the experimental results of the study. The AI was first developed by French and Steinberg (1947) in determining the effect on speech discrimination scores for normal hearers when the speech and noise signals of a communication system were analyzed in terms of the intensity and frequency components. The range of important frequencies in calculating the AI is from 200 to 6100 Hz, which the above authors divided into 20 equally contributing bands each contributing .05 of the total intelligibility if the dB difference in signal-to-noise ratio for the band under consideration is at least 30 dB. If the signal-to-noise ratio is less than 30 dB, the index of intelligibility is proportionately reduced. The sum of the contributions of each frequency band is the AI.

Kryter (1956) advanced the reliability and, therefore, the predictive power of the AI in determining intelligibility of a communication system by establishing conversion tables that accounted for other variables existent in the signal, such as spread of masking and the abnormal growth of adverse effects of noise at high intensities which Kryter believed had been weaknesses of the French and Steinberg method. Kryter also established a transfer curve that would predict the intelligibility of different types of speech.
In calculating the AI, the dB difference for each of the 20 equally contributing frequency bands is determined by subtracting the minimum noise spectrum (the threshold for the narrow bands of noise corresponding to the 20 equally contributing bands) from the speech peaks reaching the listener's ear. The dB difference values are totaled for all of the 20 equally contributing bands and the sum is divided by 600. The resultant value is the AI which is referred to the Kryter transfer curve to determine the discrimination score in percentage value.

In the present investigation the AI was calculated for each experimental condition for the purpose of deriving a difference score between the predicted discrimination score as determined by the AI and the observed discrimination score obtained for each of the three high-pass filtering conditions and the unfiltered condition.

If there was no other variable operative in the speech signal that affected the discrimination of individuals with high-frequency sensorineural hearing loss to a significant degree, other than the degree of hearing loss and the audiometric configuration, the difference score for the predicted versus observed scores would be expected to remain constant for all listening conditions. However, the results indicated that the AI predicted a drop in discrimination scores as a greater portion of the speech signal was removed, while the mean observed scores stayed relatively constant across all test
conditions. Since observed scores did not become poorer, these results suggested that discrimination was facilitated by a decrease in what could possibly be self-masking due to high-pass filtering of the speech signal.
CHAPTER V

SUMMARY AND CONCLUSIONS

The Problem

The sensorineural hypacusis with high-frequency hearing loss often demonstrates a poor ability to discriminate speech sounds. The fact that the majority of the intelligibility of speech lies in the high-frequency consonantal sounds is thought to be the major reason for such discriminatory deficits. That is, if a person suffers from high-frequency loss, a major portion of the intelligibility of speech will not be available in the speech signal. High-frequency sounds are, for the most part, characterized by the consonantal sounds in English. Most of the power of the consonant sounds appears above 1000 Hz (Miller, 1951; Hirsh, 1952). The majority of speech energy lies in the 100 to 600 Hz region, being represented by the fundamental and first formant of the vowel sounds (Denes and Pinson, 1963). However, the formants that contribute the most to speech intelligibility are the second and third formants ($F_2$, $F_3$) which lie in the 1500 to 2500 Hz region (Castle, 1963).

The present study hypothesized that an additional factor was operative in individuals with high-frequency loss which contributed
to the lack of discriminative ability. This factor is referred to as self-masking and is defined as the masking of the high-frequency speech sounds by low-frequency speech sounds. The fact that low-frequency speech sounds below 1000 Hz contain the vast majority of the energy of speech made this hypothesis a tenable one. Further support for this hypothesis was found in studies on spread of masking that demonstrated masking of a pure tone by another pure tone or masking band (Egan and Hake, 1950; Fletcher, 1953; Wegel and Lane, 1924). The above studies concerning spread of masking have found that low-frequency tones or noise produces a masking effect on much of the higher frequency tones, and this effect is more pronounced with high-frequency sensorineural hypacusics. Other research has found that the discriminatory ability of these individuals has improved when hearing aids were used that attenuated the low frequencies and amplified the higher frequencies (Bunch, 1943; Jeffers, 1962; Menzel, 1964).

As a result of the above research, the following null hypothesis was developed: Self-masking will not affect speech discrimination in subjects suffering from high-frequency sensorineural loss. A corollary hypothesis stated that no significant correlation would exist between the amount of spread of masking by pure tones and the amount of improvement in discrimination scores as a result of removal of low-frequency energy from the speech signal.
Method

Twenty subjects were selected whose audiometric configuration depicted a downward slope above 500 or 1000 Hz between 10 and 30 dB per octave in the better ear. The criteria for subject selection also specified that discrimination scores obtained by routine speech audiometry must fall between 50 and 80 percent.

Northwestern University lists (NU-6) were presented to each subject under four experimental conditions at a sensation level of 40 dB re speech reception threshold (SRT). In preparing the lists for presentation, four lists were recorded on magnetic recording tape. During the actual testing, the order of presentation of the lists was randomized so that each list was presented to the 20 test subjects five times in each position. That is, five of the subjects received List 1 first, five of the subjects received List 2 first, five received List 3 first, and five received List 4 first. Randomization controlled for the possibility of biased results due to fatigue.

As mentioned, four test conditions were used in testing the main treatments of the hypothesis. All lists were presented to the subject seated in a sound-treated audiometric test booth. The level of the intensity of the speech signal was presented at 40 dB sensation level re SRT. Condition 1, in which the word lists were presented without filtering, was a measure of the subject's discrimination ability and was representative of the discrimination scores taken
under routine speech audiometry. In the other three experimental conditions the speech signal was high-pass filtered at 600, 900, and 1200 Hz, respectively. The scores obtained under the first condition served as a base against which the discrimination scores obtained under the three high-pass filtering conditions were compared.

A spread-of-masking index (SMI) was also obtained for each subject for the purpose of deriving a correlation coefficient for testing the corollary hypothesis. In obtaining the SMI a masked audiogram was taken using a narrow band masking noise with the center frequency at 250 Hz and presented at an intensity level of 90 dB sound pressure level (SPL). The differences between threshold values of the masked audiogram and the pure tone audiogram given under quiet conditions were totaled for each octave frequency between 500 and 8000 Hz and the sum was divided by five. The mean SMI for all subjects was then correlated with the mean difference scores for Condition 1 and the three experimental conditions involving high-pass filtering. As stated previously, a high positive correlation would indicate more directly the relationship between spread of masking and self-masking.

The computational procedure of the articulation index (AI) was introduced and used as an additional measure in observing the existence of self-masking from another standpoint. The AI is a method of predicting discrimination facility of a normal listener
under the threshold and noise conditions that typified those of the experimental subjects of the present study.

The results obtained by the application of the procedures described above are summarized below.

**Results and Conclusions**

In statistically testing the main effects of the four experimental conditions, a one-way analysis of variance procedure with repeated scores was employed. No significant difference was found at the .05 level of confidence between any of the compared test conditions. Therefore, the hypothesis which stated that self-masking was not a significant variable in the discriminative ability of an individual with high-frequency sensorineural hearing impairment was accepted.

The results of establishing a correlation coefficient demonstrated a positive correlation between the SMI and the discrimination difference scores when the scores derived from the no filtering condition were compared with those from each of the high-pass filtering conditions. Although not statistically significant, the direction of the correlation indicated a positive relationship between spread of masking by pure tones and self-masking by speech.

The predictive procedure of the AI illustrated what could be termed quite different results. When difference scores were computed for the observed scores obtained in testing the subjects versus
the predicted scores derived by the AI, the following conclusions were drawn: (a) The AI could not accurately predict the discrimination scores of the subjects in this sample under high-pass filtering conditions. (b) Therefore, individuals with high-frequency sensorineural loss do suffer discriminative deficits at high signal levels to a greater degree than would the normal listener with the same audiometric configuration and degree of hearing loss.

The above experimental findings present what would seem to be two opposing results. In the statistical test for significance, the null hypothesis had to be accepted, indicating that self-masking was not a contributing factor in speech intelligibility. However, the results of the computational procedures for speech intelligibility by the AI demonstrated that a variable in speech intelligibility did exist in the sensorineural hypacusis with high-frequency hearing loss other than just the audiometric configuration of degree of hearing loss. Not only did the AI fail to predict accurately the improved discrimination scores on any of the high-pass filtered conditions, it also became less predictive as greater portions of low-frequency speech components were removed. The AI predicted that the discrimination scores should decrease at high-pass filtering conditions affecting greater portions of the speech spectrum, yet there was no significant change in mean discrimination scores for any of the test conditions. If the analysis of variance test used on the observed scores in the
present study had been run on the predictive scores, significance would have been obtained which would have indicated that as progressively more of the speech signal was removed, discriminative performance should have become less.

The positive correlation between the SMI and improvement in discrimination scores at each high-pass cutoff supports the conclusion that there exists a low-frequency component in the speech signal that is positively correlated with the spread of masking evidenced by the masked audiogram. When the results obtained from the correlation data and the predictive scores determined by the AI are considered together, it appears that self-masking does exist to a sufficient degree to affect the discriminatory performance of the sensorineural hypacusis when listening at high-intensity levels.

The purpose of the analysis of variance as designed for this investigation was to test for significance between the condition involving no filtering of the speech stimulus and each of three other conditions involving a varying degree of low-frequency filtering of the speech stimulus. The null hypothesis which stated that no significant difference would be evidenced in testing these conditions cannot be rejected. However, the removal of the information contained in the low-frequency speech elements possibly negated the positive effects of the reduction in self-masking. This statement is supported by the positive correlation of the SMI with the difference scores of the no-filtered versus the high-pass filtered conditions.
Finally, the predictive value of the AI is obviously not accurate under the conditions and design of this investigation. The absence of a positive relationship between predictive scores and observed scores lends evidence to the effect of self-masking when speech is presented at high-intensity levels to the sensorineural hypacusis.
LITERATURE CITED


APPENDIX
Table 9. Raw discrimination scores, means, and standard deviations obtained from the testing of 20 sensorineural hypacusics with high-frequency hearing loss under four experimental conditions.

|                | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | Mean | Standard deviation |
|----------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|-----|-------------------|
| Quiet          | 68 | 72 | 74 | 78 | 70 | 78 | 66 | 74 | 54 | 64 | 66 | 78 | 66 | 74 | 80 | 72 | 64 | 68 | 58 | 69   | 6.53             |
| 600 Hz high-pass filter | 74 | 78 | 82 | 80 | 68 | 78 | 72 | 82 | 60 | 76 | 60 | 68 | 80 | 72 | 70 | 78 | 76 | 60 | 66 | 52 | 72   | 8.03             |
| 900 Hz high-pass filter | 76 | 78 | 84 | 68 | 44 | 80 | 70 | 78 | 62 | 62 | 66 | 72 | 80 | 70 | 78 | 76 | 68 | 68 | 54 | 71   | 9.38             |
| 1200 Hz high-pass filter | 74 | 74 | 84 | 76 | 60 | 58 | 64 | 68 | 50 | 72 | 54 | 70 | 76 | 68 | 60 | 76 | 74 | 70 | 70 | 52 | 67.5  | 7.63             |
VITA

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Master of Science

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