The effects of hearing loss on the contribution of high- and low-frequency speech information to speech understanding

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The speech understanding of persons with “flat” hearing loss (HI) was compared to a normal-hearing (NH) control group to examine how hearing loss affects the contribution of speech information in various frequency regions. Speech understanding in noise was assessed at multiple low- and high-pass filter cutoff frequencies. Noise levels were chosen to ensure that the noise, rather than quiet thresholds, determined audibility. The performance of HI subjects was compared to a NH group listening at the same signal-to-noise ratio and a comparable presentation level. Although absolute speech scores for the HI group were reduced, performance improvements as the speech and noise bandwidth increased were comparable between groups. These data suggest that the presence of hearing loss results in a uniform, rather than frequency-specific, deficit in the contribution of speech information. Measures of auditory thresholds in noise and speech intelligibility index (SII) calculations were also performed. These data suggest that differences in performance between the HI and NH groups are due primarily to audibility differences between groups. Measures of auditory thresholds in noise showed the “effective masking spectrum” of the noise was greater for the HI than the NH subjects. © 2003 Acoustical Society of America. [DOI: 10.1121/1.1553458]

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I. INTRODUCTION

Previous research suggests that the presence of sensorineural hearing loss (SNHL) may reduce the contribution of speech information in a given frequency region to speech understanding (i.e., Pavlovic et al., 1986; Studebaker et al., 1997). What is not clear, however, is whether SNHL has a differential effect on the contribution of speech information depending on the frequency region where the hearing loss occurs. At least three differing viewpoints on this question have been expressed in the literature.

First, early work in this area suggests that the presence of hearing loss results in a “uniform deficit” in the contribution of speech information across all affected frequencies (Boothroyd, 1978; Pavlovic, 1984; Pavlovic et al., 1986; Studebaker et al., 1997). In a 1978 paper, Boothroyd discussed a series of experiments in which he measured speech understanding under various conditions of low- and high-pass filtering. He used these results to determine the relative contribution of different frequency regions to phoneme identification for children with hearing loss (Boothroyd, 1967, 1968). Study results showed that for persons with flat hearing losses the contribution of speech information was reduced across all frequencies equally. In contrast, individuals with high-frequency losses showed a reduced contribution of speech information primarily in the regions where hearing loss was present and followed the normal pattern in regions where hearing was near normal. In other words, he observed that it was primarily the presence of hearing loss that resulted in a reduction in the contribution of a frequency region to speech understanding, regardless of the frequency region where the loss occurred.

Other support for a “uniform deficit” comes from earlier work utilizing the articulation index (ANSI S3.5, 1969) or AI (now referred to as the speech intelligibility index or SII, ANSI S3.5, 1997) to investigate deficits in speech understanding of persons with hearing loss not explained by reduced audibility or adverse listening conditions such as high presentation levels. Several researchers developed correction factors to account for the negative effects of hearing loss on speech understanding (Pavlovic, 1984; Pavlovic et al., 1986; Studebaker et al., 1997) and have reported good improvements in their predictive accuracy. The magnitude of these correction factors, however, was independent of the frequency region where the hearing loss occurred.

Data from several recent studies provide a contrast view on the impact of hearing loss on speech information in various frequency regions. These studies suggest that hearing loss may result in a “frequency-specific” deficit in the contribution of speech information. Specifically, persons with hearing loss may be less able to make use of amplified high-frequency information (i.e., above 3000 Hz) than amplified low-frequency information, particularly when their thresholds are worse than 55–80 dB HL (Ching et al., 1998; Hogan and Turner, 1998; Turner and Cummings, 1999; Amos, 2001). Hogan and Turner (1998) described the “efficiency” with which persons with high-frequency sloping SNHL were able to make use of speech information in various frequency regions. They found that the persons with hearing loss were limited in their ability to make use of amplified speech information above 4000 Hz, particularly when

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the degree of hearing loss in this frequency region exceeded about 55 dB HL. This group appeared better able to make use of lower frequency information even in the presence of a similar degree of hearing loss.

Ching et al. (1998, 2001), using slightly different methods and participants with a wider range of hearing losses, reported similar findings. These authors compared the sentence recognition performance of persons with hearing loss, using filtered sentence materials in quiet, to SII predictions. The authors derived several correction factors to the standard SII procedure in an attempt to reduce the error between predicted and observed scores. The best fit occurred when “individual frequency-dependent proficiency” corrections were applied in conjunction with the standard SII correction for high presentation levels. The frequency-dependent correction factors were largest in the high-frequency regions.

Turner and Cummings (1999) reported findings similar to Hogan and Turner and Ching et al. Their study participants, primarily persons with high-frequency SNHL, listened to unfiltered nonsense syllables in quiet as presentation levels were systematically increased until asymptotic performance levels were reached. Their results also suggested that restoring the audibility of high-frequency information (above 3000 Hz) to persons with high-frequency hearing losses greater than about 55 dB HL provided limited benefits in terms of speech understanding.

A third suggestion in the literature is that persons with hearing loss differ in their ability to make use of amplified speech information in various frequency regions and that these differences may be due to the presence or absence of “cochlear dead regions” (Moore et al., 2000; Vickers et al., 2001; Baer et al., 2002). A dead region has been defined as a region of the basilar membrane associated with a “complete loss of inner hair cells” (Moore et al., 2000). Vickers et al. (2001) compared the speech understanding in quiet of two groups of persons with hearing loss at multiple low-pass filter cutoff frequencies. One group of subjects had high-frequency dead regions while the other group did not. Potential dead regions within the cochlea were identified using both psychophysical tuning curves and the threshold equalizing noise (TEN) test (Moore et al., 2000). The TEN test is a clinical test that measures auditory thresholds in quiet and in a spectrally shaped broadband noise. Thresholds in noise that are abnormally elevated (as described later in the text) are suggestive of dead regions. Vickers et al. (2001) found that, in general, individuals with identified high-frequency dead regions made limited use of amplified high-frequency information to improve speech understanding. In contrast, subjects with hearing loss but without dead regions showed more consistent improvement in speech understanding as low-pass filter cutoff frequency was progressively increased. Baer et al. (2002) reported a similar finding for subjects with and without dead regions listening to nonsense syllables in a noise background.

The research discussed here suggests that our understanding of the effects of hearing loss on the contribution of high-frequency speech information remains unclear. Recent findings suggesting a frequency-specific deficit focused primarily in the high frequencies have significant implications in terms of defining appropriate amplification requirements for persons with hearing loss and as such warrant serious consideration. For example, based in part on this research, Ching et al. (2001) suggested that to achieve maximum “effective audibility,” only minimal or even no gain should be provided in some high-frequency regions in the presence of severe or greater hearing loss, so that more gain may be provided to regions with less hearing loss. Following this suggestion would ensure that certain high-frequency speech sounds would remain essentially inaudible for those listeners with severe high-frequency hearing loss. Given the significant implications of the recent findings in this area, further research appears warranted.

This study further investigates the role hearing loss plays in limiting the contribution of speech information in various frequency regions. Specifically, to limit the confound of degree of hearing loss across frequency, subjects with flat losses are used to examine the impact of SNHL on the contribution of high-and low-frequency information to speech understanding. In addition, if frequency-specific deficits are observed, a second purpose of this study is to determine if these deficits are related to the presence of cochlear dead regions.

II. METHODS

A. Participants

A total of 27 participants, 18 with normal hearing and 9 with hearing loss, participated in this study. All participants with normal hearing passed a pure-tone air conduction screening at 20 dB HL (250–8000 Hz; ANSI S3.6, 1996) and had no history of otologic pathology. Participants with normal hearing were randomly divided into two groups (nine per group). One group, identified as the normal-hearing unshaped group (NHU), was used to obtain baseline performance on the speech recognition task used in this study. Participants in this group (two male, seven female) ranged in age from 19 to 31 years (mean 25.4). The other group, normal-hearing shaped (NHS), listened to speech that was spectrally shaped and provided a control group for the individuals with hearing loss which also listened to shaped speech. Speech shaping for listeners with normal and impaired hearing is described later. Individuals in the NHS group (three male, six female) ranged in age from 20 to 37 years (mean 27.2).

Nine persons with flat, moderate-to-severe SNHL (HI group) also participated in this experiment. Flat hearing loss was operationally defined as auditory thresholds ranging between 55 and 70 dB HL at octave frequencies of 500–4000 Hz. The slope of hearing loss, defined as the difference in thresholds at 500 and 4000 Hz, across participants was −5.6 dB, with seven of the nine participants having a slope of 0 to −5 dB.

Participants with hearing loss ranged in age from 42 to 80 years old (mean 66.4 years). Specific demographic details of the persons with hearing loss are provided in Table I. Several subjects reported that their hearing loss was due primarily to noise exposure and aging. Although a flat configuration is not typically associated with these factors, no other...
relevant factors were reported in the subject’s history.

The auditory thresholds of participants with hearing loss were assessed at octave frequencies between 250 and 8000 Hz, as well as at the interoctave frequencies of 3000 and 6000 Hz (ANSI S3.6, 1996). Participants exhibited essentially symmetrical hearing loss (interaural difference of ≤20 dB); air-bone gaps ≤10 dB at all frequencies, and other than hearing loss, reported no history or complaints of otologic pathology, surgery, or unilateral tinnitus. All testing, following the initial threshold assessment, was performed monaurally. The ear with the smallest difference in thresholds between 500 and 4000 Hz was chosen for testing. In contrast, the test ear was systematically varied for the NHU and NHS groups. Table II lists the auditory thresholds, of the ear tested, for each of the HI participants.

B. Procedures

Sentence recognition in noise, at various filter cutoff frequencies, was assessed for all three groups (NHU, NHS, and HI). In addition, the NHS and HI groups also completed threshold testing in a speech-shaped background noise and the TEN test. Participants were compensated for their time on a per session basis.

1. Sentence recognition testing

Sentence recognition was assessed using the connected speech test (CST; Cox et al., 1987, 1988). The CST uses everyday connected speech as the test material and consists of 28 pairs of passages (24 test and 4 practice pairs). The recommended key word method of scoring was used. Each passage pair contained 50 key words. A total of two passage pairs were completed for each condition, and the score for each condition was based on the average result of these two passage pairs (i.e., based on 100 key words).

Sentence recognition was assessed at multiple low- and high-pass filter cutoff frequencies (total of 10–12 filter conditions) in order to obtain performance versus filter cutoff frequency functions. These functions were used in the derivation of crossover frequency for each subject. Crossover frequencies (defined as the filter cutoff frequency at which the score for low- and high-pass filtered speech is the same) allow for the comparison of the relative importance of low- and high-frequency information between groups and thus directly test whether hearing loss results in a frequency-specific deficit in the contribution of speech information.

In all low-pass filter conditions the high-pass filter cutoff frequency was fixed at 178 Hz. Likewise, in all high-pass filter conditions the low-pass filter cutoff frequency was fixed at 6300 Hz. All subject groups completed the following six filter conditions: low pass 1600 and 3150 Hz, high pass 1600 and 800 Hz, wideband (178–6300 Hz), and bandpass (800–3150 Hz). Performance was assessed on each subject in an additional four/five filter conditions to provide a better indication of the performance versus filter cutoff frequency function for each subject. Specifically, speech recognition of the NHU group was also assessed at low-pass filter cutoffs of 800 and 1200 Hz, as well as high-pass filter cutoffs of 2000 and 2400 Hz. The NHS group completed additional speech recognition testing at low-pass filter cutoffs of 800 and 2000 Hz and high-pass filter cutoffs of 2000 and 3150 Hz. The precise filter cutoff frequencies and the total number of filter conditions tested varied somewhat between HI participants due to differences in absolute performance levels. That is, additional cutoff frequencies were inserted in order to obtain the most accurate estimate of crossover frequency. Each HI subject completed a total of two to five additional filter conditions. All testing was completed in two test sessions with at least one CST passage completed in each filter condition during a session. This methodology allowed for results between groups to be examined not only in terms of crossover frequency but also based on absolute changes in performance as filter cutoff frequencies changed.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Length of HL (in years)</th>
<th>HA use (in years)</th>
<th>Binaural aids</th>
<th>Education</th>
<th>Cause of HL</th>
</tr>
</thead>
<tbody>
<tr>
<td>DJ</td>
<td>M 76</td>
<td>20</td>
<td>18</td>
<td>Y</td>
<td>14 Noise/Presbycusis</td>
</tr>
<tr>
<td>JA</td>
<td>M 80</td>
<td>20</td>
<td>20</td>
<td>Y</td>
<td>16 Noise/Presbycusis</td>
</tr>
<tr>
<td>MB</td>
<td>M 80</td>
<td>22</td>
<td>15</td>
<td>Y</td>
<td>14 Noise/Presbycusis</td>
</tr>
<tr>
<td>DG</td>
<td>F 70</td>
<td>12</td>
<td>5</td>
<td>N</td>
<td>12 Presbycusis</td>
</tr>
<tr>
<td>JM</td>
<td>M 80</td>
<td>20</td>
<td>20</td>
<td>Y</td>
<td>14 Noise/Presbycusis</td>
</tr>
<tr>
<td>SG</td>
<td>F 42</td>
<td>40</td>
<td>30</td>
<td>Y</td>
<td>18 Congenital</td>
</tr>
<tr>
<td>AL</td>
<td>F 72</td>
<td>5</td>
<td>2</td>
<td>Y</td>
<td>15 Presbycusis/Genetic</td>
</tr>
<tr>
<td>VP</td>
<td>F 47</td>
<td>16</td>
<td>6</td>
<td>Y</td>
<td>12 Unknown</td>
</tr>
<tr>
<td>SP</td>
<td>M 51</td>
<td>15</td>
<td>15</td>
<td>Y</td>
<td>16 Noise/Unknown</td>
</tr>
<tr>
<td>Average</td>
<td>66.4</td>
<td>18.9</td>
<td>14.6</td>
<td></td>
<td>14.6</td>
</tr>
</tbody>
</table>

TABLE II. Auditory thresholds (in dB HL) for participants with hearing loss.

<table>
<thead>
<tr>
<th>Frequency (in Hz)</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>3000</th>
<th>4000</th>
<th>6000</th>
<th>8000</th>
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<td>65</td>
<td>65</td>
<td>65</td>
<td>65</td>
<td>85</td>
</tr>
<tr>
<td>JA</td>
<td>L</td>
<td>50</td>
<td>60</td>
<td>65</td>
<td>65</td>
<td>65</td>
<td>70</td>
<td>65</td>
</tr>
<tr>
<td>MB</td>
<td>L</td>
<td>55</td>
<td>55</td>
<td>65</td>
<td>70</td>
<td>65</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>DG</td>
<td>L</td>
<td>55</td>
<td>60</td>
<td>65</td>
<td>65</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>JM</td>
<td>L</td>
<td>55</td>
<td>60</td>
<td>55</td>
<td>60</td>
<td>65</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>SG</td>
<td>L</td>
<td>60</td>
<td>65</td>
<td>65</td>
<td>60</td>
<td>65</td>
<td>80</td>
<td>90</td>
</tr>
<tr>
<td>AL</td>
<td>R</td>
<td>70</td>
<td>65</td>
<td>65</td>
<td>70</td>
<td>65</td>
<td>75</td>
<td>65</td>
</tr>
<tr>
<td>VP</td>
<td>L</td>
<td>50</td>
<td>55</td>
<td>70</td>
<td>70</td>
<td>65</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>SP</td>
<td>L</td>
<td>55</td>
<td>60</td>
<td>65</td>
<td>65</td>
<td>60</td>
<td>60</td>
<td>70</td>
</tr>
</tbody>
</table>
The masking noise used in this study was created from the calibration noise (track 80, left channel) provided with the audio version of the CST (Hearing Aid Research Laboratory, Speech Intelligibility Tests, 1994). This calibration noise was modified slightly using commercially available sound editing software (Sonic Foundry: SoundForge V 4.5) to improve the match at 160 Hz. Figure 1 shows the 1/3-octave rms levels (160–6300 Hz) of the CST talker (based on the entire corpus of CST test passages, tracks 32–55) and the masking noise used in this study.

The speech and noise stimuli were digitally recorded (24.414 kHz sampling rate) and stored on a computer hard disk. Noise was on only during the presentation of speech stimuli (~250–500 ms prior to and following the speech). Digital filtering, employing steep filter skirts (i.e., 800 dB/octave), was used to create the filtered speech and noise stimuli. The Tucker-Davis Technologies (TDT) RP2 Real-Time processor was used for mixing, shaping, and real-time filtering of the speech and noise stimuli. The stimuli were digitally mixed at a +6 dB SNR. The +6 dB SNR level was employed in an attempt to limit ceiling effects among the participants with normal hearing while not causing floor effects for the participants with hearing loss.

To improve audibility for the participants with hearing loss, spectral shaping of the mixed speech and noise stimuli was performed. Subjects in the NH group also listened to this shaped speech. The spectral shaping was applied to approximate desired sensation level targets (DSL v4.1 software, 1996) for conversational speech, assuming linear amplification for a subject with a flat 65 dB HL hearing loss (Cornelisse et al., 1995). Shaping was verified by measuring the 1/3-octave rms levels of the masking noise (which spectrally matched the speech) in a Zwislocki coupler using a Larson-Davis 814 sound level meter (slow averaging, C-weighting). The rms value of the difference between coupler outputs and DSL targets (250–6000 Hz) was 1.7 dB, with a maximum difference of ~3 dB. The SNR, shaping, and presentation levels of the speech and noise were chosen, in part, to ensure that noise levels rather than quiet thresholds were the primary factor determining audibility for both the HI and NH groups.

The mixed and shaped stimuli were filtered as needed for the appropriate condition prior to being output from the RP2 (24.414 kHz sampling rate). Following output, the filtered speech and noise were low-pass filtered (10 kHz), amplified using a Crown D75 2-channel amplifier, and routed to an ER3 insert earphone (Etymotic Research). Levels were calibrated in the wideband condition (178–6300 Hz) in a Zwislocki coupler and no corrections for level were applied in the various filter conditions. Output levels were measured in a Zwislocki coupler using a Larson-Davis 814 sound level meter (C-weighting, slow averaging).

Output level for the wideband speech was 95 dB SPL for the NH groups. The 95 dB level was chosen in an attempt to present speech at levels comparable to those experienced by persons with hearing loss when wearing hearing aids, while at the same time limiting loudness discomfort for the participants with normal hearing. All participants in this experiment reported that the 95 dB SPL presentation level was loud, but not uncomfortable. Wideband levels for HI participants varied slightly depending on individual loudness comfort levels. Seven participants preferred an overall speech level of 103 dB SPL while two participants preferred a higher speech level of 108 dB SPL. Coherence measurements at the output of the earphones indicated minimal distortion (average coherence ~0.95 over the frequencies of 178–6300 Hz) when the speech-shaped noise was presented at the highest speech level used in this study (108 dB SPL).

2. Threshold assessment in noise

Monaural masked thresholds, using the same ear used for speech testing, were determined for the octave frequencies of 250–4000 Hz, as well as the interoctave frequencies of 3000 and 6000 Hz. Masked thresholds in noise were obtained for two primary reasons. First, measuring thresholds in the speech noise helps confirm that the masking noise, rather than quiet thresholds, determined the audibility of speech. Additionally, previous research has shown that masked thresholds of HI persons may be greater than those of NH subjects listening in the same noise. In other words the “effective masking spectrum” of the noise may be greater for HI persons than NH persons (i.e., Dubno and Ahlstrom, 1995). Therefore, a second reason for measuring thresholds in the speech noise is to determine the “effective masking spectrum” of this noise for each group. This information may be useful in explaining residual differences in speech understanding between groups.

A clinical method of threshold assessment (ASHA, 1978) was used, however, step sizes were reduced (4 dB down–2 dB up) to improve threshold accuracy. The background noise used during threshold testing was the same noise, previously described, used during speech testing and was on continually during threshold assessment. An attempt was made to measure masked thresholds at the same overall masker level as was used during speech testing. Levels, however, varied slightly depending on the loudness tolerance of individual participants. Overall levels of the masking noise,
measured in a Zwislocki coupler using a Larson-Davis 814 sound level meter (C-weighting, slow averaging), were 86–89 dB SPL for the NHS participants and ranged from 94 to 102 dB SPL for the HI participants.

3. Diagnosis of dead regions

Cochlear integrity was assessed for the HI and NHS groups using the CD version of the “TEN test” (Moore et al., 2000). Pure-tone thresholds for each subject with hearing loss were measured monaurally (same ear as speech testing) in quiet and in the presence of the “threshold equalizing noise,” at octave frequencies of 250–4000 Hz and interoctave frequencies of 3000 and 6000 Hz. In addition, 5000 Hz was also tested for the HI participants. TEN levels varied, depending on loudness discomfort issues, from 65 to 80 dB/ERB (overall levels of 81.5–96.5 dB SPL in a Zwislocki coupler) for the NHS participants and between 75–85 dB/ERB (overall levels of 91.5–101.5 dB SPL) for the HI participants. A subject is considered to have a dead region at a specific frequency if (1) the masked threshold is 10 dB or more above absolute threshold in quiet and (2) the masked threshold is at least 10 dB or more above the noise level per ERB (Moore, 2001).

III. RESULTS AND ANALYSIS

A. Test session effects

Recall that speech data for each participant were collected during two test sessions. To examine potential practice effects, an initial mixed model analysis of variance (ANOVA) was performed. An alpha level of 0.05 was used for this, and all other, statistical analyses reported in this paper. Prior to statistical analysis, individual percent correct scores were converted to rationalized arcsine transform units (RAUs) to stabilize the error variance (Studebaker, 1985). Only the filter conditions that all three groups (NHU, NHS, and HI) completed were used in the analysis (low pass 1600 and 3150 Hz, high pass 1600 and 800 Hz, wideband 178–6300 Hz, and bandpass 800–3150 Hz).

ANOVA results showed a significant between-subjects main effect of group ($F_{1,24} = 1097.41, p < 0.001$) and a significant within-subjects interaction between filter condition and group ($F_{10,120} = 2.28, p = 0.018$). Follow-up testing was not performed at this time since the primary focus of this ANOVA was on differences between test sessions. A significant within-subject main effect of test session ($F_{1,24} = 5.69, p = 0.025$) was also observed. Overall performance was slightly better during the second session (~2.7% improvement), however, no significant interaction effects were observed. Therefore data between test days were collapsed for further analysis.

B. Derivation and examination of crossover frequencies

To determine crossover frequencies, each participant’s average sentence recognition scores (in proportion correct) were plotted as a function of the log of their filter cutoff frequency. Then nonlinear regression, using a three-parameter sigmoid function (SPSS, Inc.: SigmaPlot V. 5.0), was used to provide a best fit to the low- and high-pass data. Regression functions were then used to determine the crossover point.

In this formula, $y$ represents the predicted CST score, $x$ represents the filter cutoff frequency and $a$, $b$, and $x_0$ are free parameters. Figure 2 shows typical single subject results from the NHS (subject RH) and HI (subject JM) groups. The symbols represent the measured scores while the solid lines represent the regression function. The fitted functions were used to determine the crossover frequency.

The polynomial functions for the NH participants provided a good fit to the data, with $r^2$ values ranging from 0.96 to 0.99. The average scores at the crossover frequency were 40% and 41% for the NHU and NHS groups, respectively. The sigmoid function also provided a good fit to the HI data, although results were more variable with $r^2$ values ranging from 0.93 (subject JM high pass data) to 0.99. The average score at crossover frequency (14%) was lower for the HI group than for the NHU or NHS groups.

NHU group data was obtained primarily to verify that spectral shaping, appropriate for a person with a flat hearing loss, would not affect the relative importance of different frequency regions to speech understanding. To examine the
impact of spectral shaping, crossover frequencies were derived for each subject in the NHU and NHS groups and a single factor between-subjects ANOVA was used to examine differences in crossover frequencies between groups. The independent and dependent variables were subject group and crossover frequency (in Hz), respectively. ANOVA results showed no statistically significant ($F_{1,16} = 0.59, p = 0.45$) differences in crossover frequencies between the NHS and NHU groups. Consequently, all further analysis focuses on results from the NHS and HI groups.

Of primary interest in this study was the effect of hearing loss on the importance of high- and low-frequency information to speech understanding. Recall that one viewpoint suggests that participants with hearing losses are less able to make use of high- versus low-frequency speech information when compared to participants with normal hearing listening under comparable conditions (i.e., similar SNRs and presentation levels). This difference would result in systematic lowering in crossover frequencies for participants with hearing loss. In contrast, if a uniform deficit occurs across all frequencies, then absolute performance levels of the HI group may be lower, but crossover frequencies should be the same between groups. To examine the effect of hearing loss on crossover frequency, a single-factor between-subjects ANOVA was used to examine differences in crossover frequencies between the HI and NHS groups. The independent and dependent variables were subject group and crossover frequency (in Hz), respectively. Figure 3 shows the average crossover frequencies for the HI and NHS groups as well as individual crossover frequencies for each HI and NHS participant.

The average crossover frequencies in this study were somewhat higher for the HI group, with mean crossover frequencies of 1600 and 1460 Hz for the HI and NHS groups, respectively. This pattern approached, but did not reach, statistical significance ($F_{1,16} = 4.13, p = 0.059$). The results in
low- or high-frequency bandwidth increased. Finally, a significant interaction between filter condition and group was also observed for the HP data only. This finding suggests that as the HP filter cutoff frequency was lowered, changes in CST performance were different between the NHS and HI groups. No such interaction was noted in the LP condition, suggesting that on average, the HI and NHS groups made similar use of increases in high-frequency information as the low-pass filter cutoff frequency increased.

Follow-up analysis was performed, using a series of planned comparisons, to determine (1) if the improvements in CST score with bandwidth increases were statistically significant and (2) to determine the cause of the significant interaction in the HP condition. Results revealed that CST scores increased significantly ($p < 0.001$) with each increase in filter cutoff frequency regardless of the condition (e.g., LP or HP conditions). Likewise, a significant effect of group ($p < 0.001$) was also observed in each follow-up analysis with the HI group performing significantly poorer than the NHS group in each condition. A significant interaction between group and filter condition, however, was present only in the analysis of the HP data when comparing performance in the HP1600 Hz and HP800 Hz conditions ($F_{1,16} = 9.76, p = 0.007$). A review of Fig. 4 shows that in these conditions average scores for the NHS group increased 42% as the high-pass filter cutoff frequency was lowered from 1600 to 800 Hz. CST scores for the HI group, however, increased only 29.8%, resulting in a significant interaction effect between filter condition and group.

The results shown in Fig. 4 also suggest that performance improvements for the NHS group may be limited in some conditions by ceiling effects. Consistent with performance in the LP and HP conditions, significant within-subjects effects of filter condition and significant between-subjects effects of group were observed (see Table III). Overall performance was reduced for the HI, compared to the NHS group, and performance improved for both groups as bandwidth increased, compared to performance listening to the mid-frequency band (800–3150 Hz) alone. Also consistent with performance in the LP conditions, no significant interaction effect between group and filter condition was observed, suggesting that the HI and NHS groups made similar use of the additional high- and low-frequency information, when added to a mid-frequency band of speech.

D. Thresholds in noise

1. Thresholds in speech noise

Masked thresholds were first compared to thresholds in quiet to confirm that the masking noise, rather than quiet thresholds, determined audibility differences between groups. Results showed that quiet thresholds for both the NH and HI groups were shifted at least 5 dB by the masking noise at all frequencies tested with the exception of 6000 Hz. At 6000 Hz the level of masking noise was not intense enough to cause a 5-dB shift in quiet thresholds for six of the nine HI participants. For these HI participants, auditory threshold at 6000 Hz rather than the masking noise dictated audibility in noise.

In addition, differences in the “effective masking spectrum” of the background noise, between the NHS and HI groups, were evaluated by subtracting the 1/3-octave band level (dB SPL) of the noise from the level of the pure tone at 3150 Hz. Since the wider bandwidth (178–3150 and 800–6300 Hz) used in these comparisons were narrower than the broadband condition (178–6300 Hz), maximum performance levels were also reduced, thus reducing the impact of ceiling effects. Results (in percent correct) are shown in Fig. 5.

Consistent with performance in the LP and HP conditions, significant within-subjects effects of filter condition and significant between-subjects effects of group were observed (see Table III). Overall performance was reduced for the HI, compared to the NHS group, and performance improved for both groups as bandwidth increased, compared to performance listening to the mid-frequency band (800–3150 Hz) alone. Also consistent with performance in the LP conditions, no significant interaction effect between group and filter condition was observed, suggesting that the HI and NHS groups made similar use of the additional high- and low-frequency information, when added to a mid-frequency band of speech.

FIG. 5. Average CST scores for NH and HI participants as a function of increasing low- or high-frequency bandwidth. The filled and unfilled symbols show scores for the HI and NH participants, respectively. Error bars show 1 standard deviation.
threshold (as measured in a Zwislocki coupler). This process provided the SNR required for threshold detection in noise. The SNRs were then compared between groups. Described in this fashion a more negative SNR is better (i.e., lower signal SPL is required for threshold in noise). The average results for the NHS and HI group, as well as individual results for HI participants, are shown in Table IV for the frequencies of 250–4000 Hz.

As seen in Table IV, average SNRs for participants with hearing loss were substantially elevated compared to the NHS group. A mixed model analysis of variance (ANOVA) was performed to examine differences in SNRs between the NHS and HI groups. The within- and between-subjects independent variables for this analysis were frequency (250, 500, 1000, 2000, 3000, and 4000 Hz) and group (NHS and HI), respectively. The dependent variable was the SNR for each participant. A significant main effect of group ($F_{1,16} = 64.201, p < 0.001$) was observed with the average SNR for HI participants about 5.4 dB poorer (higher) than for the NHS participants. In other words the “effective masking spectrum” of the speech noise was significantly greater for the HI participants than the NHS participants. This suggests that despite listening at the same acoustic SNR, audibility between groups was not equated. In addition, differences between HI and NHS thresholds did vary as a function of frequency. The group-by-frequency interaction in the ANOVA analysis showed that these frequency-specific differences in SNRs approached, but did not reach, statistical significance ($F_{5,80} = 2.12, p = 0.072$).

2. Thresholds in TEN

Although any broadband background noise (i.e., the speech noise described above) may be used to identify suspected dead regions, the TEN test (Moore et al., 2000; Moore, 2001) was specifically designed to allow relatively quick identification and quantification of suspected dead regions. Therefore cochlear integrity was assessed using the TEN. Results for all NHS participants showed that the masking noise produced at least 10 dB of masking and all NHS subjects showed masked thresholds well within ±5 dB of the expected threshold (based on the level of the TEN). Cochlear integrity in the NHS group appeared to be normal, as expected.

Due to loudness discomfort issues and the severity of hearing loss, results for the HI participants were not as easily interpreted. First, due to loudness discomfort issues, the level of masking noise/ERB could not be raised enough to cause a 10-dB shift in quiet thresholds for many participants. In fact, none of the participants demonstrated at least a 10-dB shift in quiet thresholds for many participants. In fact, none of the participants demonstrated at least a 10-dB shift in quiet threshold across all of the eight frequencies tested (250, 500, 1000, 2000, 3000, 4000, 5000, and 6000 Hz), although seven of the nine HI participants did show at least a 10-dB shift at three of the eight frequencies. Of those participants, four showed an abnormal shift in masked thresholds (i.e., thresholds at least 10 dB above the masker level/EBR and 10 dB above threshold in quiet). Results for these four participants are shown in Fig. 6.
E. Speech intelligibility index (SII) calculations

The primary focus of this experiment was to examine whether hearing loss differentially affects the contribution of speech information based on the frequency region of the hearing loss. To make this comparison it is important that audibility, as a function of frequency, be comparable between our NHS and HI groups. Measures of masked thresholds, however, revealed that thresholds were substantially poorer for the HI group compared to the NHS group. In addition, differences in masked thresholds between the NHS and HI groups varied (although not significantly) as a function of frequency. To determine whether differences in audibility between groups could account for the observed performance of the HI subjects, 3-octave band SII calculations (ANSI S3.5, 1997) were performed on the data for each subject. Measures of masked thresholds were interpolated or extrapolated to match the 2-octave center frequencies used in the SII calculations. These thresholds, along with 2-octave rms levels of the speech stimuli, were used to determine the SNR in each 2-octave frequency band. The frequency importance function specifically derived for the CST materials was used (Scherbecoe and Studebaker, 2002). In addition, the effective speech peaks for the CST proposed by Scherbecoe and Studebaker (2002) were used rather than assuming 15-dB peaks as in the ANSI standard. The correction for high presentation levels proposed in the ANSI standard was also included in the calculations, however, corrections for spread of masking effects were not since measures of masked threshold already account for these effects.

1. SII results for the NHS group

CST scores, for the NHS group, as a function of SII are shown in Fig. 7. Each data point represents the score of a single NHS subject in one of the ten filter conditions previously described. The solid lines in Fig. 7 show a transfer function and 95% confidence intervals relating the SII to CST performance.

The transfer function was derived using Eq. (1) with $x$ representing the SII value in a given filter condition for the

$$
SII = a + bx + x^2
$$

FIG. 7. CST scores as a function of SII for the NHS group. Each data point represents the score of a single NHS subject in one of ten filter conditions. The solid lines show the transfer function and 95% confidence intervals relating the SII to CST performance.

2. SII results for the HI group

Utilizing the transfer function derived from the NHS data, predictions of individual HI performance were then compared to actual performance across the various filter conditions. Figure 8 shows the individual scores of HI subjects as a function of SII values along with the transfer function for the NHS group. In addition, average results and SII predictions for the HI subjects in the LP, HP, and BW conditions are shown in panels (a) and (b) of Fig. 9.

Together these figures clearly show that, when listening under comparable conditions of audibility, the performance of the HI persons was consistent with that of the NHS group. The poorer performance of the HI group observed earlier in Fig. 4 appears to be due primarily to the increased effectiveness of the masking noise on the HI subjects, thus reducing the audibility of the speech materials. In other words, the utility of speech information appears to be limited primarily by reduced audibility and the reduction is observed uniformly across all frequencies regions.

It is important to note that the accuracy with which the SII predicts the HI data in this study occurs, in part, because the SNRs used in the SII calculations were based on measured thresholds in noise rather than acoustic measures of noise and quiet thresholds. Figure 10 shows the discrepancy between HI performance and SII predictions when the SII is calculated using the 2-octave levels of the speech and noise and individual subject thresholds in quiet. The transfer function and confidence intervals shown in Fig. 10 were derived using the same procedure described in Sect. III E 1, however, SII values were based on acoustic measures of speech and noise levels and quiet thresholds (rather than measured masked thresholds). Since masked thresholds were not used, corrections for spread of masking effects were not included in the calculation along with the correction for high presenta-
tion levels as described earlier. In this case the SII assumes that acoustic noise levels dictate audibility and that audibility is similar between groups. Therefore the performance of the HI subjects appears to be poorer than predicted based on the NHS transfer function.

IV. DISCUSSION

The focus of this study was on the effects of hearing loss on the importance of various frequency regions to speech understanding. Three potential effects were discussed in the Introduction. Specifically, hearing loss may result in (1) a uniform reduction in the contribution of speech information across all frequencies, (2) a frequency-specific deficit, focused in the high frequencies, and (3) a frequency-specific deficit that varies depending on the presence or absence of cochlear dead regions. The results of this study suggest that, in the absence of dead regions, listeners with relatively flat hearing loss configuration exhibit a more uniform, rather than frequency-specific, deficit in speech understanding.

Support for this conclusion comes from study results showing that, although absolute scores for the HI group were reduced, crossover frequencies for persons with flat hearing losses were comparable to those seen in the normal-hearing control group. The analyses of scores as a function of filter cutoff frequency also add support to the idea that persons with hearing loss are able to make good use of audible high-frequency information to improve speech understanding. On average, CST scores for HI participants improved about 16% when low-pass cutoff frequency was increased from 3150 to 6300 Hz. In contrast, average performance for the NHS group improved only about 5% with the same change in filter cutoff frequency, although ceiling effects played a large role in limiting the NHS improvement. In the band-widening condition, where ceiling effects were less pronounced, improvement in CST scores as the high-frequency bandwidth increased were essentially equivalent for the NHS and HI groups (21% and 24% improvements, respectively). In addition, the results of the SII analysis showed that the NHS and HI groups in this study made comparable use of audible acoustic information across all frequencies tested.

These results are in contrast to some recent work suggesting that moderate to severe hearing loss limits the usability of high-frequency information more than low frequency information (Hogan and Turner, 1998; Turner and Cummings, 1999; Ching et al., 1998, 2001; Amos, 2001). The reason for these findings is unclear; however, several differences between the current research and previous works may have played a role. Such differences include degree of high-frequency hearing loss, configuration of hearing loss (flat versus sloping), and use of a NH control group listening at comparable presentation levels. Other differences between studies that may make comparisons difficult include differences in speech materials, steepness of filter skirts, filter cutoff frequencies, and the presence or absence of noise. The potential impact of some of these factors is discussed below.

One difference between the current study and some previous works, showing a high-frequency deficit for persons with hearing loss, is the degree of high-frequency hearing loss among the participants. In the current study high-frequency hearing loss at 3000–4000 Hz averaged about 65 dB HL and was no greater than 70 dB HL. In contrast, previous studies reporting limited benefit of high-frequency information for persons with hearing loss included some participants with a greater degree of high-frequency hearing loss. For example, participants with flat losses in the Ching...
et al. (1998) study had average thresholds at 3000–4000 Hz of about 80 dB HL and participants with severe–profound sloping losses had average thresholds over 100 dB HL. Likewise, some participants with sloping losses in the Hogan and Turner (1998) study had thresholds greater than 70 dB HL at 3000–4000 Hz. It is possible, therefore, that differences in hearing thresholds between studies may have played some role in the discrepant findings. The fact, however, that no HI subjects in this study showed crossover frequencies substantially lower than NH subjects suggests that a cautious approach should be taken when determining a degree of high-frequency hearing loss above which the benefits of amplification may limited.

Another factor distinguishing the current study from the previously cited research is that this study focused on participants with flat rather than sloping hearing losses. It is possible that fundamental differences in the impact of SNHL on speech understanding exist between participants with flat and sloping hearing losses. For example, since participants with high-frequency hearing losses make relatively good use of low-frequency information and speech information is highly redundant across frequencies, persons with high-frequency SNHL simply do not have to rely heavily on the more degraded high-frequency speech cues. This would be especially true when the speech materials were presented in quiet, as in several previous experiments (i.e., Hogan and Turner, 1998; Ching et al., 1998). In contrast, participants with flat losses having some degradation across all frequencies may require a broader range of cues regardless of the frequency region.

Recent work by Turner and Henry (2002) suggest that the presence of background noise, as in this study, may also play an important role in determining the utility of amplified high-frequency speech information. Similar to Hogan and Turner (1998), these authors calculated the “efficiency” with which persons with sloping SNHL could make use of increases in high-frequency speech information. Speech understanding was measured at multiple low-pass filter cutoff frequencies in a multitalker babble noise rather than in quiet. In contrast to the Hogan and Turner study, but consistent with the current study, subjects with SNHL listening in noise showed positive efficiencies across all frequency regions regardless of the degree of hearing loss. That is, subjects with high-frequency hearing loss were able to use amplified high-frequency speech information to improve speech understanding regardless of the degree of hearing loss.

The authors suggest that noise substantially limited access to audible speech information and this limitation may explain the discrepant findings between studies completed in quiet and those in noise. When speech is presented in quiet, broad access to “easy” speech cues, such as voicing, are available even when the speech is heavily low-pass filtered. As the low-pass filter cutoff frequency is increased the additional information must be used to improve recognition of the more difficult speech features, such as place of articulation. These cues are often difficult for persons with HL even when the speech is presented broadband and in quiet (i.e., Wang et al., 1978). In contrast, when the speech is presented in a noisy background, access to easy speech cues may be limited as well. Thus the additional information provided as the filter cutoff frequency is increased can be used to improve recognition of the easier speech cues, resulting in performance improvements in noise that may be reduced in quiet.

Finally, the role that cochlear dead regions play in determining the utility of speech information in various frequency regions remains unclear. Although scores were consistently lower across all filter conditions for the HI participants in this study, results using the TEN test suggest large-scale frequency-specific cochlear damage was unlikely in the participants tested in this study. While the prevalence of dead regions among individuals with SNHL remains unknown, research suggests that high-frequency dead regions are more often associated with severely sloping high-frequency losses or with losses greater than 95 dB in the high frequencies (Moore, 2001; Kapadia et al., 2002). Thus the absence of large-scale high-frequency dead regions among our subjects is not unexpected, given the criteria used for inclusion in the hearing loss group. The results of our work are consistent with that of Vickers et al. (2001) and Baer et al. (2002) in that our HI subjects did not show evidence of dead regions and were able to make good use of amplified high-frequency speech information. It is possible that subjects in previous studies showing a high-frequency deficit had dead regions in the high frequencies that limited the utility of amplified speech information. The results from the current study, however, show that the presence of cochlear dead regions is not a prerequisite for poorer than normal speech understanding.

V. CONCLUSIONS

In summary, the results of this study lead to the following conclusions. First, high-frequency information (above 3000 Hz) can be quite useful, in terms of speech understanding, for persons with flat SNHL and high-frequency thresholds up to 70 dB HL. Thus a cautious approach is suggested when clinicians are considering limiting gain in the high frequencies, at least for participants with the degree and configuration of hearing loss examined in this study. Second, when hearing loss across frequencies is similar (i.e., for persons with flat HL), the relative importance of each frequency region appears to be similar to that of subjects with NH. Third, SNHL can have a significant negative impact on speech understanding even in the absence of cochlear dead regions. Finally, the overall poorer performance of HI participants in this study is well explained by reduced audibility due to the increased susceptibility to masking seen in these HI participants.


