Spectral-peak selection in spectral-shape discrimination by normal-hearing and hearing-impaired listeners

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Spectral-shape discrimination thresholds were measured in the presence and absence of noise to determine whether normal-hearing and hearing-impaired listeners rely primarily on spectral peaks in the excitation pattern when discriminating between stimuli with different spectral shapes. Standard stimuli were the sum of 2, 4, 6, 8, 10, 20, or 30 equal-amplitude tones with frequencies fixed between 200 and 4000 Hz. Signal stimuli were generated by increasing and decreasing the levels of every other standard component. The function relating the spectral-shape discrimination threshold to the number of components (N) showed an initial decrease in threshold with increasing N and then an increase in threshold when the number of components reached 10 and 6, for normal-hearing and hearing-impaired listeners, respectively. The presence of a 50-dB SPL/Hz noise led to a 1.7 dB increase in threshold for normal-hearing listeners and a 3.5 dB increase for hearing-impaired listeners. Multichannel modeling and the relatively small influence of noise suggest that both normal-hearing and hearing-impaired listeners rely on the peaks in the excitation pattern for spectral-shape discrimination. The greater influence of noise in the data from hearing-impaired listeners is attributed to a poorer representation of spectral peaks. © *2006 Acoustical Society of America.* [DOI: 10.1121/1.2216564]

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I. INTRODUCTION

Multichannel models of spectral-shape discrimination have been able to account for performance when stimuli are either spectrally sparse (i.e., stimulus components are separated by a frequency distance greater than the bandwidth of an auditory filter; Kidd *et al.*, 1991; Green, 1992; Lentz and Richards, 1997) or spectrally dense (Farrar *et al.*, 1987), but the application of multichannel models to jointly account for spectral-shape discrimination sensitivity of sparse and dense stimuli has had limited success (Versfeld, 1997; Lentz *et al.*, 1999). When modeling spectrally sparse stimuli, the number of "bands" (or the number of random variables that are used in the formation of a decision variable) is generally assumed to be the same as the number of stimulus components; those bands are also assumed to be independent (Berg and Green, 1990). When stimuli have greater numbers of components and are spectrally dense, this assumption no longer leads to accurate predictions of performance, and models that include imperfect frequency resolution become necessary (Bernstein and Green, 1987; Farrar *et al.*, 1987; Summers and Leek, 1994; Ellermeier, 1996).

Lentz *et al.* (1999) attempted to jointly model spectral-shape discrimination performance of sparse and dense stimuli using a bank of filters that represent the frequency analysis of the auditory system as a front end to a multichannel linear decision model (Durlach *et al.*, 1986). When all frequency channels were input to the decision model, Lentz *et al.* found that the model could only account for spectral-shape discrimination sensitivity of sparse and dense stimuli if the filters had bandwidths twice as narrow as measured using the notched-noise method. These very narrow filters effectively functioned as a peak-selection algorithm for their spectrally sparse stimuli. Because including a peak-selection algorithm into the Lentz *et al.* model has the potential to make the model more parsimonious with previous estimates of frequency selectivity, the following experiment tests whether spectral-shape discrimination is based on spectral peaks alone and expands the Lentz *et al.* model to include a peak-selection algorithm.

Controlled spectral-shape discrimination experiments illustrate that the auditory system is able to compare and contrast levels across frequency (Spiegel *et al.*, 1981; Green and Kidd, 1983; Green *et al.*, 1983; see also Green, 1988 for an overview). In these experiments, stimuli typically consist of the sum of tones, and listeners discriminate between a standard stimulus and a stimulus with a different spectral shape, or spectral profile. Sensitivity for detecting changes in spectral shape is dependent on the number of tones in the stimulus, the frequency spacing of the tones, and the type of spectral change. For tasks in which listeners detect a single increment added to a background of tones, spectral-shape discrimination sensitivity improves with the addition of tones when stimulus components are separated by frequency distances greater than the bandwidth of an auditory filter (i.e., for spectrally sparse stimuli; Green *et al.*, 1983; Green *et al.*, 1984; Bernstein and Green, 1987). As stimuli become spectrally dense, larger spectral prominences are needed for spectral-shape discrimination (Bernstein and Green, 1987).

Whether the auditory system uses spectral peaks or the entire stimulus in spectral-shape discrimination has important implications for the implementation of psychophysical

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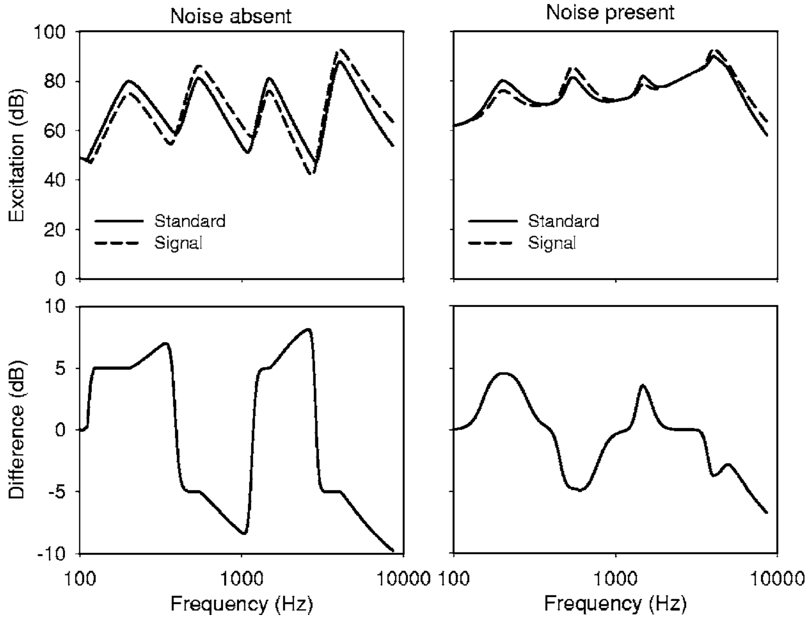

FIG. 1. The upper panels plot the excitation patterns of a standard stimulus made of four equal-amplitude components (solid line) and a signal stimulus created by decreasing and increasing the levels of every other stimulus component by 5 dB (dashed line). The left and right panels indicate the excitation patterns generated in the absence and in the presence of noise, respectively. The lower panels indicate the difference in excitation between the signal and the standard excitation patterns.

models, as selecting the appropriate channels has the potential to have a drastic effect on predicted performance. For example, broadband stimuli activate a wide frequency range of auditory channels, and each of those channels could carry information indicating that two stimuli have different spectral shapes. If the auditory system selectively uses channels that represent high intensities rather than a large spectral change between stimuli, then the actual performance might be poorer than predicted by a psychophysical model.

Figure 1 illustrates this logic by plotting excitation patterns for two stimuli in the upper left panel and the difference in the excitation patterns between those two stimuli in the lower left panel. The solid line in the upper left panel indicates a normal-hearing excitation pattern for a standard stimulus having four equal-amplitude components presented at a level of 80-dB SPL. The dashed line indicates the excitation pattern of a signal stimulus that was generated by decreasing components one and three by 5 dB and increasing components two and four by 5 dB. The difference excitation pattern in the lower left panel illustrates that the high-frequency edges of the excitation-pattern peaks have a change in excitation that exceeds 5 dB. In this way, a system that uses the entire excitation pattern would have more spectral-contrast information available than a system that selectively uses only the peaks (that have changes in excitation equaling about 5 dB) in the excitation pattern. However, peak selection would make spectral-shape discrimination relatively impervious to noise, as noise would mask the change in excitation at the high-frequency edges of the peaks.

The influence of noise on the excitation pattern is illustrated in the right panels of Fig. 1, which show excitation patterns generated when a 50 dB/Hz-broadband noise is added to the stimuli used in the left panels.[1] The upper right panels indicate standard+noise (solid line) and signal +noise (dashed line) excitation patterns. The difference in the noise-added excitation patterns (lower right panel) shows marked changes from the difference between noise-absent excitation patterns (lower left panel). Here, the noise reduces the spectral change in the frequency channels surrounding the excitation-pattern peaks.

The use of peaks in spectral-shape discrimination also has important implications for modeling and evaluating the effects of hearing loss. Hearing-impaired listeners who have poorer-than-normal frequency selectivity have a poorer representation of spectral peaks. Using stimuli with very dense spectra, Summers and Leek (1994) and Leek and Summers (1996) showed that the great difficulty experienced by listeners with hearing loss on spectral-shape discrimination tasks is primarily due to their reduced frequency selectivity. For spectrally sparse stimuli, Lentz and Leek (2003) showed that listeners with hearing loss have similar abilities to normal-hearing listeners in discriminating changes in spectral shape. However, differences in the decision weights of normal-hearing and hearing-impaired listeners when comparing levels across frequency (Doherty and Lutfi, 1996, 1999; Lentz and Leek, 2003) indicate some effect of hearing impairment, even when the stimuli are spectrally sparse. If reduced frequency selectivity changes the shape and the size of the spectral peaks, then the observed differences in decision weights might be a result of impaired peripheral processing.

The following experiment tests the hypothesis that the normal and impaired auditory systems use only the peaks in the excitation pattern for spectral shape discrimination. Spectral shape discrimination ability is measured in the presence and in the absence of a noise stimulus. The noise stimulus effectively blocks the change in excitation that is present on the edges of the peaks of the excitation pattern between signal and standard stimuli, leaving only the peaks available to cue excitation changes. If thresholds are little influenced by the presence of noise, then it will be concluded that the auditory system relies greatly on spectral peaks for spectral shape discrimination.

TABLE I. Audiometric thresholds of test ear for normal-hearing and hearing-impaired listeners (dB HL *re*: ANSI, 1996).

			Frequency (Hz)						
Observer	Age	Test ear	250	500	1000	2000	3000	4000	8000
NH1	43	R	10	5	10	10	10	10	20
NH2	40	R	10	10	10	0	0	0	10
NH3	40	R	5	0	0	0	0	0	5
NH4	48	R	10	5	5	10	10	10	5
NH5	57	L	0	5	5	0	0	0	10
HI1	78	L	10	20	35	50	45	50	65
HI2	38	R	20	20	35	35	50	50	60
HI3	64	L	10	10	25	45	50	55	60
HI4	58	L	10	15	25	35	60	65	65
HI5	19	R	30	35	60	65	35	45	45

II. METHODS

A. Observer characteristics

Five normal-hearing listeners and five hearing-impaired listeners participated in the experiment. The ages of the normal-hearing listeners ranged between 40 and 57 years, with a mean of 45.6 years, whereas ages of the hearing-impaired listeners ranged between 19 and 78 years, averaging 51.4 years. All normal-hearing listeners had pure tone audiometric thresholds of 10-dB HL or better between 250 and 4000 Hz and 20-dB HL or better at 8000 Hz. For normal-hearing listeners, the right ear was tested unless the right ear did not meet the criterion for normal hearing. Hearing-impaired listeners were selected so that the mean pure tone average threshold at 1000, 2000, and 4000 Hz was greater than 35-dB HL in their better ear (the test ear). Hearing losses were moderate and bilateral; the site of lesion was presumed to have a cochlear origin based on air and bone-conduction thresholds and normal immitance audiometry. The audiometric configurations for all test ears and the participants' ages are reported in Table I.

A sixth normal-hearing listener was excluded from the study due to an inability to achieve spectral-shape discrimination thresholds below -8.3 dB for *at least one* of the stimulus conditions. This criterion was set based on a roving-level distribution that was employed to reduce the use of overall level cues (described in the stimuli). Thresholds above this criterion level might be due to a contribution of single-channel intensity-based cues, and only thresholds below this criterion can be assured to reflect across-frequency processing.

B. Stimuli

The standard stimuli were the sum of 2, 4, 6, 10, 20, or 30 equal-amplitude sinusoids ranging from 200–4000 Hz, spaced equidistantly on a logarithmic scale, and rounded to the nearest 4 Hz. On each stimulus presentation, the starting phases of the component tones were selected randomly and independently from a uniform distribution ranging from 0 to 2π rad. The signal stimulus was generated by decreasing and increasing the levels of every other component. The up components were increased by the same decibel amount as the down components were decreased ($\Delta L_{\mathrm{up}}=\Delta L_{\mathrm{down}}$). Signal strength is described as the change in amplitude of the up components relative to the mean amplitude of the standard components [i.e., $20\log(\Delta A/A)$; sig re stan, in dB]. Each spectral component in the standard was presented at a mean level of 80-dB SPL. Stimuli were 250 ms in duration, with 30 ms cosine-squared rise/fall times.

When present, a 50-dB SPL/Hz noise stimulus was generated by summing tones up to 5000 Hz with amplitudes drawn from a Rayleigh distribution and phases randomly drawn from a uniform distribution that ranged from 0 to 2π rad. The noise components were separated by 1 Hz, yielding 1 s of independent noise. A 250-ms sample was randomly selected from the 1-s noise sample, and a new 1-s sample was generated for each noise stimulus presented. Noise stimuli had 30-ms cosine-squared rise/fall times. When present, the noise was added to the standard and signal stimuli such that onsets and offsets were shared.

Signal, standard, and noise stimuli were generated and summed digitally, and then played through one channel of a 24-bit digital-to-analog converter (DAC; TDT System III RP2.1) at a sampling rate of 4096×10^{-5} s (about 24414 Hz).[2] The output of the DAC was fed into a programmable attenuator that was adjusted to appropriately calibrate the stimuli. The output was fed into the right headphone of a Sennheiser HD 250 II Linear headset.

To reduce the impact of local intensity cues, measurements were obtained with across-interval level randomization in which the overall levels of the stimuli were varied on every presentation. The stimulus levels were randomly altered via the external attenuator based on draws from a uniform distribution with a mean of 0 dB, an 8 dB range, and a 0.1 dB gradation. The overall level across stimulus component number and roving levels ranged from a minimum of 79-dB SPL to a maximum of 98.8-dB SPL.

C. Procedure

Spectral-shape discrimination thresholds in the presence and in the absence of noise were estimated using a modified two-alternative forced-choice task, with trial-by-trial signal strengths chosen according to a three-down, one-up adaptive tracking procedure estimating the 79% correct point on the psychometric function ($d'=1.14$; Levitt, 1971). Observers were seated in a sound-attenuating room and heard three sounds separated by 450 ms. The first interval contained a standard stimulus, and the second and third intervals contained signal or standard stimuli, the order of which was selected randomly with equal likelihood. Listeners indicated which interval contained the signal stimulus by responding using a button box. Correct-answer feedback was provided to the listener following each trial.

At the beginning of every track, the signal strength was set to 10 or 15 dB above an estimate of the listener's final threshold. The initial step size of the tracking procedure was 4 dB, and after three reversals the step size was reduced to 2 dB. The track continued until a total of nine reversals of the direction of the track were obtained. The mean of the signal strengths at the last six reversal points was taken as threshold.

To control for the learning effects that are often present in spectral-shape discrimination experiments, a randomized block design was used to collect 12 threshold estimates per stimulus. The experimental design included six different numbers of components, and two noise conditions (noise present and noise absent) for a possible 12 experimental combinations. For each observer a number of components (N) and whether noise was present or absent was chosen at random. Three threshold estimates were obtained for the condition selected, and then three estimates were obtained for the remaining noise condition. Once six threshold estimates were obtained for a given N (three noise present, and three noise absent), a new N was selected randomly and the process repeated. After three thresholds were obtained for all stimulus types, three new thresholds were estimated with the stimulus types run in reverse order. Two additional sets of three threshold estimates were run with the stimulus types in their original and reverse order. Thresholds reported here represent the average of the last nine threshold estimates.

D. Modeling

An excitation-pattern model based on psychophysical estimates of frequency selectivity was used as a front-end to a linear multichannel decision model developed by Durlach *et al.* (1986; see Lentz *et al.*, 1999) according to the following procedures. Standard stimuli were generated at levels corresponding to levels ranging between 76- and 84-dB SPL per component in 1-dB steps. To shorten processing time, noise stimuli were simulated by summing equal-amplitude components at a frequency spacing of 10 Hz (i.e., the Rayleigh-distributed amplitudes were not included). The levels of frequency components were corrected such that the noise stimulus had the same overall level as that used in the psychophysical experiment, and due to the summation used in the excitation-pattern model, this noise yielded identical results to a noise made from components spaced by 1 Hz (also verified through spot checks). The elimination of the amplitude variance on the noise only has a small influence on the magnitude of an "encoding" noise source used in the decision model. For each N, signal stimuli were generated at 5 different signal strengths, which were selected to yield predicted d' values spanning between about 0.9 and 1.4.

In the peripheral auditory simulations, all stimuli were passed through 201 Roex filters, as described by the Glasberg and Moore (1990) filter bank, with center frequencies ranging between 89 and 8562 Hz. Filter center frequencies were spaced by 0.154 ERB, where ERB is defined as the Equivalent Rectangular Bandwidth of the filter. The power at the output of each filter was computed to generate the excitation patterns. The impaired auditory peripheral simulation included modifications to the Glasberg and Moore (1990) filter bank to accommodate reduced frequency selectivity. When the average hearing level at any filter center frequency exceeded 40-dB SPL, scaling of the auditory filter bandwidths was accomplished in the following way. First, the average hearing levels of the clinical audiograms were linearly interpolated so that a hearing level corresponding to each auditory filter center frequency was derived. Hearing levels corresponding to frequencies below 250 Hz were set to equal the hearing level at 250 Hz. Second, the bandwidth of each auditory filter is scaled by $\mathrm{ERB}_{\mathrm{HL}}/\mathrm{ERB}_{\mathrm{NH}}$, where $\mathrm{ERB}_{\mathrm{HL}}$ is given by Glasberg and Moore (1986) as $\mathrm{ERB}_{\mathrm{HL}} = -0.135 + 0.0097\mathrm{HL}_{\mathrm{SPL}}$, with $\mathrm{ERB}_{\mathrm{HL}}$ defined in kHz and $\mathrm{HL}_{\mathrm{SPL}}$ defined as absolute threshold in dB SPL. $\mathrm{ERB}_{\mathrm{NH}}$ is the approximate ERB at 1 kHz of a normal-hearing listener (0.133 kHz) because the previous equation was derived by Glasberg and Moore (1986) for an auditory filter centered at 1 kHz. In this way, the bandwidth of each auditory filter was broadened by an amount relative to the hearing level at that auditory filter's center frequency. The filter tail parameter was set to equal −25.2 dB. Note that this yields impaired filters having the same symmetry as the normal filters. For both healthy and impaired excitation pattern simulations, when the level at a filter's output was below the threshold of audibility for a filter's center frequency, the output level was set to be equal to the threshold of audibility (using the average audiograms).

Two types of models were evaluated: (1) the whole-spectrum model, in which the entire excitation pattern was the input to the channel model; and (2) the peaks-only model, in which the peaks in the excitation pattern were preserved and input to the channel model. The peaks-only excitation pattern was generated by first determining the maximum excitation of each peak in the standard excitation pattern. When the power at the output of a single auditory filter is P_c dB below the excitation of the nearest peak (a peak defined as excitation that exceeds excitation in adjacent frequency regions), the output of that filter is set to the corresponding threshold of audibility.

Figure 2 illustrates excitation patterns for four-component standard stimuli in the presence and in the absence of noise. For the whole-spectrum excitation patterns (top panels), the spectral representation is similar for normal-hearing and hearing-impaired listeners in the low frequencies, but the reduced frequency selectivity of the impaired auditory system degrades the spectral contrast in the high frequencies. The added noise stimulus broadens the spectral peaks and decreases the depth of the valleys in both the normal-hearing and hearing-impaired simulations. Also, the noise stimulus leads to a visible degradation of the high-frequency spectral peaks in the hearing-impaired model. For the peaks-only excitation patterns ($P_c = 5$ dB; bottom panels), spectral peaks are present for all frequency components, but broader peaks are associated with hearing impairment and the presence of noise.

The Durlach *et al.* (1986) channel model was implemented by using the formula described by van Trees (1968) as $(d')^2 = [\Delta_1, \ldots, \Delta_M] G [\Delta_1, \ldots, \Delta_M]^T$, where $[\Delta_1, \ldots, \Delta_M]$ indicates the mean change in level between signal and standard excitation patterns for channels 1 to M, G is the inverse of the covariance matrix, and T denotes the matrix transpose. Recall that the signal stimuli were generated using five signal strengths chosen to yield predicted d' values spanning between about 0.9 and 1.4. The Δ vector and

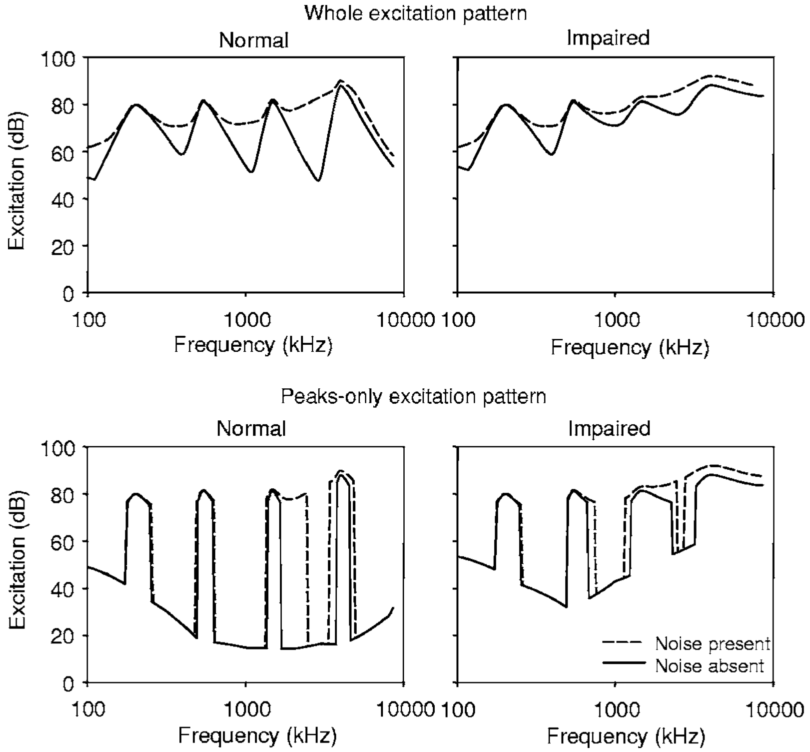

FIG. 2. Normal-hearing and hearing-impaired excitation patterns for a four-component stimulus are plotted in the left and right panels, respectively. Noise-present excitation patterns are plotted as the dashed lines, and noise-absent excitation patterns are plotted as the solid lines. The whole-spectrum model is illustrated in the upper panels, and the peak-selection model in which filters having output levels 5 dB below the nearest peak in excitation are set to the threshold of audibility is indicated in the lower panels.

the covariance matrix were estimated by corrupting the excitation patterns generated for each stimulus in the following way: Independently drawn deviates from a Normal distribution having a mean of 0 and a standard deviation of σ were added to the output of the each of the 201 frequency channels to generate 1000 randomly perturbed standard and 1000 randomly perturbed signal stimuli for each N and each signal strength. Here, σ is the standard deviation of "internal" or "encoding" noise needed to approximate imperfect auditory sensitivity. Random draws were taken from the group of excitation patterns generated at the nine different overall levels to simulate roving levels (i.e., 76–84-dB SPL per component in 1 dB steps). The correlated noise source generated by the rove is reflected in the covariance matrix, which was estimated by averaging the signal and standard covariance matrices. Psychometric functions at each of the five signal strengths were constructed. A linear least-squares fit to the psychometric function was used to determine a final estimate of threshold corresponding to $d' = 1.14$.

The two models were implemented by means of a partial grid search, using the single parameter, σ, for the whole-spectrum model and the two parameters, σ and P_c, for the peaks-only model. Note that the whole-spectrum model is the same as the peaks-only model with a P_c that is greater than the maximum excitation present in the excitation pattern. Hearing-impaired data were modeled separately from normal-hearing data. The proportion of variance accounted for in the average data (thresholds versus the number of stimulus components) was maximized in the noise-absent conditions by varying the value of σ or σ and P_c, depending on the model being fitted. Note that average data were used because, as will be illustrated in the results section, variability in the pattern of thresholds related to N is present across observers. The parameters σ and P_c were fixed, and then noise-present data were predicted using the simulated noise stimuli added to the multi-component stimuli.

The σ and P_c parameters differentially influence the pattern of the function relating predicted threshold to number of stimulus components. The parameter σ (the standard deviation of an encoding noise distribution) has the influence of either raising or lowering the entire function. Figure 3 illustrates that an increase in σ is associated with an upward shift in the function relating threshold to N (poorer sensitivity), whereas a decrease in σ is associated with a downward shift in the predicted threshold (better sensitivity). Changes to the number of channels also influence predicted sensitivity (Lentz *et al.*, 1999); an increase in the number of channels

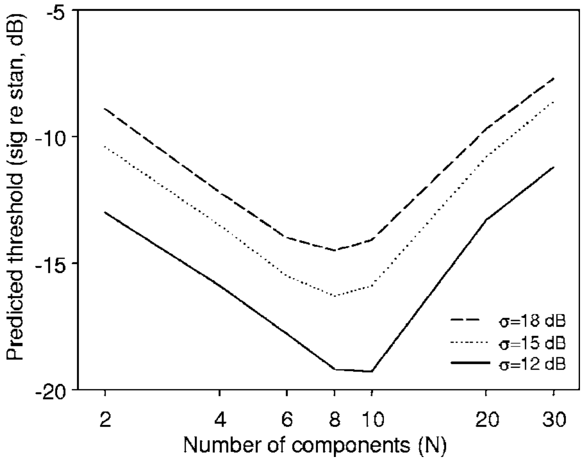

FIG. 3. The influence on model predictions for a change in the standard deviation of the "encoding" noise, σ, is illustrated. Predicted thresholds are plotted as a function of the number of stimulus components. Model predictions are based on noise-absent stimuli, normal-hearing auditory filter bandwidths, and $P_c = 7$ dB.

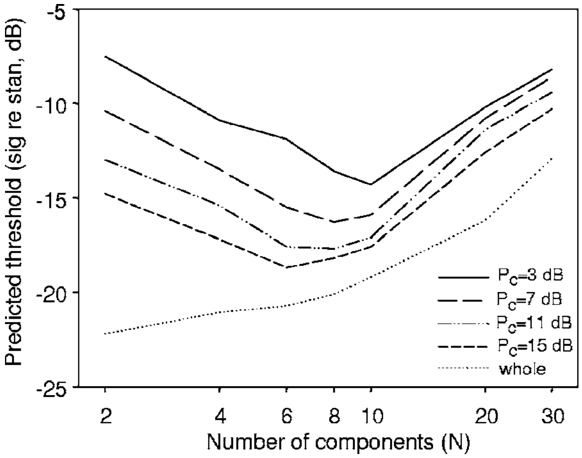

FIG. 4. The influence on model predictions for a change in the P_c parameter is illustrated. Predicted thresholds are plotted as a function of the number of stimulus components. Model predictions are based on noise-absent stimuli, normal-hearing auditory filter bandwidths, and $\sigma = 15$ dB.

(leading to better sensitivity) would necessitate an increase in σ (leading to poorer sensitivity) to yield the same predictions. Thus, the magnitude of σ has little absolute meaning, as it must be interpreted in the context of the number of channels.

In contrast to the encoding noise parameter, the peak-selection parameter, P_c, influences the shape of the function relating threshold to N. The influence of the P_c parameter on the shape of the function is illustrated in Fig. 4. Changes in the P_c parameter are associated with changes in overall sensitivity, in that larger values of P_c (broader spectral peaks) lead to a greater number of channels cueing the spectral-shape change and subsequently lower thresholds (better sensitivity). Larger P_c values also lead to a smaller N at which thresholds begin to rise, but the P_c parameter has little effect on the slope of the function relating threshold to N at small N. Note that in this implementation of the model P_c is not allowed to be 0, as this would obliterate all spectral information.

III. RESULTS

A. Experimental data

Figure 5 plots thresholds obtained from the individual listeners (upper five panels) and the thresholds averaged across listeners (bottom panels) as a function of the number of stimulus components. A repeated-measures ANOVA treating group membership as a between-subjects variable and number of components and whether noise was present or absent as within-subjects variables reveals significant main effects and two-way interactions in the data. Thresholds are dependent on the number of components $[N; F(6,48) = 12.4; p < 0.001]$, and, across most listeners, there is a general pattern of an initial decrease in threshold followed by a subsequent increase in threshold as N increases. Only NH2 in the noise-present condition and HI1 in the noise-absent condition do not show this pattern in their data.

The average data from normal-hearing listeners (bottom left panel) also indicate that the function relating threshold to N has a "W" shape. While there are some individual differences in the shape of the function relating threshold to N across observers, three of the five normal-hearing listeners show this W shape in their noise-absent data (NH1, NH3, and NH5; also reported by Lentz *et al.*, 1999), and four of the listeners show the W shape in the noise-present data, though individual observers show this W shape to different degrees. For example, the noise-present data of NH1 have a very pronounced W, with thresholds at $N = 8$ being 10 dB higher than thresholds at $N = 4$ or $N = 10$. In contrast, the noise-present data obtained from NH3 indicate a less-pronounced W shape, as thresholds at $N = 8$ are only 1.2 dB higher than thresholds at $N = 6$. In general, data obtained from hearing-impaired listeners (right panel) do not have the W shape in either condition: the W shape is evident only for HI5 when noise is absent and HI2 when noise is present.

The fact that thresholds vary nonmonotonically with increasing N suggests that listeners are comparing levels across frequency and not relying on single-channel intensity cues for discrimination. In addition, all average thresholds in the noise-absent conditions, except those obtained from the hearing-impaired listeners at $N = 20$ and $N = 30$, are below the -8.3 dB level-detection limit. Thus, on average, the noise-absent data do not reflect judgments based on overall intensity changes.

The general shape of the functions relating threshold to N is different for normal-hearing and hearing-impaired listeners, as revealed by a significant interaction between group membership and the number of components $[F(6,48) = 2.9; p < 0.015]$. For normal-hearing listeners, thresholds begin to consistently rise with increasing N when the stimulus contains more than 10 components. In contrast, thresholds obtained from the hearing-impaired listeners begin to rise at the smaller N of 6 or 8. For the larger N's, hearing-impaired listeners show poorer spectral-shape discrimination sensitivity than normal-hearing listeners. These two results (the smaller N at which thresholds begin to rise and the poorer the spectral-shape discrimination sensitivity at large N for hearing-impaired listeners) likely reflect the poorer frequency selectivity in the impaired auditory system [see also Summers and Leek (1994) and Leek and Summers (1996)].

On average, it appears that spectral-shape discrimination is poorer for hearing-impaired than for normal-hearing listeners, but this finding is not statistically significant $[F(1,8) = 3.6; p = 0.09]$, perhaps due to the small group size and large variability in performance across listeners. It is evident from the individual data (also reflected in the large error bars on the average data) plotted in Fig. 5 that overall spectral-shape discrimination sensitivity varies across listeners, regardless of whether they have hearing loss or not. For example, NH2 has very poor spectral-shape discrimination sensitivity compared to the other normal-hearing listeners and some of the hearing-impaired listeners.

The repeated-measures ANOVA also reveals a significant main effect of whether noise was present or absent $[F(1,8) = 92.5; p < 0.001]$ and a significant interaction between group membership and whether noise was present or absent $[F(1,8) = 11.6; p < 0.01]$. On average, the presence of noise leads to an increase in spectral-shape discrimination threshold by 2.6 dB. However, the spectral-shape discrimina-

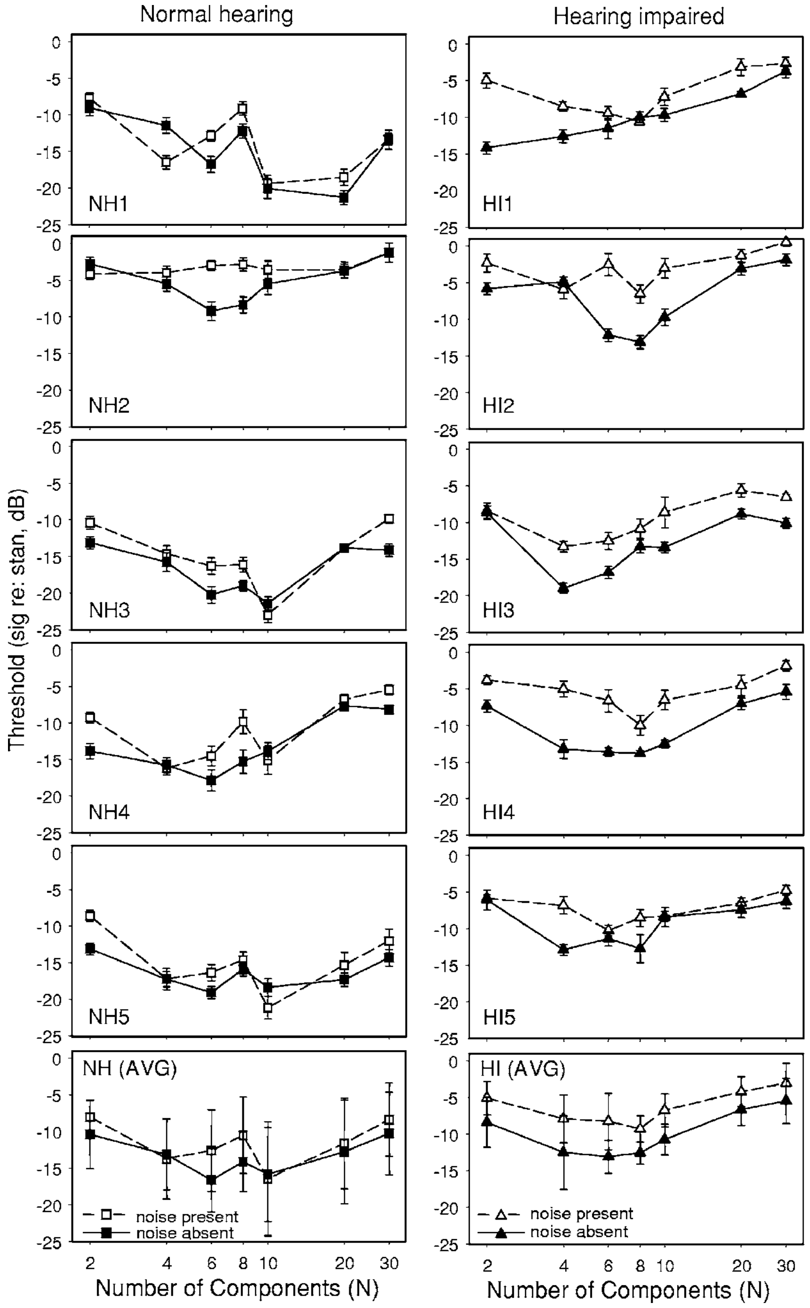

FIG. 5. Spectral-shape discrimination thresholds are plotted for five normal-hearing listeners (left panels) and five hearing-impaired listeners (right panels) as a function of the number of stimulus components. Averaged data are plotted in the bottom panels for each group. Filled and unfilled symbols denote noise-absent and noise-present conditions, respectively. For the individual data, error bars indicate standard errors of the mean across nine threshold replicates, whereas, for the averaged data, error bars indicate standard deviations across five listeners.

tion sensitivity of the hearing-impaired listeners is influenced by the noise to a greater extent than for the normal-hearing listeners (1.7 dB for normal-hearing listeners and 3.5 dB for hearing-impaired listeners). For the normal-hearing listeners, thresholds at $N=6$ and $N=8$ are more greatly influenced by the presence of the noise stimulus—these two thresholds alone are 3.8 dB higher than the corresponding noise-absent thresholds. However, the general pattern is a small effect of noise. Using slightly different stimuli, Green and Forrest (1986) also found that spectral-shape discrimination thresholds of normal-hearing listeners were not influenced by a noise stimulus having a spectrum level 30 dB below the level per component. In contrast, thresholds obtained from hearing-impaired listeners for all numbers of components are influenced by the presence of noise.

The relatively small effect of the noise on spectral-shape discrimination thresholds of normal-hearing listeners is consistent with the hypothesis that the auditory system uses only the peaks in the excitation pattern when discriminating between sounds with different spectral shapes. The small effect of noise on the spectral-shape discrimination threshold indicates that masking the information-bearing edges of peaks in the excitation pattern does not greatly degrade performance and suggests that only the peaks are used for spectral-shape discrimination. Hearing-impaired listeners, however, were influenced by the presence of noise to a greater extent than normal-hearing listeners. This result might imply that the impaired auditory system does not rely on the spectral peaks to the same extent as the normal-hearing listeners because reduced frequency selectivity broadens the peaks and makes them less pronounced. An alternative explanation is that the

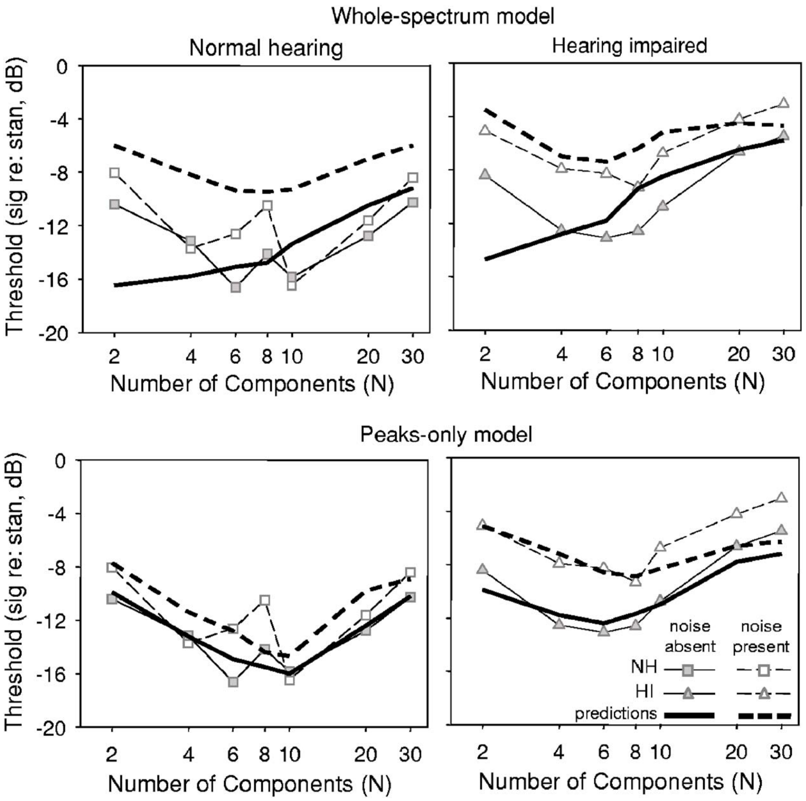

FIG. 6. Model predictions for the whole-spectrum and peaks-only models are plotted in the upper and lower panels, respectively. Normal-hearing data and predictions are indicated in left panels, whereas hearing-impaired data and predictions are indicated in the right panels. Noise-absent predictions are shown by the bold, solid lines, and noise-present predictions are shown with the bold, dashed lines. Averaged data from Fig. 5 are replotted with the noise-absent data as filled symbols and the noise-present data as the unfilled symbols.

impaired auditory system does rely on the spectral peaks, but the broader spectral peaks are more susceptible to noise. These two alternatives will be explored further in the modeling.

B. Modeling results

Model predictions are plotted along with the average normal-hearing and hearing-impaired data in Fig. 6. Whole-spectrum model predictions are plotted in the upper panels, whereas peaks-only predictions are plotted in the lower panels. Normal-hearing and hearing-impaired data and predictions are shown in the left and right panels, respectively.

The upper left panel illustrates that normal-hearing data are poorly predicted by the whole-spectrum model. The best-fitting whole-spectrum model predictions of the noise-absent data (bold, solid line; $\sigma=27$ dB) do not well capture the trends present in the data. The model predicts that thresholds increase with increasing *N* for all *N* and predicts better-than-measured thresholds at small *N*. The model fits to the noise-absent data more closely captures the initial decrease in threshold with increasing *N* and the subsequent increase in threshold with increasing *N*, but the whole-spectrum model predicts that noise-present thresholds (bold, dashed line) should be much higher than noise-absent thresholds. The elevated noise-present thresholds are not observed in the data, as thresholds are only 1.7 dB higher when noise is present over when noise is absent. Thresholds for small *N* are predicted to be about 10 dB higher in the noise-present conditions than in the noise-absent conditions, and the effect of noise is predicted to decrease with increasing *N*, to a value of 3.2 dB at $N=30$. The whole-spectrum model accounts for less than 45% of the variance in the data, and it is clear that it fails considerably to predict trends present in the normal-hearing data.

The whole-spectrum model shows a similar failure to predict the hearing-impaired data in the noise-absent conditions. As with the predictions of the normal-hearing data, predicted thresholds in the noise-absent condition (bold, solid lines; obtained using $\sigma=28$ dB) consistently increase with increasing *N*. However, model predictions of the noise-present conditions (dashed, solid lines) show an improvement in the goodness-of-fit, with a major improvement in capturing the initial decrease in threshold with increasing *N*. The general shape of the function relating the predicted threshold to N is also similar to the shape of the measured data. The whole-spectrum model, however, does not predict the consistent influence of noise on the threshold for all *N*.

Because the whole-spectrum model fails to capture the decrease in threshold with increasing *N* for small *N*, and the effect of noise is not appropriately predicted for normal-hearing and hearing-impaired listeners, a second model was used in which the whole-spectrum model was modified to include a peak-selection algorithm (see Fig. 6, bottom panel). Normal-hearing noise-absent data were best fit using the peak-selection model with $\sigma=13$ dB and $P_c=4$ dB, accounting for 85% of the variance in the data. Model predictions (bold, solid lines) accurately predict the pattern of thresholds observed in the dataset. The main deficiency is that the W shape is not captured by the model. However, peak-selection model fits are superior to the model fits obtained from the whole-spectrum model.

When the noise-present data are predicted using the same parameters as the noise-absent conditions, the model has more difficulty predicting the data, accounting for only 49% of the variance. In general, the model predicts that noise would lead to an average 1.8 dB increase in the spectral-shape discrimination threshold, an increase that is very similar to the average 1.7 dB effect of noise in the normal-hearing data. The shape of the predicted function is similar to the shape of the data. However, the pronounced W shape in the noise-present dataset again is not captured by the model, and no change to the model parameters can predict the W shape (see Figs. 3 and 4). The cause of the W shape in the data is unknown, but perhaps it is related to a shift from a peak-selection process used at small N (i.e., when a stimulus leads to a highly peaked excitation pattern) to a different decision process for stimuli having less peaked excitation patterns.

Noise-absent data from hearing-impaired listeners are best fit using the peak-selection model with $\sigma = 19$ dB and $P_c = 3$ dB, accounting for 85% of the variance in the data. The general shape of the function is very similar to that observed in the data, but the change in the predicted threshold with increasing N at large N is somewhat shallower than measured. Part of the failure in the model to capture the subtle trends present for large N might be that the auditory filter bandwidths used in the model were estimated rather than measured. To test whether changes in auditory filter bandwidth might lead to better predictions to the data collected from hearing-impaired listeners, the peaks-only model was run using scaled auditory filter bandwidths. Even better fits (over 92% of the variance accounted for) could be obtained using narrower auditory filter bandwidths. However, even with this modification, the rise in threshold with increasing N at large N is somewhat underpredicted. Clearly, the fits to the hearing-impaired data are robust, with the peaks-only model being a much better predictor of performance than the whole-spectrum model. Despite using optimal processing and generalization of frequency selectivity, the model fits do quite well in predicting the trends present in the hearing-impaired data.

The best-fitting parameters differ from those estimated from the normal-hearing data, with σ being larger to fit the hearing-impaired data (19 and 13 dB for the hearing-impaired and normal-hearing listeners, respectively), and P_c being only 1 dB different from the P_c that best-fit the normal-hearing data (3 and 4 dB for the hearing-impaired and normal-hearing data, respectively). The higher value of σ for hearing-impaired listeners might be consistent with the idea that hearing impairment can be modeled as a "second noise" (e.g., Humes *et al.*, 1988). The similarity of P_c values between the two groups suggests that processing of stimuli with different spectral shapes is very similar for normal-hearing and hearing-impaired listeners and indicates that the impaired auditory system still accomplishes some form of peak selection. The peaks-only model also predicts the data obtained from hearing-impaired listeners much better than the whole-spectrum model.

As in the predictions of the normal-hearing data, the peaks-only model does not predict the noise-present data as well as the noise-absent data, accounting for only 61% of the variance in the noise-present data. The general pattern of predicted thresholds versus N is similar to the observed pattern in the data. Unlike the normal-hearing data, the hearing-impaired data tended not to show the W shape in the function relating threshold to N. The main failure of the model to capture the trends in the hearing-impaired data is at large N where predicted thresholds are *better* than measured. Increasing the value of σ would improve the goodness-of-fit, but then the better predictions of thresholds at large N would come at the expense of more poorly predicted thresholds at small N. Changing the peak-selection parameter (P_c) does not improve the goodness of fit.

The major failure of the whole-spectrum model is to capture the decrease in threshold with increasing N when N is small for both groups of listeners. Including a peak-selection algorithm into the model successfully depicts this initial decrease in threshold. The peaks-only model captures some of the increase in threshold in the presence of noise, but generally the peaks-only model does not predict the noise-present data as well as the noise-absent data. However, the relative success of the peaks-only model in predicting both normal-hearing and hearing-impaired data compared to the whole-spectrum model suggests that listeners in both groups use the peaks in spectral-shape discrimination. The higher relative thresholds for the hearing-impaired listeners in the presence of the noise, then, could be due to differences in frequency selectivity between the two groups, rather than differences in the listeners' decision processes when discriminating between sounds with different spectral shapes.

IV. DISCUSSION

A. Peak selection in spectral-shape discrimination

Support for the conclusion that spectral-shape discrimination of sounds with a peaked excitation pattern is accomplished by selecting the peaks can be found in both the experimental data and the modeling predictions. First, the experimental data from normal-hearing listeners indicate that the presence of a noise stimulus has only a modest influence on the spectral-shape discrimination threshold. If the entire excitation pattern were used for the decision, it would be anticipated that the presence of noise would lead to a large increase in threshold. This prediction is supported by the very large influence of noise on the spectral-shape discrimination threshold predicted by the whole-spectrum model. Second, the peaks-only model is able to capture the trends apparent in the noise-absent data, though the model fits are not as robust as observed for the noise-present conditions. The peaks-only model captures trends in the normal-hearing and hearing-impaired data equally well, supporting the conclusion that the impaired auditory system also relies on spectral peaks for discriminating between sounds with different spectral shapes. Taken together, the experimental data and the multichannel modeling suggest that the healthy and the impaired auditory systems rely on spectral peaks in the stimulus for spectral-shape discrimination when the stimulus has pronounced spectral peaks.

Previous spectral-shape discrimination data are consistent with the hypothesis that the auditory system relies mostly on the spectral peaks to discriminate between sounds with different spectral shapes when those stimuli lead to peaked excitation patterns. These experiments indicate that the central auditory system may not greatly rely on the edges of the excitation pattern peaks. For example, Green *et al.* (1984) had listeners detect a single tone added in phase to the 1000-Hz central component of a three-component background and varied the spacing of the frequency components. The sensitivity for detecting a single tone added to a three-component background improved by only 4 dB when stimulus components were separated by a frequency ratio of 1.38 versus a frequency ratio of 5 (see also Green *et al.*, 1983). If the auditory system used the edges of the peaks in the excitation pattern, it might be expected that a larger improvement in threshold would have been measured.

Other evidence of using the spectral peaks for spectral-shape discrimination is that spectral-shape discrimination data do not show evidence of the near-miss to Weber's law (Mason *et al.*, 1984; Green and Mason, 1985; Versfeld and Houtsma, 1995; Lentz, 2005). The near-miss to Weber's law reflects a decrease in the ratio relating the intensity discrimination difference limen of a single tone to the intensity of that tone ($\Delta I/I$) with increasing intensity (Riesz, 1928; Viemeister, 1972; Moore and Raab, 1974). For intensity discrimination of tones, the change in excitation at the high-frequency edge of the peak in the excitation pattern provides a useful cue to the auditory system that one tone is more intense than another. Because spectral-shape discrimination experiments show no evidence for the near-miss to Weber's law (even in the absence of overall level randomization), the edges of the excitation pattern peaks might not be important for spectral-shape discrimination. These results suggest that using only the spectral peaks might be an inherent property of auditory processing for broadband listening.

These arguments regarding peak selection for spectral-shape discrimination have support in the vowel-perception literature, where it has been suggested that the frequencies of the spectral peaks (i.e., formants) provide more important cues to vowel identity than the overall shape of the spectrum (Assmann and Summerfield, 1989). Assmann and Summerfield (1989) measured single- and double-vowel identification for synthetic vowels and "vowels" with only six harmonics. The six-harmonic "vowels" contained equal-amplitude harmonic pairs, with each pair corresponding to one of the first three formant frequencies. Overall levels of performance did not differ significantly between the two vowel types, despite the richer spectrum of the synthesized vowels, indicating that the low-level valleys did not provide informative cues to the identities of the vowels.

Spectral enhancement mediated by suppression in the auditory nerve (Houtgast, 1972; Sidwell and Summerfield, 1985), might provide a mechanism for selecting the spectral peaks in a complex stimulus. Physiologic studies have also shown that the temporal responses of auditory nerve fibers are dominated by the spectral peaks in a vowel-like stimulus (e.g., Young and Sachs, 1979; Delgutte and Kiang, 1984). Enhancement of the spectral peaks in a stimulus also occurs in the impaired auditory system, although the enhancement is not as pronounced as for normal-hearing listeners (Sidwell and Summerfield, 1985; Thibodeau, 1991).

Because the results of the current experiment suggest that the edges of the peaks in the excitation pattern do not contribute greatly to spectral-shape discrimination, the selection of spectral peaks might be described as a process leading to a loss of information, indicating that two stimuli have different spectral shapes. However, as has been shown here, the presence of a low-level noise does not greatly alter sensitivity to changes in spectral shape. In contrast, the whole-spectrum model predicts a large decrease in spectral-shape discrimination sensitivity. Selecting for the spectral peaks would provide a mechanism allowing the ear to function similarly under noisy and quiet conditions.

Thresholds obtained from hearing-impaired listeners were elevated by noise by a greater amount than those obtained from normal-hearing listeners. However, the small influence of noise (3.5 dB) and the success of the peaks-only model lead to the conclusion that hearing-impaired listeners also rely on the spectral peaks to discriminate between sounds with different spectral shapes. Because hearing-impaired listeners have poorer frequency selectivity than normal-hearing listeners, the spectral peaks in a stimulus are more easily masked by the presence of noise. Thus, a major limitation experienced by the hearing-impaired listeners in spectral-shape discrimination might be reduced frequency selectivity, which impacts the perception of both spectrally sparse and spectrally dense stimuli, especially in the presence of a background noise.

B. Modeling implications

A modification of the whole-spectrum multichannel model by including a peak-selection algorithm leads to an improvement of model fits, but the peaks-only model does not capture all trends in the data. Including a peaks-only excitation pattern has the effect of accurately predicting the initial decrease in threshold with increasing numbers of components that has been commonly reported in spectral-shape discrimination data (see Bernstein and Green, 1987; Green, 1992). This modified version of the model, while very successful at predicting the general trends of spectral-shape discrimination for normal-hearing and hearing-impaired listeners, has two notable discrepancies between the predictions and the data. One discrepancy is that the model could not capture distinct W shape present in the data of the majority of the normal-hearing listeners. The inability of the model to capture this shape suggests a difference in the auditory processes responsible for coding spectral shape for stimuli with different spectral characteristics. The model also fails to predict the increase in threshold with increasing N ($N > 8$) observed for hearing-impaired listeners. Consideration of each of these discrepancies might lead to insight regarding the processes that code spectral shape in the normal and impaired auditory systems.

The inability of the peaks-only model to capture the W shape in the data from normal-hearing listeners suggests that there could be differences in the underlying processes for stimuli with peaked excitation patterns, stimuli with excitation patterns intermediate to peaked and flat, and stimuli with flat excitation patterns. Spectral-shape discrimination of sparse stimuli has been modeled fairly extensively in the past, and for the most part, multichannel models have been highly successful at predicting performance (see Berg and Green, 1990; Green, 1992; Lentz and Richards, 1997). However, despite the widespread support for an optimal combination of channel outputs, listeners do not always optimally combine information across frequency when the stimuli are spectrally sparse (Lentz and Leek, 2003). Stimulus characteristics and task demands could play a large role in the decision rules adopted by normal-hearing and hearing-impaired listeners.

Spectrally dense stimuli might also be subject to shifts in decision rules, depending on whether stimuli are spectrally flat or spectrally peaked, but there are few quantitative evaluations of a multichannel model to spectrally dense stimuli. Farrar *et al.* (1987) successfully applied a multichannel model to the discrimination of noise bursts modeled after English consonants. Other applications of excitation patterns to the spectral-shape discrimination of spectrally dense stimuli have used a modified version of the multichannel model. Summers and Leek (1994) successfully modeled spectral-shape discrimination of stimuli having a sinusoidally rippled spectral envelope using a simple "two-channel" algorithm in which a minimum excitation level was subtracted from a maximum excitation level. Versfeld (1997) also argued that a modification of the multichannel model in which only a limited number of channels are combined would lead to better predictions of spectral-shape discrimination of narrow bands of noise. Applied to the current model, using a subset of channels will only improve predictions if a different number of channels is used for spectrally sparse stimuli than for spectrally dense stimuli.

The presence of the W shape in the normal-hearing data could arise from differences in the decision processes adopted by listeners across stimuli with different spectral densities (or different spectral shapes, such as peaked or flat), but another possible explanation of the W shape is that temporal cues could play a role in the presence of the W shape. As the spectral density of the stimuli used in this experiment increases, the temporal interactions between adjacent components would also increase, leading to a second cue present in the current experiment. Support for the idea that temporal cues might be at play here is found in an auxiliary experiment by Lentz *et al.* (1999). They showed that temporal cues could have a modest influence on spectral-shape discrimination sensitivity. However, none of the subjects who participated in the auxiliary experiment had data that reflected the W shape (in conditions both with and without reliable temporal cues). These subjects ($N=3$) received a large amount of practice on the spectral-shape discrimination tasks (about 18 h). Another explanation is that the W shape might reflect different decision strategies across spectral densities with the spectral-shape change being more difficult to learn for certain types of stimuli. Why this might differ for normal-hearing and hearing-impaired listeners is unclear.

As mentioned previously, the peaks-only model does not successfully capture the increase in threshold for spectrally dense stimuli, especially for the hearing-impaired listeners. Perhaps the decision strategies adopted by listeners with hearing loss are different from those adopted by listeners with normal hearing for both spectrally sparse and spectrally dense stimuli. Using spectrally sparse stimuli, Doherty and Lutfi (1996) and Lentz and Leek (2003) showed that listeners with hearing loss adopt decision strategies that are different to the strategies adopted by listeners with normal hearing. Whether these results on spectrally sparse stimuli are due to peripheral or central differences in auditory processing remains unknown, but if spectral shape processing does differ for spectrally sparse (or spectrally peaked) and spectrally dense (or spectrally flat) sounds, there could also be differences in the decision strategies adopted by normal-hearing and hearing-impaired listeners for spectrally dense sounds. Differences in decision strategies could lead to differences in the success of the model at predicting thresholds for large N. Better fits of the model might also be expected if actual auditory filter bandwidth estimates were used.

V. SUMMARY AND CONCLUSIONS

The current experiment shows that the presence of noise has little effect on spectral-shape discrimination ability for normal-hearing listeners and leads to a moderate increase in threshold for hearing-impaired listeners. An excitation pattern model based on psychophysical estimates of frequency selectivity and a peak-selection algorithm coupled with a linear multichannel decision model is able to account for more than 85% of the variance in the data for normal-hearing and hearing-impaired groups in conditions when noise is absent. The relatively small influence of noise on spectral-shape discrimination sensitivity and the success of a multichannel model that included a peak-selection algorithm suggest that the normal and impaired auditory systems selectively use peaks in the excitation pattern. It is therefore concluded that the somewhat larger influence of noise on spectral-shape discrimination sensitivity for hearing-impaired listeners is due to a broadening of peaks in the excitation pattern rather than an inability to use those peaks.

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[1] The noise used for the excitation patterns contain equal-amplitude components.

[2] The TDT RP2.1 does not generate aliased stimuli below the sampling rate, eliminating the need for an antialiasing filter.

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