
A Psychophysical Evaluation of Spectral Enhancement

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Listeners with sensorineural hearing loss have well-documented elevated hearing thresholds; reduced auditory dynamic ranges; and reduced spectral (or frequency) resolution that may reduce speech intelligibility, especially in the presence of competing sounds. Amplification and amplitude compression partially compensate for elevated thresholds and reduced dynamic ranges but do not remediate the loss in spectral resolution. Spectral-enhancement processing algorithms have been developed that putatively compensate for decreased spectral resolution by increasing the spectral contrast, or the peak-to-trough ratio, of the speech spectrum. Several implementations have been proposed, with mixed success. It is unclear whether the lack of strong success was due to specific implementation parameters or whether the concept of spectral enhancement is fundamentally flawed. The goal of this study was to resolve this ambiguity by testing the effects of spectral enhancement on detection and discrimination of simple, well-defined signals. To that end, groups of normal-hearing (NH) and hearing-impaired (HI) participants listened in 2 psychophysical experiments, including detection and frequency discrimination of narrowband noise signals in the presence of broadband noise. The NH and HI listeners showed an improved ability to detect and discriminate narrowband increments when there were spectral decrements (notches) surrounding the narrowband signals. Spectral enhancements restored increment detection thresholds to within the normal range when both energy and spectral-profile cues were available to listeners. When only spectral-profile cues were available for frequency discrimination tasks, performance improved for HI listeners, but not all HI listeners reached normal levels of discrimination. These results suggest that listeners are able to take advantage of the local improvement in signal-to-noise ratio provided by the spectral decrements.

KEY WORDS: psychoacoustics, hearing aids, hearing loss, sensorineural hearing loss, speech perception in noise

Modern hearing aids have used amplification and compression as the primary methods for accommodating sensorineural hearing loss (SNHL), providing significantly improved speech audibility without causing discomfort. However, restoration of speech audibility has not yet resulted in full speech understanding, especially in noise. Plomp (1978) described two components of SNHL: (a) attenuation and (b) distortion. Hearing aids compensate for the attenuation factor but do not overcome the distortion component of hearing loss. Recent signal-processing techniques have been suggested to improve the effective signal-to-noise ratio (SNR), which partially compensates for the distortion factor. One processing scheme that has been introduced to improve speech understanding is spectral enhancement. When a signal consisting of speech and noise is input to a digital spectral enhancement-system, the formants (or spectral peaks) in the

speech are selectively amplified, while the spectral valleys between the peaks are either unaffected or attenuated. The peak-to-trough decibel difference is increased through spectral enhancement, which effectively improves the local speech-to-noise ratio. Several groups have implemented algorithms for increasing spectral contrast, but the results have been mixed at best (e.g., Baer, Moore, & Gatehouse, 1993; Franck, Sidonne, van Kreveld-Bos, Dreschler, & Verschuure, 1999; Lyzenga, Festen, & Houtgast, 2002; Miller, Calhoun, & Young, 1999a; Simpson, Moore, & Glasberg, 1990). The reason for the lack of success is not clear, but it may be that spectral enhancement is a theoretically flawed strategy or that the implementation of spectral enhancement has been done ineffectively. The purpose of this study was to determine whether spectral enhancement is viable.

Numerous studies of psychophysical tasks have shown differences between normal and impaired listeners in spectral-resolution abilities. These investigations provide theoretical motivation for the idea that enhancing peaks in a complex spectrum may be beneficial in restoring speech intelligibility for listeners with SNHL. Leek, Dorman, and Summerfield (1987) showed that hearing-impaired (HI) listeners required greater relative intensity of spectral peaks when identifying simulated two-formant vowels. They observed that normal-hearing (NH) listeners (in quiet and in noise) identified vowels with 90% accuracy when the peak-to-trough ratio reached 6 dB or greater. Six HI listeners, however, identified vowels about 70% correctly with a peak-to-trough ratio of 8 dB. HI listeners therefore required a greater peak-to-trough ratio to accurately identify vowels accurately. Further psychophysical support for this finding has been provided by studies of rippled noise. Summers and Leek (1994) studied the internal representation of spectral contrasts of multicomponent complex stimuli with sinusoidal spectral ripples. They found that individuals with cochlear hearing loss required a significantly greater spectral-ripple height, or spectral peak-to-trough ratio, than did NH individuals. Mean thresholds for detecting ripples (when ripples were spaced by two to three ripple peaks per octave) were approximately 7 dB for NH listeners, whereas five HI listeners required ripple depths of 10 to 17 dB. These results suggested that ripple detection by listeners with SNHL could be explained by auditory filters that were two to three times the normal width. Spectral-peak amplitudes must therefore be increased to accommodate the reduced spectral resolution imposed by broad auditory filters associated with SNHL. Taken together, these studies suggest that enhancing peak-to-trough ratios in complex signals may at least partially restore spectral-shape discrimination for HI

individuals. Thus, a hearing aid that processes sounds to increase the peak-to-trough ratio may be expected to improve understanding of speech for HI listeners. The possibility of success with this type of processing requires further study, because the stimuli used in these studies differs greatly from speech.

Physiological studies also are relevant and offer evidence in support of the potential benefits of spectral enhancement. Investigators measuring the neural representation of speech have shown that decreased spectral resolution causes inaccurate representation of complex signals in the auditory nerve and that increasing spectral contrast in complex signals can partially compensate for that loss (Geisler, 1989; Miller, Calhoun, & Young, 1999a, 1999b; Miller, Schilling, Franck, & Young, 1997). Models of cochlear function also suggested that SNHL might significantly affect the frequency-specific neural representation of speech sounds (e.g., Geisler, 1989). Measurements made on acoustically traumatized cats have confirmed these models. Miller et al. (1997) measured the representation of a synthesized vowel in normal and acoustically traumatized cat auditory nerve fibers and found a strong synchronization to places of stimulation corresponding to formant peaks for cats with normal neurons. Neural synchrony was not maintained at higher frequencies for the traumatized cats even when the speech levels were high enough to overcome the loss of sensitivity. Miller et al. (1999b) subsequently observed that acoustic trauma eliminated the ability to discriminate F2 frequency via discharge-rate patterns. Thus, Miller et al. (1997; Miller et al., 1999b) have demonstrated that reduced frequency selectivity associated with SNHL degrades the neural representation of complex signals and that amplification alone is insufficient to overcome processing limitations in damaged cochleae.

Although these psychophysical and physiological data provide strong theoretical motivation for the need for improved spectral contrast for HI listeners, at least one cochlear model did not predict significant benefit of spectral enhancement in impaired ears (Giguère & Smoorenburg, 1998; Giguère & Woodland, 1994). Giguère and Smoorenburg (1998) simulated the excitation pattern of the synthesized vowel /æ/ for a normal ear and an ear with a 50% outer hair cell loss. They found no difference in the excitation patterns for cochlear-impaired ears when the simulations were implemented with and without spectral enhancement. They argued that spectral enhancement is not a viable processing strategy because of the broad auditory filters observed in listeners with SNHL.

In contrast to these predictions of Giguère and Smoorenburg (1998), other cochlear models and physiological data based on neural synchrony suggest that

spectral enhancement can be successful. Lyzenga, Festen, and Houtgast (2002) used a place model to predict whether improvements would be observed with their spectral-enhancement algorithm. To simulate hearing impairment, they broadened and tilted the simulated auditory filters. The low-pass tilt characteristic made the auditory filters asymmetric. They showed when their spectral enhancement algorithm was applied to the vowel /a/, the predicted excitation pattern was characterized by more detail than without the enhancement. Miller et al. (1999a) tested a method of achieving increased spectral contrast called *contrast-enhanced frequency shaping* (CEFS). They measured the auditory neural responses of acoustically traumatized cats when presented with vowels that were either unmodified or modified by CEFS. The CEFS algorithm provided a high-frequency emphasis in the F2 and F3 regions while not amplifying the spectral trough between F1 and F2. Miller et al. (1999a) showed that phase-locked neural representation of vowel formants was substantially improved with the CEFS algorithm. These findings suggest that spectral-enhancement algorithms may be successful for restoring normal neural representation of complex spectra in the presence of SNHL.

Speech-perception tests of spectral-enhancement algorithms, however, have shown outcomes that ranged from somewhat successful to unsuccessful. Simpson, Moore, and Glasberg (1990) tested nine listeners with SNHL on speech-in-noise tests. They found that spectral enhancement improved identification of words and sentences. This algorithm, with a few parameter changes, was tested in greater detail by Baer, Moore, and Gatehouse (1993), with less success. The only condition in which they found a significant advantage for their algorithm was when a moderate amount of spectral enhancement was combined with a moderate amount of wide dynamic range compression. They showed a 0.8-dB effective increase in SNR after listeners had time to acclimate to this condition (Baer et al., 1993). A similar spectral-enhancement algorithm, combined with phonemic compression (based on Baer et al.'s [1993] study), was tested by Franck, Sidonne, van Kreveld-Bos, Dreschler, and Verschuure (1999), with little success. They found that vowel perception improved in the spectral-enhancement-alone and the spectral-enhancement-plus-single-channel-compression conditions at the sacrifice of final-consonant perception in noise. The best overall intelligibility scores were found in the unprocessed condition (Franck et al., 1999). Accordingly, the results of these algorithm trials have been disappointing.

It seems from the literature that restoring full-speech audibility for listeners with SNHL is insufficient to achieve normal speech recognition in noise.

The potential benefit of spectral enhancement, however, is unclear. The lack of benefit from spectral-enhancement algorithms to date may be because spectral enhancement is not a viable concept or, alternatively, because specific algorithms have had unexpected and undesirable negative effects on speech. The goal of this study was to examine the effects of increasing spectral contrast on the detection and discrimination of simple, well-defined noise signals for NH listeners and listeners with SNHL. In these experiments, listeners detected and discriminated a narrowband peak (with the approximate width of a vowel formant) in a broadband noise. Spectral contrast was increased by removing energy from frequencies adjacent to the target narrowband signal, thus improving the peak-to-trough ratio around the particular spectral area of interest. Simple stimuli were used so that we could maintain full stimulus control over the levels, bandwidth, and depths of the various stimulus components. These simple stimuli were selected to be consistent with known characteristics of speech. For the enhancement conditions, we chose parameters that are viable for spectral-enhancement algorithms (3- and 6-dB deep and 100- and 200-Hz wide decrements in broadband noise).

Experiment 1: Detection of a Narrowband Noise in Broadband Noise

Overview

In all conditions, the threshold for detection of a narrowband noise was measured in the presence of broadband noise. In some conditions, spectral gaps (decrements) were introduced adjacent to the narrowband noise target. The hypothesis under test was that these spectral decrements would improve detection relative to a condition without spectral decrements. Thus, the goal was to determine whether the spectral decrements would improve performance for persons with hearing loss. If so, then would spectral decrements improve to the levels seen for persons without hearing loss for unprocessed conditions (no spectral decrements)?

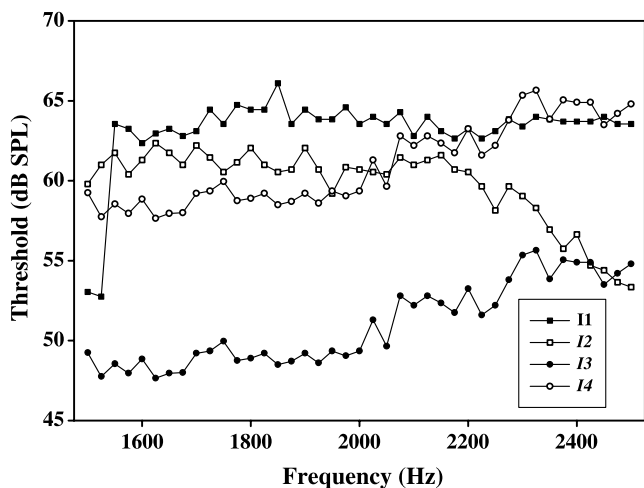
Method

Participants

A group of 4 NH persons and a group of 4 individuals with SNHL participated in this study. Informed consent was obtained from all participants.

The NH participants had auditory thresholds of 15 dB HL or better from 0.25 to 8.0 kHz and a negative report of auditory pathology. Their ages ranged from

Figure 1. Audiometric microstructure between 1.5 and 2.5 kHz for each hearing-impaired (HI) listener. I1, I2, and so on, refer to individual participants.



20 to 29 years. The second group consisted of 4 individuals from 19 to 79 years of age with moderate to moderately severe SNHL. Auditory thresholds for this second group were measured at octave intervals from 0.25 to 8.0 kHz, and thresholds were measured at 25-Hz intervals between 1.5 kHz and 2.5 kHz, to ensure that hearing sensitivity was relatively constant in the region around 2000 Hz, the signal frequency in the experiment. Thresholds measured between 1.5 kHz and 2.5 kHz were obtained using a computer-implemented version of Békésy discrete-frequency audiometry. Participants pressed buttons to raise or lower the signal level in 1.5-dB steps. Participants were instructed to press the “louder” button if the signal was inaudible and the “softer” button if it was audible. The stimulus for the Békésy audiometry task was a 250-ms tone (with 50-ms raised cosine ramps) presented with an interstimulus interval of 250 ms. Thresholds for each frequency were based on the mean levels of the last 10 of 12 response reversals. The results of the Békésy audiometry task for the participants with SNHL are illustrated in Figure 1. Audiometric thresholds mea-

sured using conventional audiometry are shown in Table 1, along with the ages of the participants with hearing loss.

Stimuli

The stimuli were generated digitally using a sampling frequency of 22.05 kHz. The computer (Hewlett Packard, Model Vectra VL600) was equipped with a 16-bit digital-to-analog converter (Tucker-Davis Technologies [TDT], Model DD1) that produced the stimuli. The stimuli were routed through an anti-aliasing low-pass filter (TDT, Model FT6-2; -60 dB at 1.15 times the corner frequency) with a corner frequency set to 7500 Hz and an attenuator (TDT, Model PA4) prior to presentations to one ear of a listener through an earphone (Telephonics, Model TDH-39P).

The standard stimulus was a broadband noise. The noise was formed by digitally mixing bands of noise. In the simplest case, the standard stimulus comprised three bands of noise: (a) a low-frequency band (50–1975 Hz), (b) a center band (50 Hz wide, 1975–2025 Hz), and (c) a high-frequency band (2025–5000 Hz). These bands were presented at a spectrum level of 46.3 dB/Hz. In conditions where spectral decrements were applied, the standard stimulus comprised five noise bands. The spectral decrements were placed in flanking bands on both sides of the center band. The flanking bands, containing the spectral decrements, were either 100 Hz wide or 200 Hz wide. The decrements were introduced by multiplying the waveform for the flanking band by a scaling factor that reduced its spectrum level by either 3 or 6 dB relative to all of the other bands, including the center band. The particular experimental conditions in this article are based on the characteristics of the spectral decrements inserted into the flanking bands as defined by their depth (dB)/width (Hz). For example, a 3-dB deep, 200-Hz wide decrement inserted on both sides of the center band is referred to as a *3/200 condition*. A control condition with no decrements is referred to as *0/0*.

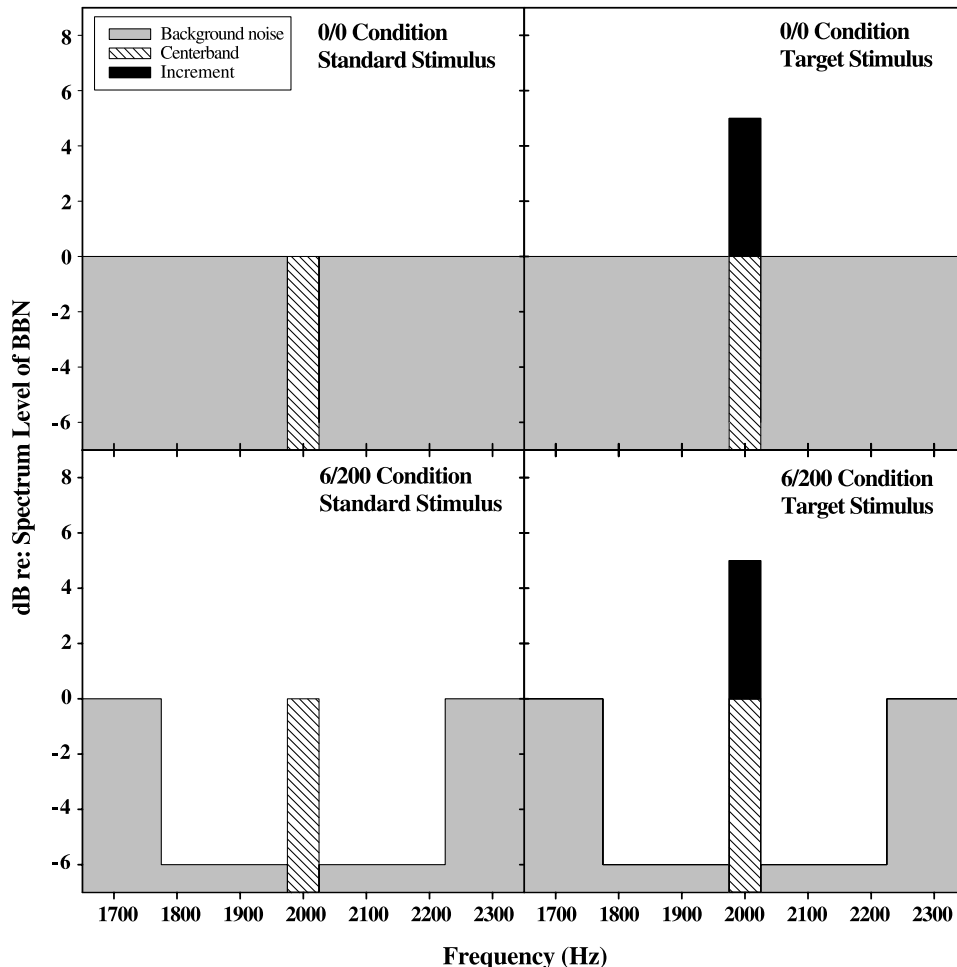
The comparison or signal stimulus was identical to the standard stimulus, including decrements, except

Table 1. Audiometric thresholds and ages of participants in the hearing-impaired group.

Participant	Age	Audiometric thresholds (kHz)							
		0.25	0.5	1.0	1.5	2.0	3.0	4.0	8.0
I1	79	10	10	20	55	55		60	65
I2	19	45	55	50		50	30	15	10
I3	49	35	40	40		45		45	70
I4	74	30	25	45		55		60	65

Note. Threshold data are in dB HL.

Figure 2. Schematic representations of the stimuli used in Experiment 1. Shown in the two left panels are the standard stimuli for the 0/0 (upper panel) and 6/200 (lower panel) conditions. Shown in the two right panels are the signal stimuli for the 0/0 (upper panel) and 6/200 (lower panel) conditions. In this example, the signal stimuli are shown with an increment of 5 dB relative to the spectrum level of the broadband noise (BBN) background.



that the spectrum level of the center band of noise was adjusted adaptively to find a listener's detection threshold. The resulting task was effectively increment detection. The relative intensity increment ($10 \log [\Delta I/I]$) of the narrowband noise was adjusted by multiplying its amplitude by the appropriate scaling factor. A schematic of the spectra for the standard and signal stimuli for two conditions is shown in Figure 2.

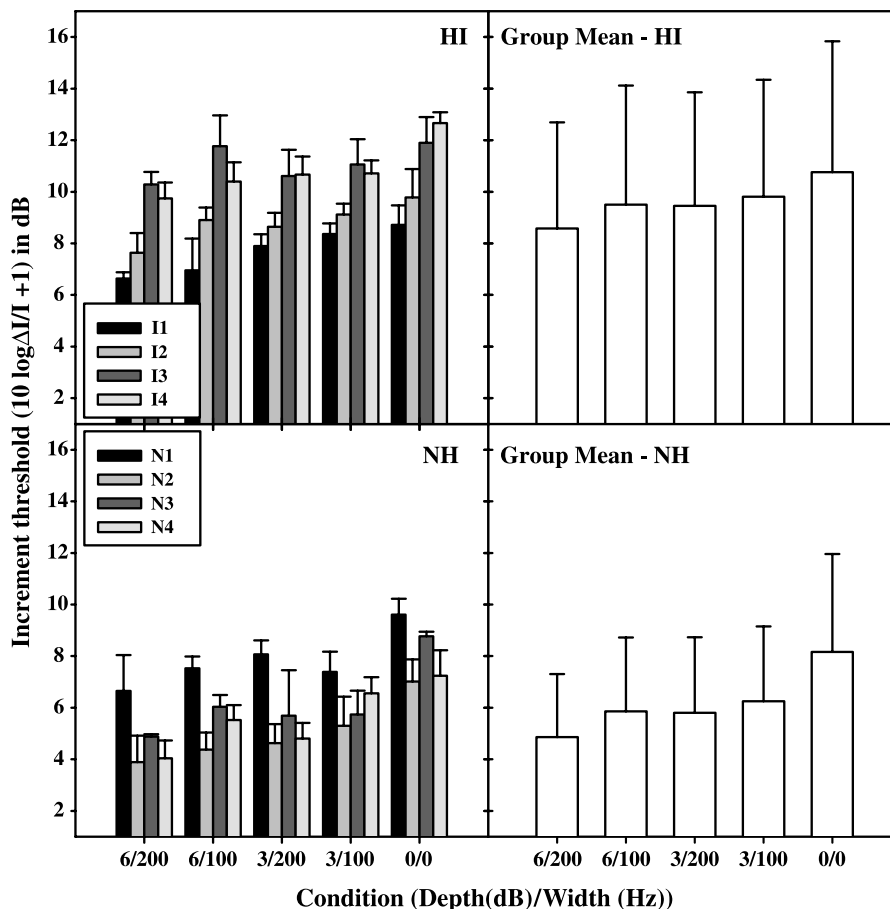
Procedure

Threshold for detection of an increment in the center band was measured using a 3-alternative forced-choice adaptive procedure that targeted 79.4% correct detection (Levitt, 1971). A trial consisted of three 500-ms observation intervals marked by lights and separated by 500 ms. The observation intervals were the same duration as the stimuli, which included

10-ms cosine-squared rise and fall times. The signal, an increment in the center band, was randomly placed in one of the three intervals. The participant selected the interval thought to contain the signal by depressing a key on a computer keyboard corresponding to that interval. If the listener was correct on three consecutive trials, then the signal level was reduced. If the listener was incorrect, then the signal level was increased. The signal level was changed in 3-dB steps for the first 2 reversals and in 1-dB steps for the remaining reversals in $10 \log (\Delta I/I)$. A block of trials ended when 10 response reversals had been completed. The first 2 reversals in the block were discarded, and threshold was calculated on the basis of the mean levels of the remaining 8 response reversals.

Participants listened in the following conditions: 0/0, 3/100, 6/100, 3/200, and 6/200. The order of the

Figure 3. The detection results of the normal-hearing (NH) and HI groups in Experiment 1 are shown. The data are presented after they were converted into ΔL (i.e., the difference between the centerband spectrum level of the signal and standard intervals). Data for individual participants are shown in the left panels for each group, and the group-mean data are shown in the right panels. The increment thresholds, in decibels, are shown with corresponding standard deviation bars.



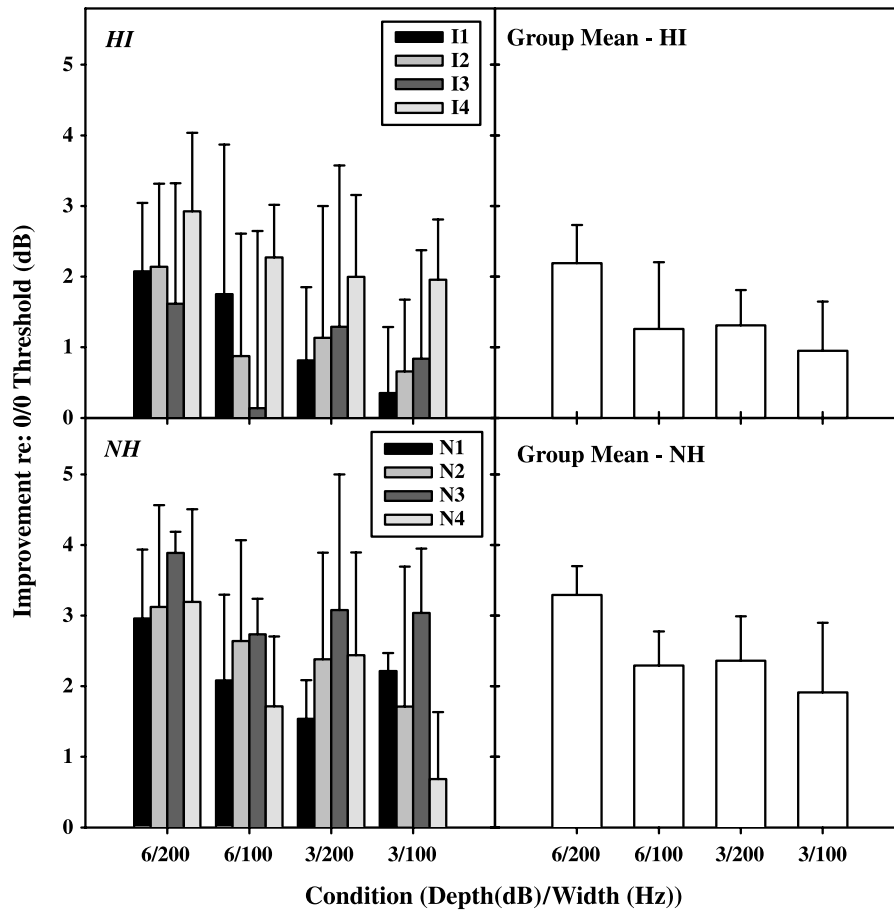
conditions was randomized within participants. Reported thresholds are based on mean values from a minimum of three blocks of trials per condition. More than three blocks were run if the standard deviation of the three blocks was greater than 3 dB. More blocks were run until the standard deviation was less than 3 dB. Collecting more than three blocks was required in three instances. The number of blocks never exceeded six.

Results

Detection thresholds for the narrowband stimulus in a broadband noise are shown in Figure 3 for varying degrees of spectral contrast. To illustrate the relative difference at threshold between the signal increment and the broadband masker, narrowband target thresholds were converted from $10 \log (\Delta I/I)$ to $10 \log (\Delta I/I + 1)$ and are reported this way. This conversion yields a decibel increment above the noise-spectrum level of

the unprocessed broadband noise for each of the four spectral-enhancement conditions. The spectral-enhancement conditions ranged from no enhancement (0/0) to the maximum enhancement, which was achieved with a spectral decrement of 6-dB depth and 200-Hz width on either side of the narrowband target (6/200). Shown in the upper left panel of Figure 3 are the results from each of the 4 listeners in the HI group. The HI group-mean data (with standard deviations) are shown in the upper right panel. Shown in the lower left panel are the results from each of the four NH listeners; their mean data are shown in the lower right panel. NH thresholds ranged between 7.0 and 9.6 dB for the 0/0 (no-enhancement) condition and between 3.9 and 6.6 dB for the condition with greatest enhancement. HI thresholds ranged between 8.7 and 12.7 dB for no enhancement and between 6.6 and 10.2 dB for the greatest enhancement. Two trends emerged for all listeners; namely, detection was poorest in the 0/0

Figure 4. The benefit measured for each decrement condition in Experiment 1 is shown relative to the 0/0 condition. The comparisons were made from the ΔL converted data. Individual benefit for the two groups is shown in the left panels, and group benefit is shown in the right panels.



(no-enhancement) condition and best in the extreme (6/200) spectral-enhancement condition.

We performed an analysis of variance with repeated measures on the entire listener pool for all enhancement conditions to formally assess the benefit of spectral enhancement. Overall, listeners in the NH group performed better than did those in the HI group, $F(1, 6) = 8.58, p < .05$. Significant effects of decrement width, $F(2, 12) = 66.77, p < .001$, and depth, $F(2, 12) = 68.04, p < .001$, were found. This result indicates that both wider and deeper decrements lead to better detection thresholds. There were significant Depth \times Group, $F(2, 12) = 4.50, p < .05$, and Width \times Group, $F(2, 12) = 4.36, p < .05$, interactions, suggesting that there was a differential effect of decrement depth and width on each group. The amount of improvement each participant showed for each test condition is shown in Figure 4. It is clear that the NH group showed more improvement than the HI group. Furthermore, a significant interaction between width and depth was

found, $F(4, 24) = 37.57, p < .001$, suggesting that the relative importance of the decrement width varied depending on the depth of the decrement. The three-way interaction (depth \times width \times group) was not significant, $F(4, 24) = 2.21, p = .098$. Taken together, these results suggest that the decrements had a beneficial effect for both groups, whereas the specific effects of the decrement depth and width were likely to be more beneficial to the NH group.

The improvement in decibels for individual listeners and listener groups relative to each listener's 0/0 (no enhancement) performance is shown in Figure 4. Overall, NH listeners improved more than HI listeners. For both groups, the greatest improvement was measured in the extreme 6/200 enhancement condition, and the least improvement was seen for the 3/100 enhancement condition. Some benefit was measured for every listener when spectral enhancement was applied regardless of the depth and width of the enhancement.

Discussion

Both the NH and HI groups showed threshold improvements when a spectral decrement of any width or depth was inserted around a narrowband signal. Increasing either the depth or the width of the spectral enhancement improved thresholds for all listeners. Thus, detectability is improved for all NH and HI listeners when the local SNR is increased by reducing the level of the noise immediately surrounding the narrowband signal.

In general, NH listeners had better detection thresholds and showed more improvement from spectral enhancement than did HI listeners. The NH mean thresholds averaged 8.2 dB for the no-spectral-enhancement condition and 4.9 dB for the 6/200 condition. The HI mean thresholds were poorer, averaging 10.8 dB for the no-enhancement condition and 8.6 dB for the 6/200 condition. Nevertheless, all HI listeners demonstrated significant benefit from spectral enhancement. In fact, thresholds for HI listeners in the condition of greatest enhancement (6/200) were equivalent to those of NH listeners in the no-enhancement (0/0) condition (see Figure 3). Thus, spectral enhancement was successful in restoring the detectability of narrowband signals to levels that were achieved by NH listeners with no enhancement.

The NH and HI listeners' thresholds obtained in this study were similar to thresholds reported by Summers and Leek (1994) for rippled noise. In Summers and Leek's investigation, NH thresholds for ripple density of one to three ripples per octave ranged between 7 and 9 dB (peak to valley), whereas HI thresholds ranged between 8 and 17 dB. Summers and Leek concluded that the HI listeners' poorer detection thresholds could be explained by their broader-than-normal auditory filters, which caused reduced internal spectral contrast. The present results for both the NH and HI groups may also be explained by assuming broader auditory filters. Nevertheless, despite apparently broader filters, HI listeners were still able to benefit from the improved local SNR that resulted from the increased spectral enhancement, and their thresholds for enhanced signals were similar to normal thresholds obtained with no enhancement.

Experiment 2: Frequency Discrimination

Overview

Detection of spectral peaks is necessary for speech understanding but is not sufficient for discriminating speech sounds. Therefore, inferences made from detection data have limited extension to speech under-

standing. Discrimination of spectral-peak frequencies might be considered as analogous to discrimination of vowel-formant frequencies. To measure the potential effect of spectral enhancement in a task requiring more sophisticated auditory processing, we conducted a frequency discrimination experiment in which we measured the difference limen for frequency (DLF) for the center frequency of a narrowband noise in a background of broadband noise. In some conditions, spectral gaps (decrements) were introduced in frequency regions just above and just below the narrowband noise signal to assess the influence of spectral enhancement on frequency discrimination.

Method

Participants

Participants were the same listeners as those described in Experiment 1.

Stimuli

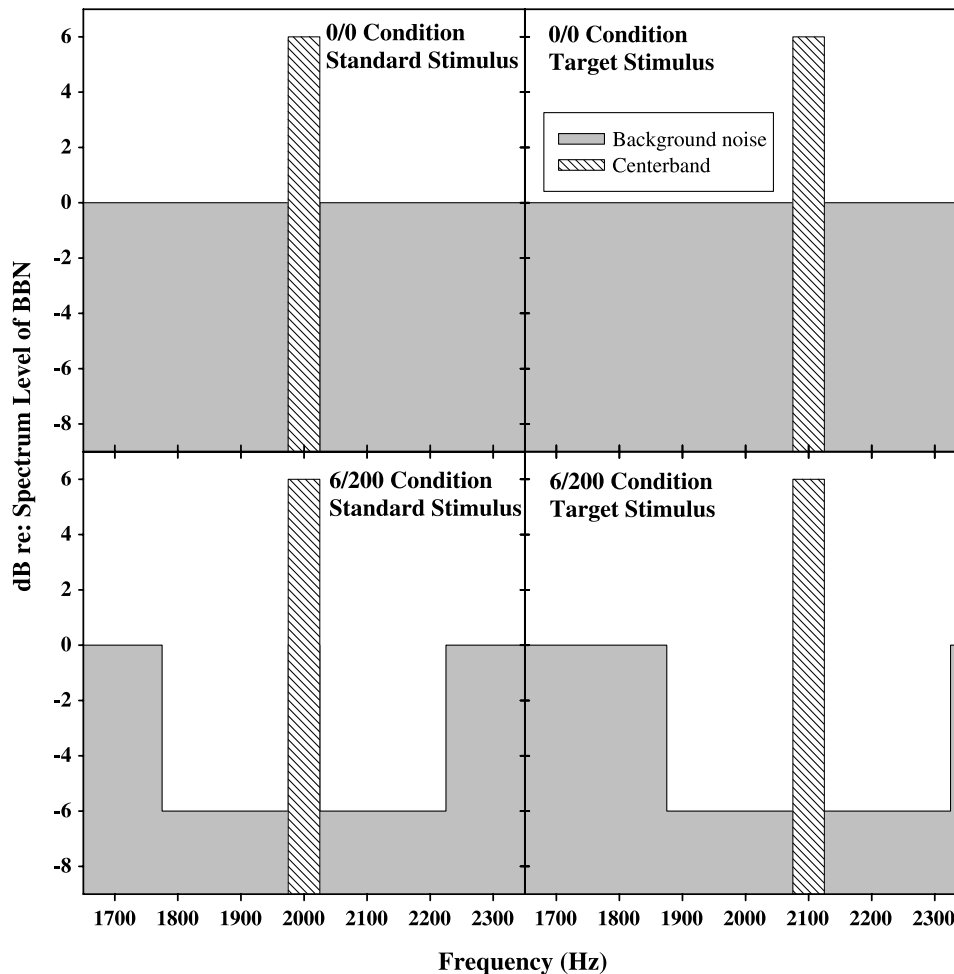
Stimulus generation and experimental control were accomplished using the same equipment described in Experiment 1. Participants listened monaurally through an earphone (Telephonics, Model TDH-49P).

The standard stimulus was identical to the one described in Experiment 1 except that the mean level of the center band was presented at a fixed sensation level. This sensation level was a fixed amount above the individual threshold obtained for the detection of the center band in the 0/0 condition of Experiment 1. The presentation level was 6 dB SL for the NH group and 10 dB SL¹ for the HI group. The mean spectrum level of the low-frequency and high-frequency band was 46.3 dB/Hz. The spectral notches were placed in flanking bands on both sides of the center band, and the notch levels were referenced to the spectrum levels of the low-frequency band and high-frequency band.

The comparison stimulus differed from the standard stimulus in that the spectral position of the center band (and of the flanking bands, when present) was higher in frequency than that of the standard. The spectral position of the center band (and of the flanking bands) was adjusted adaptively in frequency to measure the DLF of the center band. The center band and the flanking bands (spectral notches) did not change in width or level; only the center frequencies of these bands changed. Additionally, the overall bandwidth of the broadband noise remained fixed (50–5000 Hz).

¹The NH data were completed with increments of 6 dB SL. However, results from the first pilot HI listener indicated that 6 dB SL was insufficient to obtain stable DFL performance. His performance stabilized when the center band SL was increased to 10 dB SL. Therefore, we elected to use 10 dB SL for all HI listeners, so that we could obtain stable performance at levels that were similar to those used by the NH listeners.

Figure 5. Schematic representations of the stimuli used in Experiment 2 for the frequency-discrimination task. The standard stimuli for the 0/0 (upper panel) and 6/200 (lower panel) conditions are shown in the left panels. The signal stimuli for the 0/0 (upper panel) and 6/200 (lower panel) conditions are shown in the right panels. In this example, the signal stimuli are 100 Hz higher than the standard stimuli. The center band was presented at a fixed sensation level (6 or 10 dB SL for the NH and HI groups, respectively) above each individual's mean detection threshold measured in the 0/0 condition in Experiment 1.



Attempts were made to restrict loudness cues that may confound in the frequency-discrimination task. No level change occurs as the decrements and center band change in frequency; however, small changes in absolute threshold may result in small changes in loudness for the listeners. Because the hearing loss for all HI participants was sensorineural, and because the levels of the stimuli were relatively high, loudness would be expected to be normal or near normal for stimuli presented at sound levels producing full recruitment. Therefore, any change in loudness due to differences in absolute threshold would be expected to be minimal. However, to confound the listeners' use of a residual cue, we added a 4-dB rove (i.e., random level variation). The amount of the roving level was constrained by each listener's loudness discomfort levels and by his or her

audibility thresholds. Therefore, the presentation level was roved randomly ± 2 dB on a trial-by-trial basis.

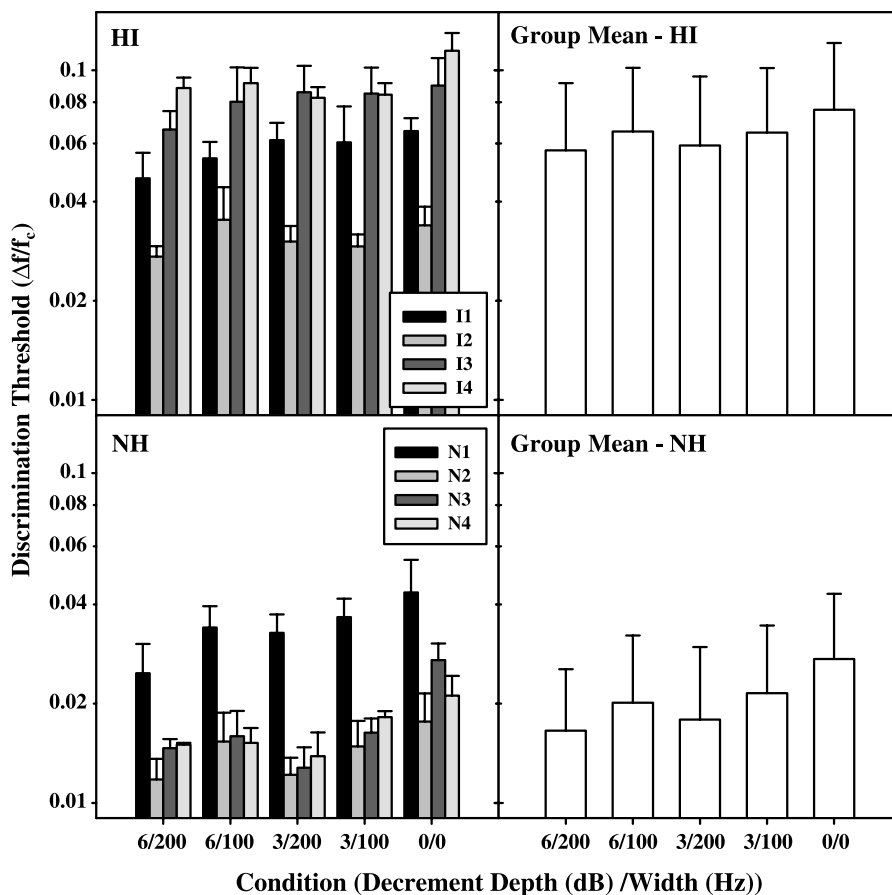
A schematic of spectra for the standard and signal stimuli is shown in Figure 5 for the 0/0 and 6/200 conditions.

Procedure

The DLF in the spectral position of the center band was measured using a 3-AFC adaptive procedure that targeted 79.4% correct detection (Levitt, 1971). The procedure was identical to that of Experiment 1, except that the signal frequency was varied rather than level.

For all blocks, the mid-frequency of the center band for the signal stimulus began at 2350 Hz. The mid-frequency of the center band for the standard stimulus

Figure 6. The difference limen for frequency results are shown for the NH and HI groups in Experiment 2 as a ratio of $\Delta f/f_c$. Results for individual participants are shown in the left panels for each group, and the group-mean data are shown in the right panels. Corresponding standard deviation bars are shown.



was always 2000 Hz. For the first two response reversals, the difference in frequency between the midpoint in the center band for the standard and the midpoint in the center band for the signal changed by a factor of 2. For subsequent response reversals, the frequency changed by a factor of 1.4.

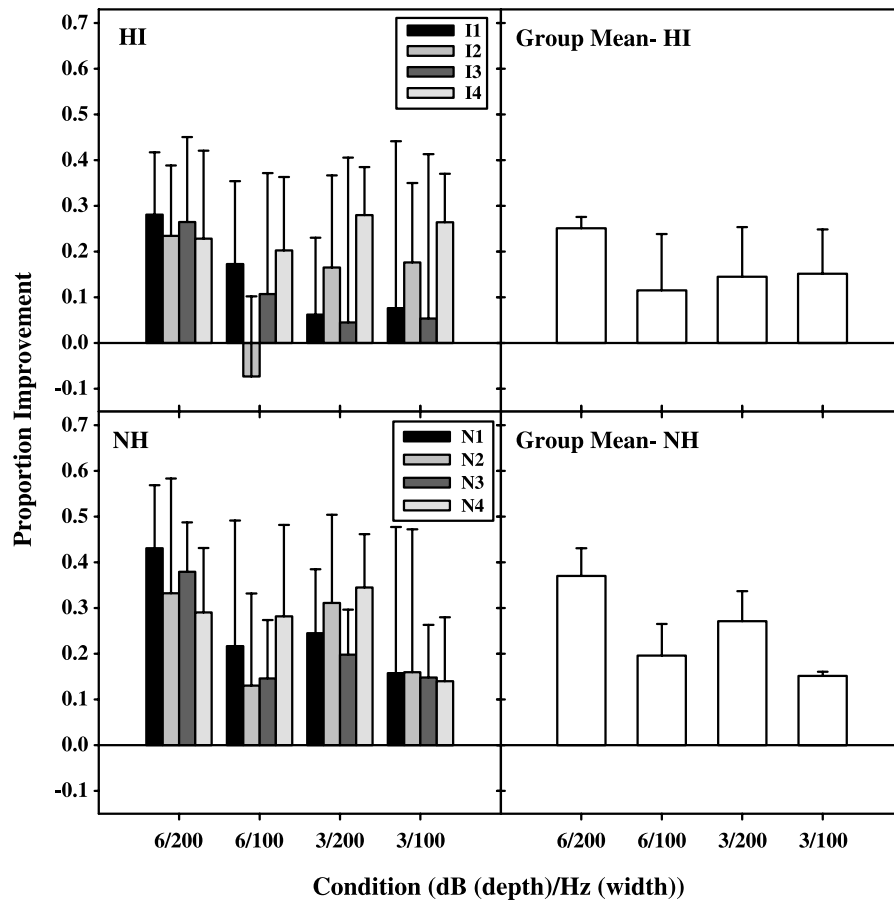
Participants listened in the following conditions: 0/0, 3/100, 6/100, 3/200, and 6/200. The order of the conditions was randomized within participants. Thresholds for a block of trials were calculated on the basis of the mean value for the last 8 of 10 response reversals. The DLF was defined by the difference in frequencies between the midpoint of the center band of the signal and the midpoint of the center band of the standard stimulus. Reported thresholds are the mean thresholds from three blocks of trials.

Results

The DLFs for the narrowband signal in the broadband noise are shown in Figure 6 for varying degrees

of spectral enhancement. The DLFs are shown in $\Delta f/f$ for HI listeners in the upper panels and for that group in the top panel and for individual NH listeners and for NH listeners in the lower panels. NH listeners performed better than HI listeners across all conditions. The NH group mean DLF for the 0/0 condition was smaller than the corresponding HI group mean value by a factor of approximately 2.8. NH listeners had an average DLF of 57 Hz ($\Delta f/f$: 0.029) for the no-enhancement condition, with individual performance ranging from 35 to 87 Hz ($\Delta f/f$: 0.018–0.043). In contrast, the HI group achieved an average DLF of 152 Hz ($\Delta f/f$: 0.076) when there was no spectral enhancement, with individual DLFs ranging from 68 to 229 Hz ($\Delta f/f$: 0.034–0.11). For the condition of greatest enhancement, the NH participants' mean DLFs improved by 19 Hz ($\Delta f/f$: 0.01), on average, to a mean DLF of 36 Hz (range: 24–50 Hz; $\Delta f/f$: 0.018, range: 0.012–0.025), whereas the HI participants' mean DLFs improved by 38 Hz to 114 Hz (range: 52–177 Hz; $\Delta f/f$: 0.019–0.057, range: 0.026–0.089).

Figure 7. The benefit measured for each decrement condition in Experiment 2 is shown relative to the 0/0 condition, with corresponding standard deviation bars displayed. Individual benefit is shown in the left panels for the two groups. Mean benefit is shown for each group in the right panels.



The HI and NH listeners vary widely in their abilities to discriminate the center frequency of the signal, but the NH listeners routinely had smaller DLFs than do the HI listeners. Despite the variability, the trend for both groups is consistent: A listener's ability to discriminate the frequency of a narrowband noise signal in the presence of broadband noise generally improved with spectral enhancement. This is obvious when one views the results plotted in terms of proportion improvement, as shown in Figure 7. The NH group-mean DLF improved by 37% with the maximum enhancement applied, whereas the HI group-mean DLF improved by 25%. Therefore, the NH group showed a greater percentage improvement than the HI group. Discrimination performance deteriorated for only 1 listener in one enhancement condition relative to performance in the 0/0 condition.

To assess the significance of the DLF data, we performed an analysis of variance with repeated measures on the logarithm of the threshold measurements (Sek & Moore, 1995). There was a significant

performance difference between groups, $F(1, 6) = 11.62, p < .05$. Both the spectral decrement width, $F(2, 12) = 24.70, p < .001$, and depth, $F(2, 12) = 42.23, p < .001$, had a significant effect on DLF. Furthermore, the Width \times Depth interaction was significant, $F(4, 24) = 15.65, p < .001$, suggesting that the relative importance of the decrement width varied depending on the depth of the decrement. The Depth \times Group interaction, $F(2, 12) = 6.4, p < .05$, reveals that decrement depth had a differential effect on each group. In contrast, no Width \times Group interaction was found, $F(2, 12) = 3.23, p = .075$. Therefore, the Depth \times Width \times Group interaction, $F(4, 24) = 3.35, p < .05$, further shows the differential effect of width and depth on each group. That is, the decrement width seemed to have the same beneficial effect for both groups, but decrement depth did not. We performed a post hoc analysis to follow up on the differential effect of spectral decrements for the HI listeners. We used a Friedman post hoc test to compare the DLF values for the 0/0 and the 6/200 conditions. A significant difference was

observed between the 6/200-enhancement and no-enhancement conditions, demonstrating the benefit of adding a 6-dB, 200-Hz-wide decrement around the narrowband signal, $t(3) = 4.3, p < .05$.

Discussion

Our listeners' performances on the DLF were consistently poorer than typical frequency discrimination results reported in literature for pure tones in quiet presented at a low sensation level (e.g., Wier, Jesteadt, & Green, 1977). This difference might be expected for narrowband-noise signals in broadband noise. Nevertheless, the relative performance differences between the NH and HI groups in this study are consistent with other literature (e.g., Nelson & Freyman, 1986; Turner & Nelson, 1982). Turner and Nelson (1982) measured DLFs for NH and HI listeners at 3.0 kHz and found that HI listeners require about a threefold greater frequency difference relative to that measured for NH listeners. This is quite similar to the current finding in which the DLFs of HI listeners were 2.8 times greater than the DLFs measured for the NH listeners.

In contrast to the results of the detection task (Experiment 1), spectral enhancement did not restore DLF values for all HI listeners to the corresponding values obtained by the NH listeners with no spectral enhancement (see Figure 6). NH listeners with no spectral enhancement achieved DLFs ranging from 0.015 to 0.045. HI listeners with the maximum enhancement (6/200) obtained DLFs ranging from 0.025 to 0.088. Two HI listeners (I1 and I2) had DLFs with spectral enhancement that were within the baseline range of the NH group without enhancement (0.025 and 0.045, respectively). The 2 other HI listeners did not perform as well. Their DLFs improved over their own individual performance for the 0/0 condition but remained poorer than normal despite the contrast enhancement. These 2 listeners did not have significantly poorer hearing thresholds than the other 2; neither were they the oldest of the HI listeners.

In general, listeners' abilities to discriminate the frequency of a narrowband noise in the presence of broadband noise improved with an enhanced spectrum. The depth and width of enhancement had significant positive effects for most listeners in discriminating the narrowband noise frequency.

General Discussion

Both NH and HI listeners in this study demonstrated benefit from spectral enhancement for detection and discrimination of narrowband noise signals. Our results are consistent with the findings of Summers

and Leek (1994) for HI listeners. They proposed that the broader auditory filters effectively flatten the internal spectra for HI listeners, resulting in higher-than-normal thresholds for ripple detection. Their results were generally consistent with auditory filters two to three times the width of filters for persons with normal hearing.

In this study, broader auditory filters are also presumed to contribute to differences in performance for our NH and HI listeners. Despite these presumed broader filters, spectral enhancement still provided significant benefit to HI listeners. This positive finding is in contrast to cochlear model predictions of Giguère and Smoorenburg (1998). Our results suggest that spectral enhancement may still be a viable goal for hearing aid signal processing, at least for listeners with thresholds similar to those we tested.

To follow up on the potential relation between auditory filters and potential benefit from spectral enhancement, consider again the results of Experiment 1. This experiment may be considered either a masking experiment (detecting a narrowband noise in broadband noise) or an intensity discrimination task (detecting an increment in narrowband noise). This distinction is probably moot because, as Bilger (1978) noted, masking and intensity discrimination can be viewed interchangeably. Regardless, masked threshold represents the discrimination of an intensity difference between a critical band of noise plus the signal (signal interval) versus the critical band of noise alone (non-signal interval). Bilger suggested that the width of the auditory filter determines the effective power of the stimulus in an intensity-discrimination task in any situation in which the masker is a broadband noise and the signal is narrower than an auditory filter. Thus, in Experiment 1, spectral enhancement may be viewed as a means to reduce the level of the effective noise within an auditory filter and thereby improve the listener's ability to detect an increment in the background noise level. As the auditory filter bandwidth widens, the effect of spectral enhancement would, at some point, become negligible. This was the presumed basis of Giguère and Smoorenburg's (1998) model predictions.

Bilger's (1978) assumptions suggest quantitative predictions for assessing the potential benefit from spectral enhancement in Experiment 1. The benefit is calculated by assessing power differences within an auditory filter with and without spectral enhancement. First, we assume that the auditory filter width at 2000 Hz for persons with normal hearing is 450 Hz for a 46-dB/Hz noise (Wier, Schlauch, & Norton, 1984). Auditory filters for persons with mild to moderate SNHL are assumed to be 650 Hz (e.g., Dubno & Dirks, 1989). The predicted improvements in threshold

Table 2. The predicted improvements for the four spectral-enhancement conditions, as well as measured improvements for the hearing-impaired (HI) and normal-hearing (NH) groups, for three hypothetical analysis bands.

Condition	Overall energy model			Measured improvement (dB)	
	250-Hz band	450-Hz band	650-Hz band	NH	HI
3/100	2.2	1.1	0.7	1.9	1.0
3/200	2.2	2.5	1.6	2.4	1.3
6/100	4.0	1.8	1.1	2.3	1.3
6/200	4.0	4.8	2.7	3.3	2.2

corresponding to changes in power within an auditory filter relative to the unprocessed condition (0/0) are shown in Table 2. Overall, the experimental results are in good agreement with the calculations in Table 2. NH listeners achieved benefit from spectral enhancement that is similar to that predicted by a 450-Hz analysis band. They did not, however, achieve the full 4.8 dB of benefit that was predicted for the 6/200 condition. We presume that in the 6/200 condition (a potentially perfectly optimal analysis bandwidth, exactly encompassing the center band and the spectral decrements), the spectral decrements were perceptually filled and were not fully available to the listener (e.g., Ellermeier, 1996). In addition, NH listeners continued to improve as the notch width was increased. This also is consistent with our assumption that auditory filters for NH persons are wider than 250 Hz, the width of the notch plus the center band in the 3/100 and 6/100 condition. It is further apparent from Table 2 that wider auditory filters reduce the predicted benefit of spectral enhancement. The HI listeners tended to perform as if their analysis bands were closer to 650 Hz wide, which the data from Dubno and Dirks (1989) predict. Despite the apparent broadened filters for our HI listeners, they still accrued some benefit from spectral enhancement for these simple signals.

The power within auditory filters described performance reasonably well for most conditions for the intensity-discrimination task in Experiment 1. However, a power difference was not a consistently available cue for the frequency discrimination task in Experiment 2. The audiometric configuration was flat in the region of the study, and the stimulus level within a trial was roved. Listeners had to rely on perceived differences in the spectral profile of these stimuli to perform the frequency discrimination task successfully.

Spectral profile analysis has been studied extensively for pure tone intensity discrimination for a single tone in the presence of tonal maskers, usually measured with equally spaced tones on a logarithmic frequency scale (Green, 1988). The listener's task is to

detect an increment in one of the tones of the standard complex spectrum compared to the standard complex spectrum alone. The overall stimulus level in these experiments is roved randomly in level between observation intervals to prevent the listener from relying on sequential level cue to detect the interval that contains the signal (i.e., the tone with an added intensity increment). Green (1988) suggested that a listener accomplishes this task by either comparing levels in adjacent auditory filters (e.g., Durlach, Braida, & Ito, 1986; Formby, Heinz, Luna, & Shaheen, 1994) or by using a pitch cue produced by a change in the level of the stimulus (e.g., Stover & Feth, 1983).

Participants in Experiment 2 were forced to attend to the spectral profile of the stimuli to perform the frequency-discrimination task. This task can be accomplished either by using a pitch cue or by comparing levels in adjacent auditory filters. The level cue for frequency discrimination would be based on the memory of the level in different auditory filters compared across observation intervals. Our results from Experiment 2 showed that all 4 HI listeners obtained benefit from the insertion of spectral decrements adjacent to the target narrowband noise. However, in contrast to the detection task in Experiment 1, inserting spectral notches did not restore normal discrimination performance for 2 HI listeners to values for NH listeners measured in the unprocessed condition (0/0). In other words, 2 HI listeners benefited less from spectral enhancement on a task that required discrimination of a spectral profile than they did on a task that they could accomplish with an intensity-difference cue alone. This outcome is consistent with a recent study showing that some listeners with SNHL place more perceptual weight on intensity cues than on frequency cues (such as formant transitions) in a speech-understanding task (Hedrick & Younger, 2001).

The results of these experiments suggest that spectral enhancement remains a viable goal for hearing aid signal processing. Even though HI performance with spectral decrements was not always equal to that

for the NH group in the unprocessed condition, all HI listeners in this study obtained some benefit from spectral enhancement, which was designed to cause local improvement in the SNR. On the basis of the data, we make the following conclusions:

- (1) NH and HI listeners can benefit from the addition of spectral decrements when detecting and discriminating narrowband signals in broadband noise.
- (2) NH listeners show a greater benefit from spectral enhancement than do HI listeners in detecting and discriminating narrowband signals, which is consistent with HI listeners' having broader than normal auditory filters.
- (3) Although broader auditory filters may be expected to reduce benefit from spectral enhancement, all HI listeners in this study showed a significant benefit from the addition of spectral decrements around the signal.

Furthermore, the present data suggest that a 200-Hz-wide spectral decrement that is 6-dB deep may be effective when inserted on each side of a narrowband noise signal in the region of 2000 Hz. Any direct relevance of this finding to the application of spectral enhancement to speech, however, is made with reservations. Specifically, the extreme condition tested in this study was the most beneficial condition that we evaluated. Whether a decrement greater than 200 Hz and deeper than 6 dB might be feasible and might achieve a result closer to the theoretical maximum benefit remains to be seen. Furthermore, the relative contributions of the lower frequency side and the higher frequency side of the decrements have not been assessed. When considering upward spread of masking, it may be necessary to use only a single decrement. More important, this experiment is a first step in a series of experiments needed to determine the value of spectral enhancement for applications to improve hearing aid processing of speech stimuli. A systematic evaluation of spectral enhancement to increasingly complex stimuli (e.g., harmonic tone complexes, synthetic vowels, and real speech) is needed before algorithms of this kind can be implemented in digital hearing aids.

Summary and Conclusions

Previous arguments have suggested that broad auditory filters in HI listeners may render spectral enhancement of speech ineffective. Animal studies, however, indicate that spectral enhancement is effective for restoring neural responses to speech formants. To evaluate the theoretical viability of spectral enhancement, two psychophysical experiments were

designed to test NH and HI benefit from spectral enhancement. These tasks included narrowband signal detection with and without adjacent spectral decrements and frequency discrimination of narrowband signals with and without adjacent decrements. Our results revealed the following:

- (1) Spectral decrements surrounding the signal improved the detection and discrimination of spectral signal peaks in noise.
- (2) Both NH and HI listeners benefit from spectral enhancement for noise detection and discrimination tasks, although HI listeners benefit less than NH listeners.
- (3) The HI listeners showed the most consistent and greatest improvement for the 6/200 condition, which afforded maximum spectral enhancement. Despite this benefit, the NH group showed greater improvement, on average, than did the HI group.
- (4) Spectral enhancement remains a viable goal to make modest improvements in the local, effective SNR for detection and discrimination of spectral peaks.

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