Frequency discrimination as a function of tonal duration and excitation-pattern slopes in normal and hearing-impaired listeners

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Frequency difference limens were determined as a function of stimulus duration in five normal-hearing and seven hearing-impaired subjects. The frequency DL duration functions obtained from normal-hearing subjects were similar to those reported by Liang and Chistovich [Sov. Phys. Acoust. 6, 75–80 (1961)]. As duration increased, the DL's improved rapidly over a range of short durations, improved more gradually over a middle range of durations, and reached an asymptote around 200 ms. The functions obtained from the hearing-impaired subjects were similar to those from normal subjects over the middle and longer durations, but did not display the rapid changes at short durations. The paper examines the ability of a variation of Zwicker's excitation-pattern model of frequency discrimination to explain these duration effects. Most, although not all, of the effects can be adequately explained by the model.

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INTRODUCTION

Recent work in the area of pure-tone frequency discrimination by Hall and Wood (1984) and Freyman and Nelson (1984) has shown that most subjects with moderate degrees of sensorineural hearing impairment are able to discriminate frequency changes in very short-duration tones as well as normal-hearing subjects. This is true even when their discrimination performance for long-duration tones is abnormal. Freyman and Nelson (1984) showed further that these data are consistent with an excitation-pattern model of frequency discrimination. This model posits that the frequency discrimination of two pure tones depends on the detection of intensity changes along the steep lower frequency slopes of the auditory excitation patterns that they evoke. Since, with this type of model, the size of the frequency difference limen (DLF) is directly related to the steepness of the excitation-pattern slopes, the model can be extended to state that the poor frequency discrimination performance of hearing-impaired listeners is due to (presumably) flatter excitation-pattern slopes.

The predictions of the excitation-pattern model may be very different for very short-duration tones, where the spectral slopes are less steep than those of the excitation pattern. Moore (1973) suggested that for these short, broad-spectrum tones, the excitation-pattern model predicts that the DLF is limited by the spectral slopes of the stimulus itself. Using this reasoning, the DLF's obtained from hearing-impaired listeners for short-duration tones should not be larger than normal, since the DLF is assumed to be limited by the same stimulus spectrum slopes for all listeners. Therefore, the results of the two studies that show normal short-tone frequency discrimination performance by hearing-impaired listeners are consistent with the predictions of the excitation-pattern model.

Although the data for hearing-impaired subjects agree qualitatively with the predictions of the model, quantitative predictions have not been studied. Moore (1973) has shown discrepancies between the predictions of an excitation-pattern model and the frequency discrimination abilities of normal-hearing subjects for short-duration tones. This result suggests the need for a more quantitative analysis of the performance of hearing-impaired subjects. In the current paper, we examine the short-tone frequency discrimination performance of hearing-impaired subjects in more detail than has been done previously. Here, DLF's are obtained as a function of stimulus duration in both normal-hearing and hearing-impaired observers, estimates of excitation-pattern slopes are obtained with a forward-masking procedure, and differences in the data obtained from the two groups are described quantitatively in terms of the excitation-pattern model.

A. Description of the excitation-pattern model

The model to be evaluated is only a slight variation of the excitation-pattern model described by Zwicker (1970). His model was based on the assumption that two pure tones of slightly different frequency produce identically shaped, but slightly shifted, auditory excitation patterns. At any one frequency, the level of excitation produced by the tones differs by an amount dependent on the steepest slopes of the excitation patterns. Zwicker (1970) suggested that the steepest portion of the excitation pattern is usually the low-frequency side and that the average slope in normal-hearing listeners is about 27 dB/bark. He postulated that a subject can discriminate between the two tones when the difference in excitation level equals or exceeds a criterion difference of 1 dB. Therefore, the predicted frequency DL is always 1/27 bark. The model that will be evaluated in this paper differs from the one just described in that the two constants, the excitation-pattern slope and the criterion, are permitted to vary across subjects and conditions, and individual DLF's

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rather than group mean DLF's are predicted.

This paper focuses on the excitation-pattern model's specific predictions about the form of the DLF duration function. For stimulus durations less than some *"critical duration,"* where the stimulus spectral slope and excitation-pattern slope are equal, the DLF presumably depends on the spectral slope and should become steadily larger as duration is decreased and spectral slopes broaden. For stimulus durations greater than this critical duration, the DLF is determined by the excitation-pattern slope and should change more gradually or not at all with changes in stimulus duration. Therefore, the DLF duration function should be a two-part function with a knee or *"breakpoint"* that occurs at some critical duration where the spectral slope and the excitation-pattern slope are equal.

This general form of the DLF duration function has been observed in data obtained previously (e.g., Turnbull, 1944; Oetinger, 1959; Liang and Chistovich, 1961). Perhaps the most straightforward data to interpret in terms of the model are those of Liang and Chistovich (1961). They were able to fit their DLF duration data with three linear functions in log-DLF versus log-duration coordinates: a steep slope over the shortest durations, a more gradual slope over the middle durations, and a constant over the longest durations. The intersection between the steep and gradually sloped lines was the critical duration (their "T_1") at which they assumed that the signal bandwidth and the auditory filter bandwidth were equal. Their support for this hypothesis was the result that T_1 displayed a frequency dependence consistent with their predictions from critical bandwidth data. Liang and Chistovich assumed that for stimulus durations less than T_1 the DLF was determined by the signal bandwidth, and that the gradual changes in the DLF for durations greater than T_1 were related to an increasingly precise estimation of the peak of the auditory excitation pattern as the duration of the observation period was increased.

Thus there is some evidence for the existence of a knee or breakpoint in the DLF duration function that is predicted by an excitation-pattern model. The current paper evaluates the ability of the model to predict the location of this breakpoint, given independent estimates of excitation-pattern slopes. Piecewise linear equations are fitted to DLF duration functions in order to establish breakpoints in the functions. These breakpoints are then compared to the critical durations predicted by equating estimates of the low-frequency excitation-pattern slopes with the stimulus spectral slopes. Because of presumably broader excitation-pattern slopes in hearing-impaired subjects, their critical durations are predicted to be shorter than for normal-hearing subjects. Finally, quantitative predictions are made of the DLF's obtained at stimulus durations less than the breakpoint.

I. EXPERIMENT I. DLF DURATION FUNCTIONS

A. Method

1. Subjects

Five normal-hearing and seven sensorineural hearing-impaired subjects participated in these experiments. All subjects except hearing-impaired subject EJ were college students. The normal-hearing subjects ranged in age from 21 to 28 years (median = 23), and had detection thresholds below 10 dB HL from 125 to 4000 Hz. The hearing-impaired subjects ranged in age from 20 to 46 years with a median age of 24. The severity of hearing losses ranged from mild to severe, but most subjects had relatively flat moderate losses. Audiometric data obtained from the seven hearing-impaired subjects are shown in Table I. Specific etiologies of most of the hearing losses were unknown, although audiological test results were, in every case, indicative of cochlear pathology. Two of the hearing-impaired listeners (GR and JC) had extensive experience as subjects in psychoacoustic experiments. Among the normal-hearing listeners, only the first author (RF) was an experienced subject. Only one ear of each subject was tested.

2. Stimulus generation

The standard test signals were pure tones with frequencies of 500, 1000, or 2000 Hz with durations ranging from 5 to 300 ms. Each tone consisted of a 2-ms linear rise time (0% and 100% of full amplitude) followed by a steady-state portion equal to the stated stimulus duration, and then a 2-ms linear fall time. The standard pure tones were created digitally on a PDP-8 computer, and were presented via digital-to-analog (D/A) conversion at 20 000 points/s. The variable tones were always lower in frequency than the standards and were generated through D/A conversion of these same waveforms at rates below 20 kHz. A Rockland frequency synthesizer with 0.001-Hz resolution served as the clock that controlled the D/A conversion rate. Therefore, the frequency of the stimulus was easily controlled by changing the frequency of the synthesizer. At slower D/A conversion rates, additional points were added to the waveform to preserve constant overall durations and rise–fall times. The onset phase of the stimuli was varied randomly.

The output of the D/A converter was low-pass filtered at 5600 Hz with an attenuation characteristic of 24 dB/oct. The output of the filter was attenuated, then passed through a passive mixer, a transformer, and finally, to a TDH-49 earphone mounted in an MX-41/AR cushion. The low-pass filter, in combination with the high-frequency attenuation provided by the TDH-49 earphone, was sufficient to insure that the level of distortion components arising from aliasing were so low that they could not have provided cues for discrimination. Acoustically measured harmonic distortion

TABLE I. Audiometric data for hearing-impaired subjects.

				Air-conduction thresholds (dB HL)					
				Frequency (kHz)					
Subject	Age	Sex	Test ear	0.25	0.50	1.0	2.0	4.0	8.0
GR	24	M	R	35	40	55	60	65	60
JC	25	M	L	25	40	50	50	60	50
EJ	46	F	R	20	30	60	80	85	>90
BA	20	F	L	50	45	50	50	60	60
DU	20	M	L	25	25	45	40	20	15
KE	24	F	L	40	40	50	50	50	50
RX	20	F	L	50	50	75	70	65	80

components were more than 60 dB down from the fundamental.

B. Psychophysical procedures

A four-alternative forced-choice (4AFC) adaptive procedure, similar to that described in Nelson *et al.* (1983), was employed. Standard-frequency tones were presented in three of the intervals, while the fourth, randomly chosen interval contained the variable-frequency tone which was always lower than the standard. The time between the onset of one stimulus and the onset of the following stimulus was a constant 550 ms.

A two-hits-down one-miss-up adaptive procedure was used to estimate the 70.7% point on the psychometric function (Levitt, 1971), down indicating a smaller frequency difference and up, a larger difference. The starting frequency difference was 10% of the standard frequency. The initial adaptive step increased or decreased the frequency difference by a factor of 2.0 following one miss or two consecutive hits, respectively. After four reversals, the step size was reduced to a factor of 1.19 ($2^{\frac{1}{4}}$). Threshold was taken as the geometric mean of the frequency differences existing on the last 8 out of 12 total reversals.

Stimulus durations were 5, 10, 15, 25, 40, 60, 90, 170, and 300 ms. Due to the additional 2-ms rise–fall times, the half-power durations were actually 1.2 ms longer than those listed above. The durations displayed in later figures are the half-power durations. However, in the text, the durations will continue to be referred to by the above steady-state values. DLF's were determined for all nine durations in random order during each experimental run. Three or four runs were obtained during a 2-h session.

The sound-pressure levels at which the duration functions were obtained were determined from another study (Freyman and Nelson, 1986), in which DLF's were measured as a function of stimulus intensity in these same subjects. Stimulus levels for the duration functions were chosen to be the lowest at which both the long- and short-duration DLF intensity functions appeared to reach an asymptote. Because the short-duration DLF intensity functions obtained from normal-hearing subjects showed pronounced level effects at high intensities, the DLF duration functions were obtained at two levels in these subjects, one at the approximate minimum of the 5-ms function, and the other at its approximate maximum. Figure 1 shows two examples of how the levels were selected for obtaining duration functions. The 5- and 300-ms DLF's are plotted as a function of stimulus sound-pressure level for normal-hearing subject JH and hearing-impaired subject JC. The vertical dashed lines indicate the sound-pressure levels at which the duration functions were measured in the current experiment.

All subjects received at least 6 h of practice before their data were used for DLF estimates. Final estimates were based on the geometric means of at least four and as many as nine retests, but typically five or six. The existence of high standard deviations was the primary reason for the inclusion of the larger numbers of retests for some subjects on certain conditions.

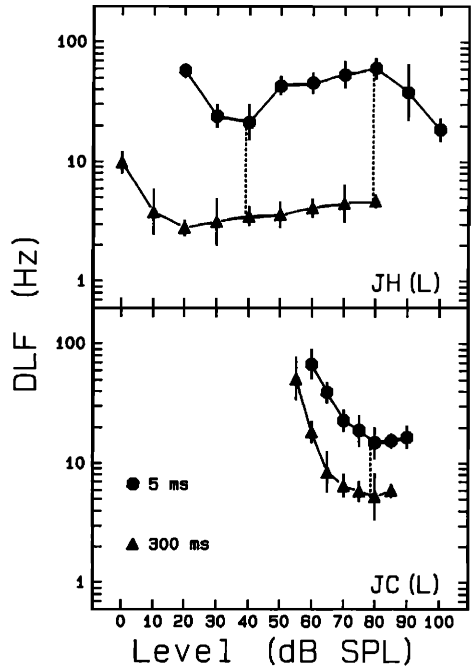

FIG. 1. DLF intensity functions from Freyman and Nelson (1986) for normal-hearing subject JH and hearing-impaired subject JC. Functions are plotted in SPL rather than SL as in the previous paper. Dashed lines indicate the SPL's at which the DLF duration functions were obtained in the current experiments.

C. Model calculations

The procedures outlined below were used to produce a quantitative description of each DLF duration function. (See Fig. 2 for an example of the results of applying these procedures.) The functions were fitted with linear equations (L_1 and L_2 in Fig. 2) that were then used to quantify the breakpoint in those functions between L_0 and L_1. This allowed us to compare the breakpoints calculated for normal- and hearing-impaired subjects. In addition, excitation-pattern model predictions were calculated for durations less than the breakpoint, and those predictions (function L_0 in Fig. 2) are compared with actual DLF's.

1. Breakpoint calculation

The method used to objectively specify the breakpoint (between L_0 and L_1 in Fig. 2) was to fit two piecewise linear equations to the longer duration portions of each DLF duration function, and then search for a slope change at shorter durations. The two linear equations were similar in form, and carry the same underlying assumptions, as those used by Liang and Chistovich (1961) to describe their middle- and long-duration data. One function (L_1) had a negative slope, and the other (L_2) was constrained to a slope of zero. The purpose of performing these statistical fits was to objectively specify the portion of each function that could be well described by these two lines and their underlying assumptions. Then the breakpoint could also be objectively estimated by searching for a criterion slope change as consecutively shorter duration data points were added to the fit of L_1.

An examination of the data (shown in later figures) indicated that, in most cases, only small differences existed

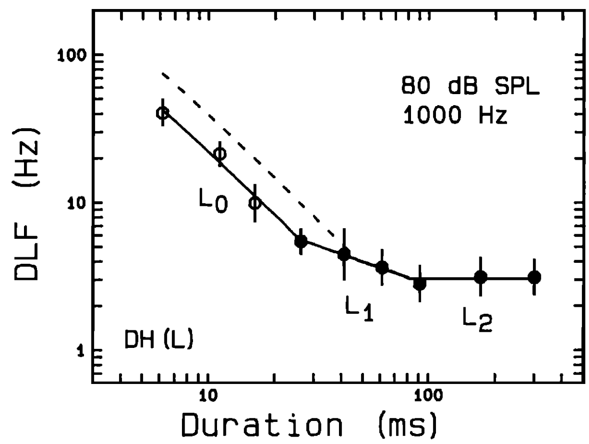

FIG. 2. Example of a DLF duration function and model predictions. Solid lines are model predictions based upon "best fits" of the data (see text). The dashed line is the prediction based on the high-frequency slope of a forward-masked tuning curve.

between the DLF's obtained at 170 and 300 ms. Therefore, it was reasonable to fit these last two points in the DLF duration functions with a horizontal line (L_2). All of the functions were fitted this way, even though a few did not reach a complete asymptote. In some of the DLF duration functions, where little change in the DLF was observed as stimulus duration was decreased from 170 to 90 ms, the DLF at 90 ms was included in the horizontal fit as well. In two cases, L_2 was extended down to 40 ms. The linear function L_1 was always fitted to a minimum of three data points at durations below those used for L_2. The longest duration data point included in L_1 was also included as the shortest duration data point in L_2.

The breakpoint between L_0 and L_1 was defined as the shortest duration data point of L_1. That point was determined by finding the duration at which the slope between that point and the adjacent shorter duration data point was more negative than the slope of L_1 by a criterion amount of 0.25. That criterion was the same for all subjects and conditions. It was also required that this criterion change in slope be maintained through one additional shorter point.

2. Predicted DLF's below the breakpoint

At durations below the breakpoint, it was assumed that the DLF is determined by two factors: the stimulus spectrum slope, and the detection criterion (in dB) that represents a just-discriminable difference in excitation level. Specifically, the DLF was predicted to be equal to the criterion divided by the spectral slope, in the same way that for long-duration tones the DLF is predicted to be equal to the criterion divided by the excitation-pattern slope. Derivations of the detection criterion and of the stimulus spectral slope are considered separately in the sections below, and the results are illustrated in Fig. 2.

a. Spectral slope calculation. Closed-form solutions of the Fourier transform were calculated for all of the 5-, 10-, 15-, 25-, 40-, and 60-ms signals. The spectra have a central peak at the nominal frequency of the tone and additional peaks at higher and lower frequencies. Therefore, the spectral slope is a constantly changing function of frequency and is extremely steep on the edges of these peaks, or side lobes, no matter how short the tone is made. In the current analysis, it will be assumed, following Moore (1973), that due to the width of the critical band and the spread of masking, these spectral peaks are not resolved by the auditory system. Therefore, the excitation-pattern slopes produced by short-duration tones are assumed to be approximated by the envelopes of the signal spectra. Because these envelopes do not have constant slopes, it is necessary to specify the slope that is assumed to be most relevant to frequency discrimination. According to the model under consideration in this paper, it is the steepest excitation-pattern slope that determines the long-duration DLF. To be consistent with this assumption, the stimulus spectrum slope relevant to frequency discrimination was also specified as the steepest portion of the envelope, which is the slope of the line connecting the central peak and the first side lobe. The spectral slopes were converted to units of dB/bark to facilitate the comparison between those slopes and estimates of the excitation-pattern slopes. The calculated spectral slopes for each frequency and duration are listed in Table II.

b. Criterion calculation. The criterion at any particular duration was determined by first establishing its value for long-duration tones, then describing changes that occur with duration. Since the DLF for long-duration tones is predicted to be equal to the criterion divided by the excitation-pattern slope, the criterion is equal to the product of the excitation-pattern slope and the DLF. Estimates of both of these variables are available. The DLF at long durations is represented by the intercept of L_2, and the excitation-pattern slope can be derived from the breakpoint duration. Because the breakpoint presumably represents the duration at which the spectral and excitation-pattern slopes are equal, the spectral slopes provided in Table II also represent the excitation-pattern slopes corresponding to different breakpoint durations.

It was assumed that the criterion becomes larger as the signal is shortened. A duration-dependent criterion is necessary in order for the model to explain changes in the DLF that occur above the breakpoint, i.e., the nonzero slope of L_1, because the excitation-pattern slope is presumably constant at these durations. The assumption of an inverse relationship between duration and the criterion is consistent with the suggestion of Liang and Chistovich (1961) that the precision with which the peak of the excitation pattern is estimated should improve as the duration of the signal increases. That suggestion implies that smaller differences between excitation patterns are required to discriminate long tones rela-

TABLE II. Spectral slopes of test stimuli in dB/bark.

	Duration in ms					
	5	10	15	25	40	60
500 Hz	8.74	13.35	18.34	28.74	44.63	65.82
1000 Hz	11.60	17.92	24.73	38.89	60.53	89.38
2000 Hz	23.07	35.59	49.05	77.03	119.80	176.82

tive to short tones. The assumption is also consistent with data showing increasing DL's for intensity with decreasing stimulus duration (e.g., Henning, 1970).

It was further assumed that the function relating the criterion to stimulus duration proceeds at the same rate below the breakpoint as it does above the breakpoint (i.e., in proportion to the slope of L_1), as if L_1 extended below the breakpoint down to the shortest duration plotted. The theoretical extension of L_1 represents the DLF's that would be predicted if the spectral slope had not become less steep than the excitation-pattern slope.

At each duration below the breakpoint, predicted DLF's were calculated by dividing the criterion at that duration by the spectral slope at that duration. A solid line (L_0) was drawn connecting the points to provide a means of comparing predicted and measured DLF's.

D. Results: Normal-hearing listeners

DLF duration functions were obtained from normal-hearing subjects CE and DH at 500 Hz, for all five subjects at 1000 Hz, and for DH and RF at 2000 Hz. The high-SPL functions are plotted together with the two- or three-line description (solid lines) in Figs. 3 and 4. Most of the functions are well described by the three lines; the most obvious exception is the 500-Hz function obtained from subject DH in Fig. 4. Across test frequencies, the breakpoints (defined by the intersection of L_0 and L_1) occur at 40 ms for 500 Hz, at 25 ms for 1000 Hz (except for CE), and at 15 ms for both subjects at 2000 Hz. The trend toward shorter breakpoints with increasing stimulus frequency was also observed by Liang and Chistovich (1961). As suggested by Liang and Chistovich, this trend is consistent with the predictions of a model based on place of excitation since the degree of spectral splatter of a tone of constant duration is independent (on a linear Hz scale) of the frequency of the tone, while the bandwidth of the frequency analyzing mechanisms within the auditory system, measured either psychophysically or physiologically, becomes larger in Hz as the center frequency is increased above 500 Hz. Therefore, the signal bandwidth becomes smaller relative to the auditory filter bandwidth as stimulus frequency is increased. The same explanation can be applied in the current analysis, using excitation-pattern slopes instead of filter bandwidths.

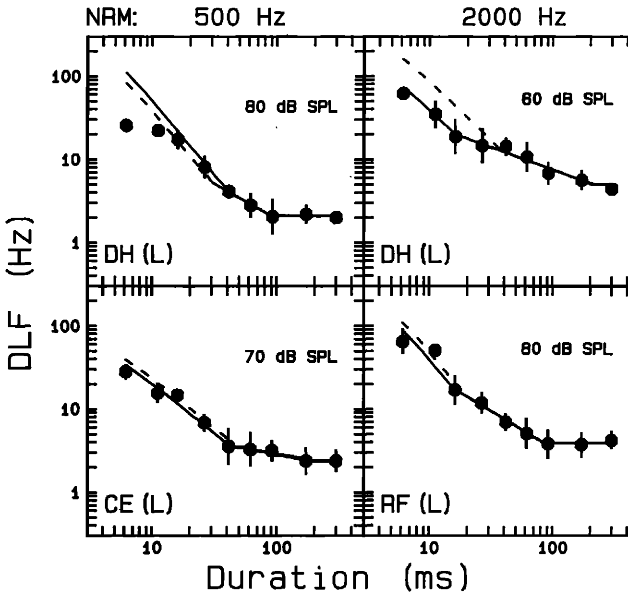

FIG. 4. DLF duration functions with predictions of the model for normal-hearing subjects: 500 and 2000 Hz at high SPL's. Legend as in Fig. 2.

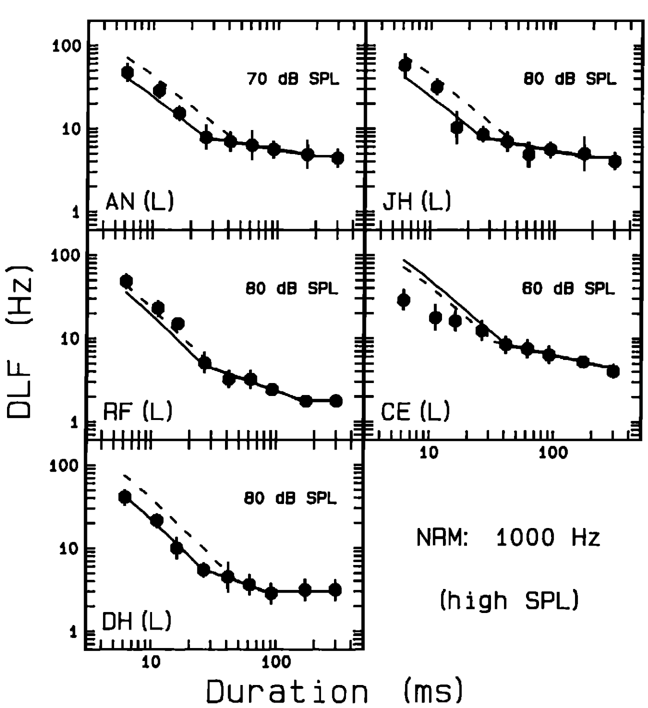

FIG. 3. DLF duration functions with predictions of the model for normal-hearing subjects: 1000 Hz at high SPL's. Legend as in Fig. 2.

At durations that compare to those represented by our L_1, Liang and Chistovich (1961) fit their functions with a straight line constrained to a slope of -0.5. Although many of the functions obtained in the current experiment would have been reasonably well described by a line with this fixed slope, a substantial improvement in the quality of the fit is achieved by allowing the slope of L_1 to vary. In that case, the mean slope is -0.533.

The slope of the solid line (L_0) below the breakpoint depends on both the slope of L_1 (the rate at which the criterion changes with duration) and the data in Table II (the rate at which the spectral slope changes with duration). Since the latter contribution is constant for a given frequency, the only source of variability in the slope of L_0 is the slope of L_1. In our judgment, the slopes of L_0 describe the slopes of the data fairly well.

E. Results: Hearing-impaired listeners

DLF duration functions were obtained from all seven hearing-impaired listeners at 1000 Hz. Two subjects (RX and EJ) were also tested at 500 Hz, and four subjects (GR, JC, KE, and BA) were tested at 500, 1000, and 2000 Hz. The results are displayed along with the fits in Figs. 5–7.

The most striking difference from the normal data is that most of the functions are very well fitted by two straight

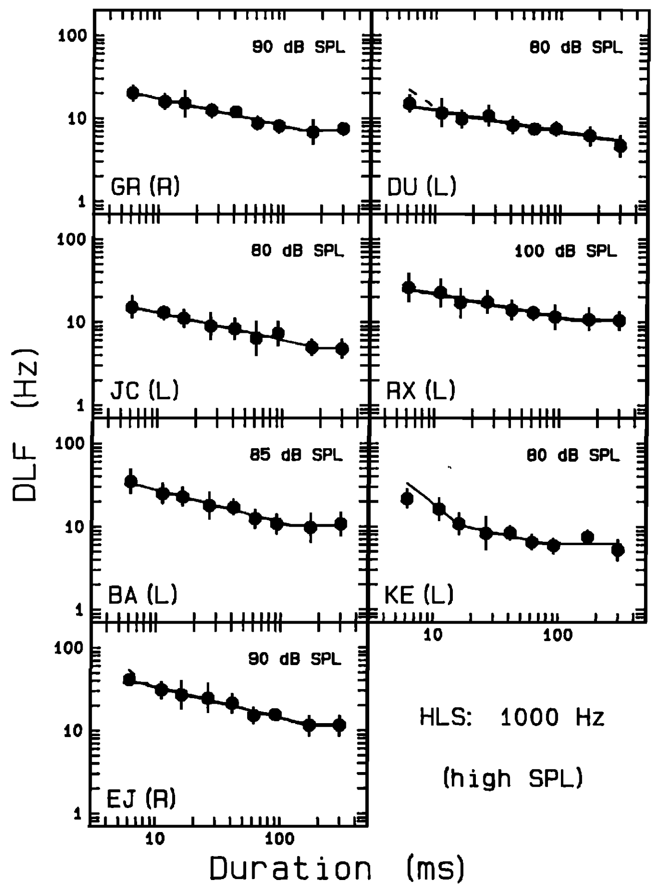

FIG. 5. DLF duration functions with predictions of the model for hearing-impaired subjects: 1000 Hz at high SPL's. Legend as in Fig. 2.

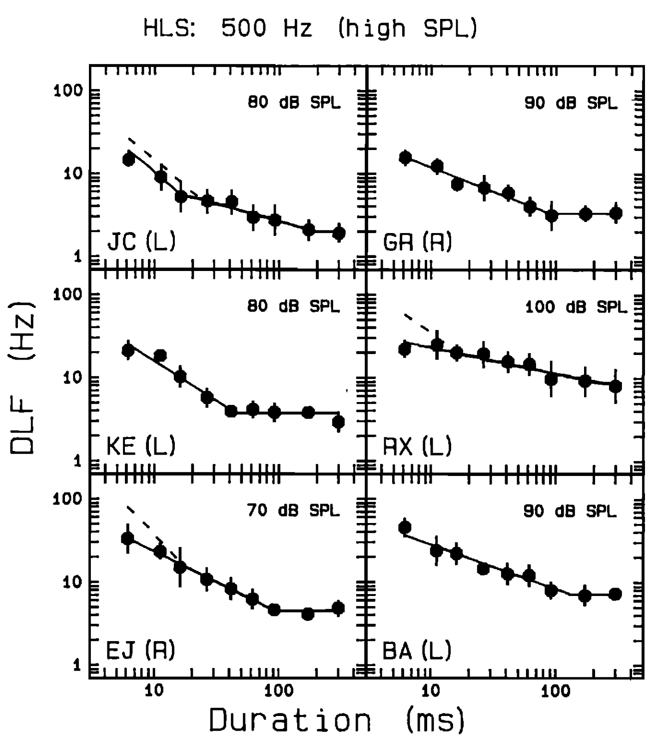

FIG. 6. DLF duration functions with predictions of the model for hearing-impaired subjects: 500 Hz at high SPL's. Legend as in Fig. 2.

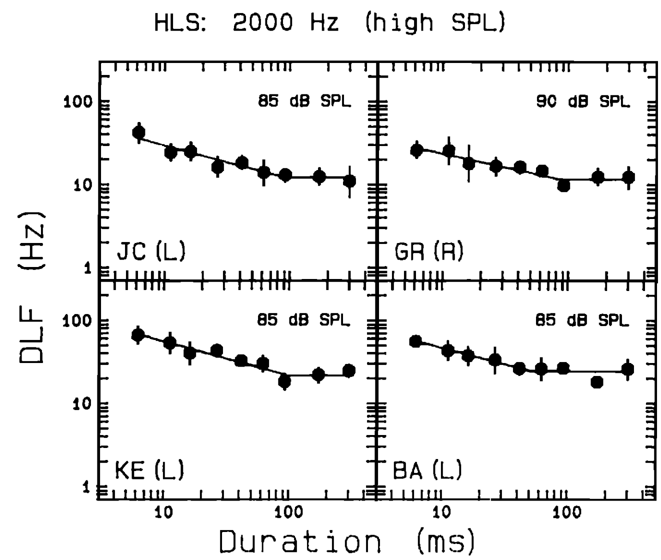

FIG. 7. DLF duration functions with predictions of the model for hearing-impaired subjects: 2000 Hz at high SPL's. Legend as in Fig. 2.

lines, rather than three.[1] That is, there was usually no breakpoint according to the criteria described earlier. This absence of abrupt increases in DLF's at short durations was also observed for hearing-impaired subjects by Hall and Wood (1984). The most difficult data to interpret are those of KE at 500 Hz. The horizontal portion of the function (L_2) is unusually long, extending down to 40 ms. It is conceivable that 40 ms represents the breakpoint rather than the intersection of L_1 and L_2.

The absence of a breakpoint in these functions is consistent with the predictions of the excitation-pattern model. The model predicts that the abnormal DLF's observed in the hearing-impaired listeners at long durations are due to more gradual excitation-pattern slopes. Therefore, it also predicts that the duration at which the spectral slopes are steeper than the excitation-pattern slopes should be shorter than normal. The fact that breakpoints are absent in most cases suggests that the excitation-pattern slopes are so gradual that they are less steep than the spectral slope of even the 5-ms tones. This possibility will be explored in experiment II.

An examination of the slopes of L_1 revealed a second difference in the hearing-impaired data. The lines are less steep (overall mean slope of L_1 is -0.388) than those that were fit to the functions obtained from normal-hearing subjects. This finding is consistent with Gengel's (1973) data, which show a smaller mean difference (if the data are plotted on a log scale) between 50- and 500-ms DLF's in hearing-impaired than in normal-hearing subjects. The theoretical implications of this difference are not immediately obvious, at least to the present authors. To a first approximation, it is similar to the differences observed in hearing-impaired subjects in the temporal integration of detection threshold. However, it is not clear that there is a common underlying mechanism. Hall and Wood (1984) found no relationship between the effects of duration on frequency discrimination and temporal integration of threshold.

One limitation of the current analysis, thus far, is that the existence of flatter excitation-pattern slopes in the hearing-impaired subjects has only been assumed and not demonstrated empirically. In the second experiment, we attempt to verify that this assumption is reasonable by obtaining estimates of the low-frequency slopes of the excitation patterns evoked by the high-SPL standard tones used in the DLF experiment. Obtaining independent measures of excitation-pattern slopes also permits, for each DLF duration function, a quantitative comparison to be made between the breakpoint and the critical duration predicted by the model.

II. EXPERIMENT II. MASKING PATTERNS AND TUNING CURVES

A. Background

A variety of methods have been used in previous research to estimate the shape of an excitation pattern. One of the most widely used methods is the masking pattern, in which the threshold of a signal in the presence of a masker is plotted as a function of the frequency of the signal. The threshold of the signal is assumed to be proportional to the strength of excitation produced by the masker in the frequency region of the signal. Unfortunately, because the masker and probe may interact nonlinearly, the relationship between masking and excitation is not always straightforward. The effects of masker–probe interactions are eliminated in forward masking, because the probe follows the masker offset. Therefore, a forward-masking technique was used to estimate excitation-pattern slopes in this experiment.

The forward-masking method that is seemingly most directly related to an excitation pattern is the forward-masking pattern. The forward-masking pattern is identical to the simultaneous-masking pattern except that, as noted above, the presentation of the probe follows the masker offset. The probe masked thresholds presumably reflect the amount of excitation produced by the masker at the probe frequency, minus the amount of recovery from adaptation (decay of masking) that has occurred at the time the probe is presented (e.g., Moore and Glasberg, 1981; Nelson and Freyman, 1984). If the amount of recovery in decibels were the same at every frequency, then the forward-masking pattern would lie below the excitation pattern, but would be parallel to it. However, it has been shown (Widin and Viemeister, 1979) that the rate of recovery from adaptation depends on the amount that was originally produced. Larger amounts of adaptation produce faster rates of decay. Therefore, for a given probe time delay, the greatest amount of decay of masking occurs near the peak of an excitation pattern and the least occurs near the edges. Thus the forward-masking pattern is assumed to be less peaked than the original excitation pattern evoked by the masker. This assumption is supported by data showing increasingly broad forward-masking patterns as masker–probe temporal separation increases (Kidd and Feth, 1981).

The forward-masked tuning curve paradigm eliminates this problem. With this method, the level of a masker required to just mask a fixed signal is plotted as a function of the masker frequency. Because the amount of adaptation produced at the probe frequency is presumably held constant for all masker frequencies, it follows that the rate of recovery from that adaptation is also independent of masker frequency. Therefore, unlike the forward-masking pattern, the shape of the forward-masked tuning curve is not directly affected by the decay of masking. For this reason, forward-masked tuning curves were used to estimate the slopes of excitation patterns in this study. The level of the maskers on the high-frequency side of the tuning curve, when compared with masker levels near the probe frequency, reflects the slope of the low-frequency side of the excitation patterns evoked by those higher frequency maskers. The relationship between the tuning curve and excitation-pattern slopes is most direct when the high-frequency side of the tuning curve can be described by a straight line. In that case, the low-frequency slopes of the excitation patterns evoked by the maskers may be approximated by the best fit line through the tuning curve data.

To be sure, the relationship between the tuning curve and the excitation-pattern slope may not always be as straightforward as described above. It may be complicated by several factors, such as the spread of excitation of the probe, as suggested by Verschuure (1981), and the possible existence of nonlinearity on the high-frequency side of the tuning curve. Nevertheless, in our opinion, the tuning curve is the preferable method. We have found that the high-frequency side of most forward-masked tuning curves from normal-hearing subjects can be reasonably well described by a straight line on a logarithmic or critical-band-rate frequency scale. Further, any possible effects of the probe's spread of excitation should not be greater in the tuning curve than in the masking pattern. Finally, as discussed above, the tuning-curve method avoids many of the problems described earlier with simultaneous masking and with forward-masking patterns. Forward-masking patterns were, in fact, obtained in this study, using maskers fixed at the frequencies and levels of the high-SPL standard tones in the DLF experiment. These data were used to provide a means of selecting probe parameters that forced the tuning curve to pass through the frequency and level of the corresponding DLF standard tone.

B. Methods

1. Masking patterns

The maskers were 200-ms (time above 90% of peak amplitude) pure tones fixed at the level and frequency at which a DLF duration function was obtained. In the normal-hearing subjects, DLF duration functions were measured at two levels for each frequency; for masking patterns the masker was fixed at the higher of those two levels. The masker was generated by a Rockland frequency synthesizer and gated with 10-ms rise–fall times (10%–90% of peak amplitude) by an electronic switch. The 20-ms pure-tone probe signals were presented immediately following the termination of the masker (the time between 10% masker peak amplitude and 10% probe peak amplitude was 2 ms). The probe tones were generated and gated identically to the masker using another Rockland synthesizer and a different channel of the electronic switch.

A 4AFC adaptive procedure was employed that was similar to that used in the frequency discrimination experiments. The masker was presented alone in three of the intervals, while in the fourth randomly chosen interval, both the masker and the probe were presented. Subjects were again instructed to press the button corresponding to the interval that was "different." The time between the offset of one masker and the onset of the masker in the following interval was 200 ms.

A two-hits-up one-miss-down stepping rule was used to estimate the 70.7% correct point on the psychometric function. The probe level was initially set to be 10 dB above the level of the masker. The initial adaptive step size was 8 dB. After four reversals, it was reduced to 2 dB. Threshold was taken as the mean of the probe sound-pressure levels existing on the last six of ten total reversals.

Individual experimental sessions consisted of the measurement of probe thresholds at the masker frequency and below the masker frequency in either six or twelve steps per octave. Final threshold estimates were taken as the mean of at least three and as many as nine retests, depending on the degree of variability in the data collected from individual subjects.

2. Tuning curves

For each subject, the high-frequency sides of forward-masked tuning curves were obtained at each standard DLF frequency in each subject using a probe frequency that was below that of the standard DLF frequency. The forward-masking pattern obtained for each standard DLF stimulus was examined to determine the frequency at which the masked threshold was between 5-dB and 10-dB sensation level (detection thresholds for 20-ms tones were also measured). The probe tone used to obtain the tuning curve was then set near that frequency and level. Equating the probe with one of the thresholds obtained from the masking pattern produced the desired result that the high-frequency side of the tuning curve would pass through the point corresponding to the frequency and level of the standard DLF signal. The masker level that was required to just mask the probe was then determined for masker frequencies at and above the probe with a frequency step size of either 1/6, 1/12, or 1/24 oct, depending on the steepness of the tuning-curve slope. Otherwise, the methods used to obtain the tuning curves were identical to those used to obtain the masking patterns. After the high-frequency side of the tuning curve was obtained, the frequency axis was transformed to critical band rate, and the data were fit with a linear regression line.

C. Results

Forward-masking patterns and tuning curves were obtained at all DLF frequencies from all subjects with the exception of KE, who withdrew from the study following the frequency discrimination experiments. The following observations were made of the data as a whole:

(1) The goal that the tuning curve should pass through the approximate level of the DLF standard was achieved in most cases.

(2) Following the transformation of the frequency axis to critical band rate, most of the tuning-curve high-frequency sides appeared to be linear over a substantial portion of their range. Several of the functions showed initially steep linear increases in masker level, but displayed a definite "bend-over" at remote frequencies and high levels. Others had a broadened tip region, so that the steep portion of the high-frequency sides began at frequencies above the probe frequency. In order to describe the high-frequency side of each tuning curve with a linear equation, it was necessary to specify the data that best represented this assumed linear high-frequency slope. As many data points as possible were included in the fit, with the restriction that the distribution of the residuals appeared random. In most cases, the high-frequency slope of the tuning curve was clearly separable from both the broad tip regions and the bend-over that occurred in some subjects at high levels. The data obtained from subject DU (Fig. 8) serve as examples of a masking pattern, a tuning curve, and a tuning-curve fit. The slopes of the tuning curves are shown for each subject in Table III.

Several additional characteristics of the tuning-curve fits are presented in the table to provide the reader with some idea of the overall quality of the fits. These include the R^2 of the fit and the "range%," the percentage of the range of the tuning curve (in decibels, from the minimum-masker level to the maximum-masker level) that is encompassed by the data points represented by the fitted line.

(3) The calculated slopes of the tuning curves obtained from the hearing-impaired listeners were much less steep than those obtained from normal-hearing listeners. The mean tuning-curve slope averaged across all three frequencies for the hearing-impaired listeners was 13.3 dB/bark with a standard deviation of 5.9, and for the normal-hearing listeners was 62.7 dB/bark with a standard deviation of 21.8. The steepest slope calculated for any hearing-impaired subject was 25.9, which is less steep than the most gradual slope calculated for any of the normal-hearing subjects (33.6).

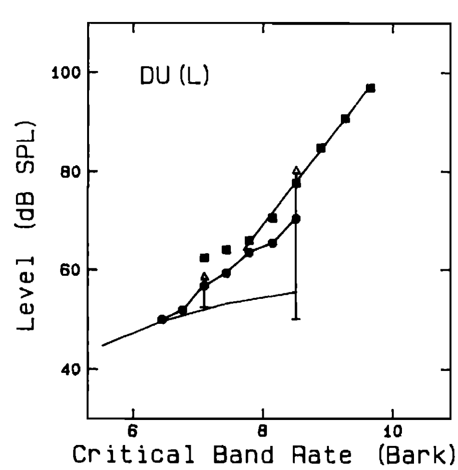

FIG. 8. Forward-masked masking pattern (circles) and forward-masked tuning curve (squares) obtained from hearing-impaired subject DU. The arrow to the left indicates the level and frequency of the probe tone used to obtain the tuning curve. The arrow to the right indicates the level and frequency of the masker used to obtain the forward-masked masking pattern. The solid line through the high-frequency side of the forward-masked tuning curve (squares) illustrates the goodness-of-fit of a regression line on these dB/bark coordinates.

TABLE III. Tuning-curve fit parameters. The slope is in dB/bark. The "range%" is the percentage of the total range (in dB) of the tuning curve that is encompassed by data points represented by the regression line.

	500 Hz			1000 Hz			2000 Hz		
	Slope	R^2	Range%	Slope	R^2	Range%	Slope	R^2	Range%
Normal-hearing subjects									
JN	...	...	...	70.75	0.99	62	...	...	...
AN	...	...	...	69.89	0.96	100	...	...	...
CE	52.05	0.97	87	50.13	0.98	100	...	...	...
RF	...	...	...	47.30	0.98	100	60.22	0.99	86
DH	33.62	0.95	100	69.63	0.90	94	110.35	0.90	97
Hearing-impaired subjects									
DU	...	...	...	17.16	0.99	91	...	...	...
EJ	19.46	0.99	97	14.52	0.98	95	...	...	...
RX	17.96	0.97	76	12.96	0.99	92	...	...	...
GR	7.42	0.95	100	7.88	0.96	81	14.60	0.98	93
JC	25.95	0.96	100	10.02	0.99	66	15.69	0.98	91
BA	3.05	0.87	100	10.05	0.95	100	9.60	0.99	94

These results support our earlier assumption that the low-frequency slopes of excitation patterns are abnormally flat in hearing-impaired subjects. As a result, they reinforce the validity of the prediction that the breakpoints in the DLF-duration functions should occur at shorter-than-normal durations in these subjects.

III. DISCUSSION

A. DLF duration function predictions

Obtaining estimates of excitation-pattern slopes allowed a quantitative comparison to be made between the predicted critical duration and the breakpoint determined for each DLF duration function. The critical duration was computed by interpolating between the spectral slope values displayed in Table II to find the duration of the signal having a spectral slope equivalent to the measured tuning-curve slope. The predicted DLF's for durations below this critical duration were calculated by applying the same methods used earlier for calculating predictions below the breakpoint. However, this time the calculations were made using independent estimates of the excitation-pattern slopes (the tuning-curve slopes). These predictions are indicated by the dashed lines in Figs. 2–7. Where the dashed line is absent, the computed critical duration is below 5 ms. The critical durations and breakpoints are also displayed for each subject in Table IV.

In the normal data, the critical durations are very close to be observed breakpoints in some cases, but in others they overestimate the breakpoints by between 10 and 25 ms, i.e., the dashed lines lie to the right of the solid lines. These errors are such that the obtained tuning-curve slopes are sharper than those that would have produced the best fit. However, considering the very large range of potential error, the degree of agreement between the predictions and the actual data appears to be satisfactory.

There is excellent agreement between the model predictions and the actual breakpoints observed in the functions obtained from hearing-impaired subjects. As shown in Figs. 5–7 and in Table IV, most of the predicted critical durations were below 5 ms. This is entirely consistent with the fact that the functions were, in most cases, extremely well fit by two straight lines rather than three, i.e., there was no breakpoint. Only in a few cases (e.g., EJ at 500 Hz) is there a critical duration above 5 ms in the absence of a corresponding breakpoint.

Moore (1973) obtained DLF duration functions from three normal-hearing listeners and evaluated the ability of an excitation-pattern model to explain short-duration frequency discrimination data. He found that at low and middle frequencies, the model overestimated the actual DLF's obtained from his subjects by as much as an order of magnitude. Our analysis procedures appear to produce much better agreement between the data and the predictions of the model, especially when the excitation-pattern slope is determined from the breakpoint duration. Some of the difference can be attributed to the superior frequency discrimination performance of Moore's subjects relative to our normal-hearing subjects. For example, Moore's subject TC had a DLF of only 7.3 Hz for 1000-Hz, 6.25-ms tones, which is smaller than the DLF's obtained for 1000-Hz signals of comparable duration in our study. However, much of the difference in the accuracy of the model predictions can be attribut-

TABLE IV. Breakpoints (B.P.) and critical durations (C.D.) in ms.

	500 Hz		1000 Hz		2000 Hz	
	B.P.	C.D.	B.P.	C.D.	B.P.	C.D.
Normal-hearing subjects						
JH	...	...	25.0	47.1	...	...
AN	...	...	25.0	46.5	...	...
CE	40.0	47.0	40.0	32.8	...	...
RF	...	...	25.0	30.8	15.0	19.0
DH	40.0	29.6	25.0	46.3	15.0	36.7
Hearing-impaired subjects						
DU	...	...	<5.0	9.4	...	...
EJ	<5.0	16.1	<5.0	7.3	...	...
RX	<5.0	14.6	<5.0	6.1	...	...
GR	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
JC	15.0	22.3	<5.0	<5.0	<5.0	<5.0
BA	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0

ed to differences in the specification of the spectral slopes of the short-duration tones. We used the steepest slope of the spectral envelope, which is the slope of the line connecting the central peak with the peak of the first side lobe, while Moore used the more gradual slope of the line between the peaks of the first and second side lobes. Therefore, our spectral slopes are much steeper than Moore's for equivalent test signals. Hence, we predict smaller DLF's for those signals. For example, had we calculated spectral slopes using the more gradual slope between the first and second side lobes, the predicted DLF's for 5-ms, 1000-Hz tones would have more than tripled, and the agreement between our predicted and experimentally measured DLF's would have been considerably poorer. It is clear that the adequacy of the excitation-pattern model's predictions of DLF's at short durations depends on the details of the assumptions that are made in order to derive those predictions.

B. Low-SPL DLF-duration functions in normal-hearing listeners

One surprising result described by Freyman and Nelson (1984) was the existence of nonmonotonic DLF intensity functions in normal-hearing listeners. The DLF's at moderately high SPL's were poorer than they were at low SPL's, and were also poorer than the DLF's obtained from hearing-impaired subjects. We were extremely interested in determining the extent to which the differences between the duration functions obtained from the normal- and hearing-impaired groups reflect this nonmonotonicity. As mentioned earlier, the low-SPL DLF duration functions were measured at the approximate minimum of the 5-ms DLF intensity functions obtained in Freyman and Nelson (1986). These low-SPL DLF duration functions are shown in Figs. 10 and 11 together with the linear fits and excitation-pattern model predictions.

The first aspect of the data that deserves mention is that the general form of the functions is the same as that of the high-SPL DLF duration functions. Most are reasonably well described by three straight lines and are markedly different than those obtained from the hearing-impaired subjects. Neither the breakpoints nor the slopes of L_1 are systematically different from the high-SPL functions. The calculated critical durations are the same because only one tuning curve was measured for each DLF standard frequency. Therefore, the degree of agreement between the predicted critical durations and the breakpoints is similar to that observed for the high-SPL functions. The slope of L_0 was usually very similar to that calculated for the high-SPL functions (it could only vary by the amount that L_1 varied). Perhaps the most notable difference from the high-SPL functions was that in some of the low-SPL functions L_0 did not describe the shortest duration data points as well. In a few subjects, the slope of L_0 was steeper than the slope of the data. In others, the DLF's showed a clear "bend-over" at 5 ms.

C. Criterion across subjects

Under the assumptions of the model, the larger than normal long-duration DLF's observed in hearing-impaired subjects are due only to their abnormally broad excitation-pattern slopes. Because of the broader slopes, larger frequency differences are necessary to yield discriminable differences in excitation level. However, the just-discriminable differences themselves are not expected to differ systematically between the two groups. The criterion at long durations was computed for each condition by multiplying the excitation-pattern slope by the long-duration DLF, which was defined as the intercept of L_2. A difference in criterion between

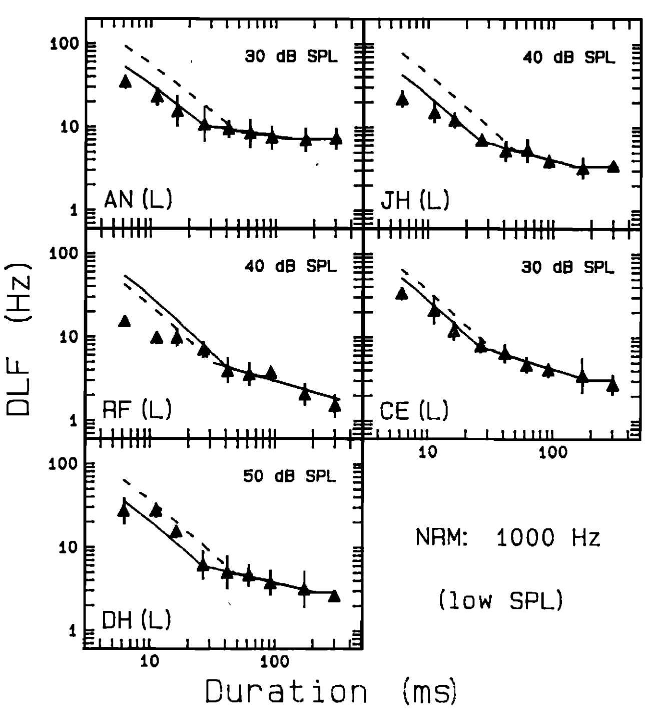

FIG. 9. DLF duration functions with predictions of the model for normal-hearing subjects: 1000 Hz at low SPL's. Legend as in Fig. 2.

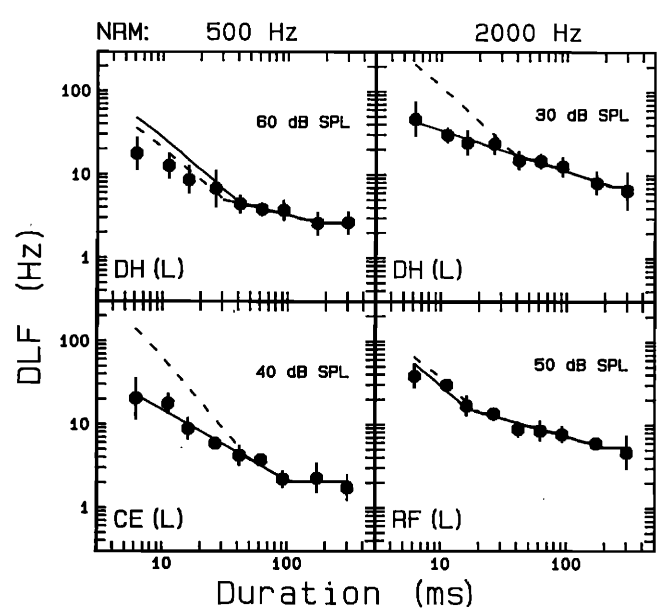

FIG. 10. DLF duration functions with predictions of the model for normal-hearing subjects: 500 and 2000 Hz at low SPL's. Legend as in Fig. 2.

the two groups is readily apparent in the current results. The mean criterion (high-SPL data only for normal subjects), collapsed across all three frequencies, is 1.32 dB (s.d. = 0.61) for the normal-hearing subjects and is much lower, 0.62 dB (s.d. = 0.33), for the hearing-impaired subjects. Although the mean tuning-curve slope for normal-hearing subjects is 4.7 times as steep as the mean for hearing-impaired subjects, the mean long-duration DLF is better by a factor of only 2.4.

At least three explanations for the differences in criterion are possible: (1) The slope of the high-frequency side of the tuning curve does not provide an accurate estimate of the slope of the low-frequency side of the excitation pattern; (2) the excitation-pattern model is correct in principle, but the assumption that the criterion reflects a process that is independent of peripheral auditory function is incorrect; or (3) the excitation-pattern model, alone, cannot account for these data. The current results do not differentiate between these three possible explanations for the group differences in criterion. However, it is of interest to note that both the large criterion and the overestimation of the breakpoint described in the above section are due to the extreme sharpness of the high-frequency sides of the tuning curves obtained from the normal-hearing subjects.

D. Criterion across frequency

It is difficult to draw any strong conclusions from an analysis of frequency effects on the criterion. Only a narrow range of frequencies were tested and only a few subjects were tested at all three frequencies. However, the data that were obtained do show a trend toward a higher criterion at higher frequencies. Five of the seven subjects who were tested at both 500 and 1000 Hz showed the larger criterion at 1000 Hz, and all five subjects who were tested at both 1000 and 2000 Hz showed the larger criterion at 2000 Hz. On a narrow scale, the current results show that the size of the relative DLF is an increasing function of test frequency when it is computed relative to the high-frequency slope of the forward-masked tuning curve, and that this trend is apparent in both normal-hearing and hearing-impaired subjects. This trend is consistent with that shown for normal-hearing subjects by Moore (1974), who compared the DLF with the critical bandwidth at various standard test-tone frequencies. In terms of the excitation-pattern model, the increase in the relative DLF at high frequencies can be explained only if the criterion becomes larger as frequency is increased. However, we have no theoretical basis for expecting that this should occur.

E. Summary

The excitation-pattern model appears to adequately describe the details of individual DLF duration functions obtained from normal-hearing subjects. It also provides an accurate description of the differences in those details observed in the functions obtained from hearing-impaired subjects. However, the current results are in agreement with previous results (e.g., Moore, 1974) in that they show that the effects of test frequency on the DLF are not easily accounted for by the excitation-pattern model.

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[1]Note that in some of the figures, e.g., DU's data in Fig. 5, no horizontal line (L_2) is apparent. In these cases, the intersection of L_1 and L_2 occurs at durations greater than 300 ms. This occurred most often in functions that did not reach a true asymptote at long durations.

Freyman, R. L., and Nelson, D. A. (**1984**). "Intensity and duration effects in frequency discrimination with normal-hearing and hearing-impaired listeners," J. Acoust. Soc. Am. Suppl. 1 **75**, S6. Paper presented at the 107th meeting of the Acoustical Society of America.

Freyman, R. L., and Nelson, D. A. (**1986**). "Frequency discrimination of short- vs long-duration tones by normal and hearing-impaired listeners," J. Speech Hear. Res. (submitted).

Gengel, R. W. (**1973**). "Temporal effects in frequency discrimination by hearing-impaired subjects," J. Acoust. Soc. Am. **54**, 11–15.

Hall, J. W., and Wood, E. J. (**1984**). "Stimulus duration and frequency discrimination for normal-hearing and hearing-impaired subjects," J. Speech Hear. Res. **27**, 252–256.

Harris, J. D. (**1952**). "Pitch discrimination," J. Acoust. Soc. Am. **24**, 750–755.

Henning, G. B. (**1970**). "A comparison of the effects of signal duration on frequency and amplitude discrimination," in *Frequency Analysis and Periodicity Detection in Hearing*, edited by R. Plomp and G. F. Smoorenburg (Sijthoff, Leiden, The Netherlands), pp. 350–359.

Kidd, G., Jr., and Feth, L. L. (**1981**). "Patterns of residual masking," Hear. Res. **5**, 49–67.

Levitt, H. (**1971**). "Transformed up–down methods in psychoacoustics," J. Acoust. Soc. Am. **49**, 467–477.

Liang, C.-a., and Chistovich, L. A. (**1961**). "Frequency difference limens as a function of tonal duration," Sov. Phys. Acoust. **6**, 75–80.

Moore, B. C. J. (**1973**). "Frequency difference limens for short-duration tones," J. Acoust. Soc. Am. **54**, 610–619.

Moore, B. C. J. (**1974**). "Relation between the critical bandwidth and the frequency difference limen," J. Acoust. Soc. Am. **55**, 359.

Moore, B. C. J., and Glasberg, B. R. (**1981**). "Auditory filter shapes derived in simultaneous and forward masking," J. Acoust. Soc. Am. **70**, 1003–1014.

Nelson, D. A., and Freyman, R. L. (**1984**). "Broadened forward-masked tuning curves from intense masking tones: Delay-time and probe-level manipulations," J. Acoust. Soc. Am. **75**, 1570–1577.

Nelson, D. A., Stanton, M. E., and Freyman, R. L. (**1983**). "A general equation describing frequency discrimination as a function of frequency and sensation level," J. Acoust. Soc. Am. **73**, 2117–2123.

Oetinger, R. (**1959**). "Die grenzen der horbarkeit von frequenzund tonzahlanderungen bei tonimpulsen," Acustica **9**, 430–434.

Turnbull, W. (**1944**). "Pitch discrimination as a function of tonal duration," J. Exp. Psychol. **34**, 302–316.

Verschuure, J. (**1981**). "Pulsation patterns and nonlinearity of auditory tuning II: Analysis of psychophysical results," Acustica **49**, 296–306.

Widin, G. P., and Viemeister, N. F. (**1979**). "Intensive and temporal effects in pure-tone forward masking," J. Acoust. Soc. Am. **66**, 388–395.

Zwicker, E. (**1970**). "Masking and psychological excitation as consequences of the ear's frequency analysis," in *Frequency Analysis and Periodicity Detection in Hearing*, edited by R. Plomp and G. F. Smoorenburg (Sijthoff, Leiden, The Netherlands), pp. 376–394.