Frequency discrimination at 1200 Hz in the presence of high-frequency masking noise

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(Received 21 April 1981; accepted for publication 8 December 1981)

To evaluate the possible contribution of high-frequency hearing to frequency discrimination at lower frequencies, pure-tone frequency discrimination tasks at 1200 Hz, with and without high-frequency masking noise, were performed by two highly practiced normal-hearing listeners. Signal levels ranged from 10 to 80 dB SPL. Spectra of the three high-frequency masking noises ranged from 1.8 to 2.1 kHz, from 2.8 to 3.1 kHz, and from 4 to 8 kHz. The frequency difference limen (DLF) intensity functions, describing DLFs as a function of signal level which were obtained in the presence of high-frequency masking noise, were essentially the same as the DLF intensity functions obtained without masking noise. These results indicate that high-frequency hearing is not necessary for acute frequency discrimination at low and at middle frequencies.

PACS numbers: 43.66.Fe, 43.66.Dc [FLW]

INTRODUCTION

A recent investigation of the frequency difference limen (DLF) in hearing-impaired listeners (Turner and Nelson, 1981) found larger DLFs than normal at low and middle frequencies where sensitivity thresholds were normal. In some listeners with high-frequency losses, DLFs at 1200 Hz (where sensitivity was normal) were two to three times larger than DLFs from listeners who exhibited normal high-frequency sensitivity. Those results confirmed earlier reports of similar findings by McCandless (1960) and by Konig (1957, 1969). One possible explanation for those results is that the integrity of the basal region of the cochlea may be necessary for acute low-frequency and mid-frequency DLFs, as well as for acute high-frequency DLFs.

The present experiment was designed to determine whether or not the basal end of the cochlea contributes to frequency discrimination at lower frequencies. To accomplish this, DLFs were obtained from normal-hearing listeners both in the absence and in the presence of high-frequency masking noise. The presence of intense high-frequency masking noise may be expected to saturate the responses of sensory elements located in the basal region of the cochlea, thereby eliminating any changes in discharge rate that might occur with small changes in signal frequency. If information from sensory elements in the basal region of the cochlea was necessary or at least was important for a frequency-discrimination task at middle frequencies (around 1200 Hz), one would expect that DLFs obtained in the presence of high-frequency masking noise would be larger than those obtained in quiet.

I. METHOD

Two listeners were first tested for frequency discrimination and sensitivity thresholds under quiet listening conditions. They were then tested for frequency discrimination and sensitivity thresholds in a series of listening conditions with high-frequency masking noise. Finally, they were tested in quiet listening conditions again to see if there were any changes in DLFs over time that might be the result of learning.

A. Experimental listeners

Two young adults, a 22-year-old male and a 24-year-old female, were the listeners. Both demonstrated normal hearing, defined by air-conduction hearing threshold levels no poorer than 15 dB HL (ANSI, 1969), and provided a negative history of hearing loss or ear disorders. Listener AT was a musician, MS (the second author) was not.

B. Psychophysical paradigm

A four-interval, four-alternative, forced-choice (4IFC) paradigm was used to measure DLFs and sensitivity thresholds. In a single frequency-discrimination trial, illustrated in Fig. 1, tones were presented sequentially during each of four time intervals marked by indicator lights. One of the four intervals always contained the variable frequency; that interval was randomized. The listener was instructed simply to identify which interval of the four was different from the other three, and to press the appropriate response key for that interval. Feedback about the correct interval was given following each response.

C. Adaptive procedures

A transformed up–down adaptive procedure was used for DLF and sensitivity-threshold measurements. Frequency differences, test frequencies, and signal levels were varied automatically according to specific adaptive rules that determined how much the stimuli changed and under what circumstances. The specific adaptive rules used in the present investigation were patterned after Levitt's (1971) analysis of adaptive procedures and followed those described for a 71% performance criteria. To obtain estimates of the 71% point on the psychometric function, a one-up, two-down, adaptive rule was used. Stimulus values were changed in one direction by one step size following every incorrect response, and they were changed in the other direction by one step size following two consecutively correct responses.

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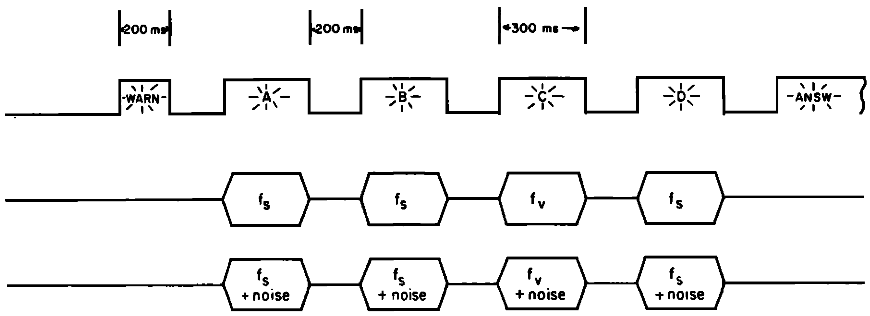

FIG. 1. Time-line illustrations of the four-interval forced-choice procedure used to obtain DLFs. The top time line depicts the spatial orientation of the indicator lights that also served as response keys. The middle time line represents presentations of standard-frequency (fs) and variable-frequency (fv) tone bursts during the frequency discrimination task. The bottom line represents the timing of the bursts of tone-plus-noise that were used for the high-frequency DLF masking conditions.

1. *Frequency difference limen*

For DLF estimation the initial variable frequency was always lower in frequency than the standard frequency (1200 Hz). Following the first response, the variable frequency was altered by a constant step size of 6 Hz. If an incorrect response occurred, the variable frequency for the following trial was decreased by 6 Hz. A correct response increased the variable frequency by 6 Hz. The step size remained at 6 Hz until two reversals in the direction of the frequency change occurred. After the second reversal, the step size was reduced to 1 Hz and the one-up, two-down, transformed adaptive rule was employed. Listening trials continued until a total of 14 reversals were obtained, two with a step size of 6 Hz, and 12 with a step size of 1 Hz. A DLF was calculated from the average of the frequencies of the last 12 reversals.

2. *Sensitivity thresholds*

An adaptive procedure was also used to obtain sensitivity thresholds. At the beginning of an adaptive run, the step size was 16 dB until two reversals were obtained. After the second reversal, the step size was reduced to 4 dB and a one-up, two-down, adaptive rule was employed. Listening trials continued until a total of six reversals were obtained, two with a step size of 16 dB, and four with a step size of 4 dB. Sensitivity threshold was calculated as the average of the levels of the last four reversals.

D. Experimental sequence

DLFs and hearing threshold levels were obtained in four listening conditions: in quiet, and in the presence of three different high-frequency masking bands. For each DLF condition, five DLF estimates were obtained from each listener at eight sound pressure levels. For each sensitivity-threshold condition, five estimates were obtained at each of 11 test frequencies.

DLFs were measured at 1200 Hz as a function of intensity level (dB SPL) for all conditions. The intensity levels used were 80, 70, 60, 50, 40, 30, 20, 10 dB SPL. Following a difference-limen estimate at one intensity level, a new "run" of trials was automatically presented at the next lower intensity level. In order to familiarize the listener with the stimuli to be discriminated, the highest intensity level was presented first. Sensitivity threshold estimates at each of the 11 frequencies were obtained within a single test session. In order to reduce the effects of practice on the results, DLFs and sensitivity-threshold estimates obtained during the first two (out of five) test sessions of each listening condition were not included in the analysis. Means and standard deviations reported in this investigation were determined by averaging the thresholds obtained from the last three test sessions in each listening condition.

E. Apparatus

Pure-tone stimuli were generated by a programmable oscillator (Krohn-Hite, 4141R) with harmonic distortion more than 70 dB below the levels of the fundamental frequencies. High-frequency masking noise was generated by multiplying a low-pass noise with a pure tone. The low-pass noise was generated by a random noise generator (General Radio, 1381) that had a rejection slope of 24 dB per octave above 2000 Hz, filtered by a 24-dB per octave low-pass filter (Frequency Devices, 742), and then fed to an analog multiplier (Teledyne Philbrick, 4452) for multiplication with a pure tone from a second programmable oscillator. Except for the low-pass filter, all of the instruments used in the investigation were controlled by a DEC PDP8/F computer.

The pure-tone and the noise stimuli were simultaneously gated by separate electronic switches, with 10-msec rise and decay times. The levels of the stimuli at the earphone were controlled by a pair of programmable attenuators for both the pure-tone channel and the noise channel. The pure-tone and noise signals were then combined by a resistive mixer, and routed through an impedance-matching transformer (UTC, 33A) to a TDH-49 earphone mounted in an MX/41-AR cushion. Frequencies were calibrated with a frequency counter (Hewlett Packard, 2633) using 10-sec samples of the frequencies both before and after the experiment.

II. RESULTS

A. DLFs in quiet

Results from both listeners for the initial quiet listening condition are presented in panels (a) and (b) of Fig. 2. Sensitivity thresholds are presented in panel (b). In general, both AT and MS possessed normal hearing sensitivity under quiet listening conditions; and, with the exception of 8000 Hz, sensitivity thresholds for both listeners were equivalent.

DLFs for listener AT and MS in the quiet condition are shown in panel (a) of Fig. 2. DLFs are plotted as a

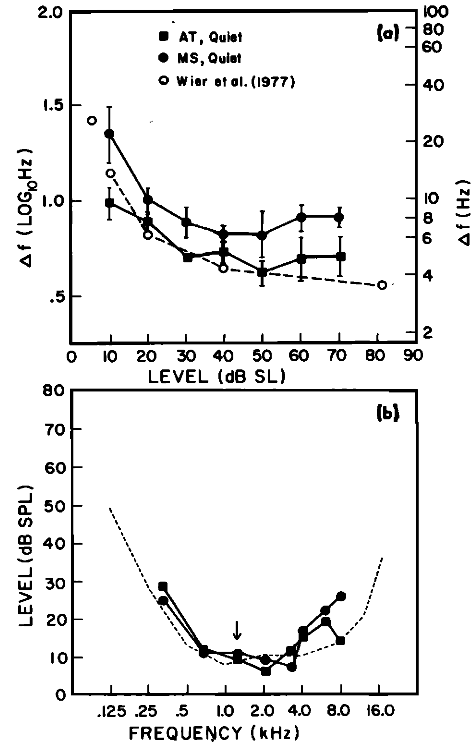

FIG. 2. DLF intensity functions and sensitivity thresholds for both listeners in the quiet listening condition. Panel (a): Mean DLFs ($\log_{10}$ Hz) as a function of sensation level. DLFs in Hz are also indicated along the right ordinate. One standard deviation above and below each mean is indicated by vertical lines for each DLF. The dashed line shows the interpolated mean DLF intensity function at 1200 Hz of three normal-hearing listeners from Wier *et al.* (1977). Data from Wier *et al.* have been multiplied by 1.91 to equate their 2IFC DLFs with 4IFC DLFs.[1] Panel (b): Sensitivity thresholds for each listener as a function of frequency. The dashed line indicates the curve of normal hearing (ANSI, 1969); the arrow points to the sensitivity thresholds at the 1200-Hz DLF test frequency.

function of the intensity of the test signal, expressed here as dB sensation level (SL). For convenience, these functions are called DLF intensity functions. The form of the DLF intensity functions was comparable for the two listeners. Those functions were also comparable in form with the mean DLF intensity function for three listeners in the Wier *et al.* (1977) study (shown by the dashed line).[1] DLFs decreased with increasing sensation level (SL) up to about 40 dB; at sensation levels greater than 40 dB, DLFs remained relatively constant (Harris, 1952; Zwicker, 1953).

Variability in frequency discrimination from test to test is represented by vertical lines showing one standard deviation above and below each mean. Variability did not change consistently with level or with the size of the DLF.

Although the DLF intensity functions for both listeners were similar in form, there were consistent differences between the acuities of listener AT and MS. Listener AT appeared to be just as acute as the three highly trained listeners in the Wier *et al.* study, while listener MS obtained DLFs that were approximately one and a half times poorer than listener AT at all signal intensities.

B. DLFs with high-frequency masking bands

The DLF intensity functions and sensitivity-threshold curves obtained in each of the three noise conditions are presented in Figs. 3 and 4 for listeners AT and MS, respectively. DLF intensity functions are shown in the upper panels; sensitivity threshold curves are shown in the lower panels. In order to evaluate the effects of high-frequency masking noise, the DLFs and the sensitivity thresholds obtained in the initial quiet listening conditions are included in each figure. Since each of the high-frequency noise bands masked 1200 Hz to some degree, the number of data points constituting DLF intensity functions varied with the particular noise used. The greater the amount of threshold shift at 1200 Hz produced by the high-frequency masking noise, the fewer were the number of levels available for testing DLFs.

For all of the listening conditions, the DLFs obtained from listener AT remained consistently smaller than those obtained from listener MS. Due to the differences in discrimination ability of the two listeners, the results from the listeners were not combined and are presented separately in the figures.

The DLFs and sensitivity thresholds that were obtained in the presence of a masking noise from 2875 to 3125 Hz at a spectrum level of 75 dB/Hz are presented in the left pair of panels in Figs. 3 and 4. This was the first high-frequency masking noise we investigated. In the panels labeled (b), it can be seen that all test frequencies were masked by the noise to some extent. Threshold shifts were minimal for frequencies up to 1800 Hz and at 8000 Hz. The largest threshold shifts occurred between 2000 and 8000 Hz. The maximum threshold shift occurred at 3000 Hz, as expected, since 3000 Hz was the center frequency of the noise band.

The DLF intensity functions are shown in panel (a). It is apparent, from the overlapping DLF intensity functions, that the presence of the 2875–3125-Hz masking noise did not significantly reduce frequency discrimination performance. The DLF intensity functions of both listeners were, for all practical purposes, identical to the functions obtained in the initial quiet listening condition. These results are consistent with those reported by earlier investigators for DLF intensity functions in broadband masking noise (Brandt and Small, 1963; Harris, 1948; Henning, 1967; Jesteadt and Bilger, 1969).

The effects of moving the edge of the high-frequency masking noise closer to the 1200-Hz DLF test frequency can be seen in the center pair of panels in Figs. 3 and 4. In this case, a noise band from 1875 to 2125 Hz at 75 dB/Hz was used. Similar threshold shifts were produced for both listeners. Sensitivity thresholds were shifted maximally between 1200 and 5600 Hz. The greatest threshold shift was at 2000 Hz, which corresponded to the center frequency of the noise band. Sensitivity thresholds at 1200 Hz were shifted by 15 dB for listener AT and by 11 dB for listener MS.

The DLF intensity functions obtained in the presence of the 1875–2125-Hz masking noise were less consis-

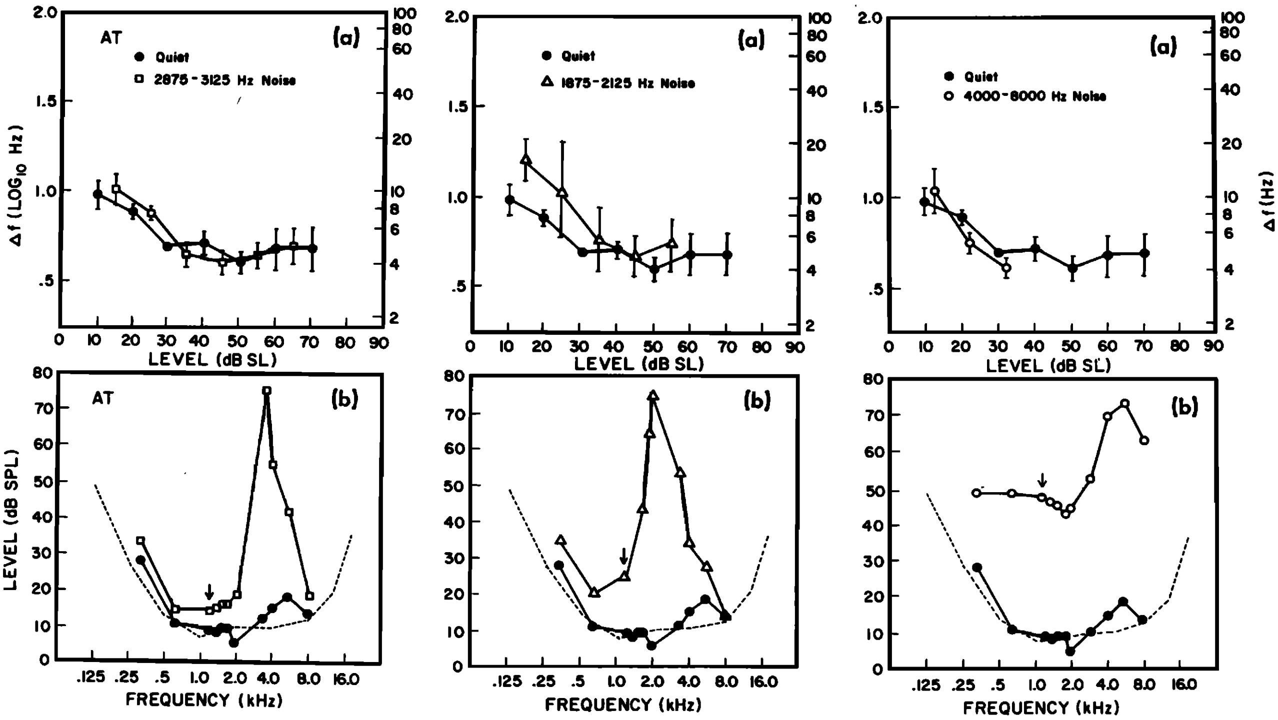

FIG. 3. DLF intensity functions (upper panels) and sensitivity thresholds (lower panels) from listener AT in the masking-noise conditions (open symbols) compared with the initial quiet listening condition (filled symbols). The spectrum level was 75 dB/Hz for the 2875–3125-Hz noise and the 1875–2125-Hz noise, and it was 55 dB/Hz for the 4000–8000-Hz noise.

tent between the two listeners, but in general there still were no significant elevations of the DLF intensity functions. Listener AT's DLFs were poorer relative to those from the quiet condition at low sensation levels, with greater variability at all levels. At the low sensation levels, listener MS performed as well in masking noise as she did in quiet. At sensation levels greater than 20 dB, the mean DLFs for MS were larger in the presence of the masking noise. However, at levels where mean DLFs in masking noise were larger than in quiet, the variability was too large to conclude that the differences were meaningful.

Since the 1875–2125-Hz and the 2875–3125-Hz mask-

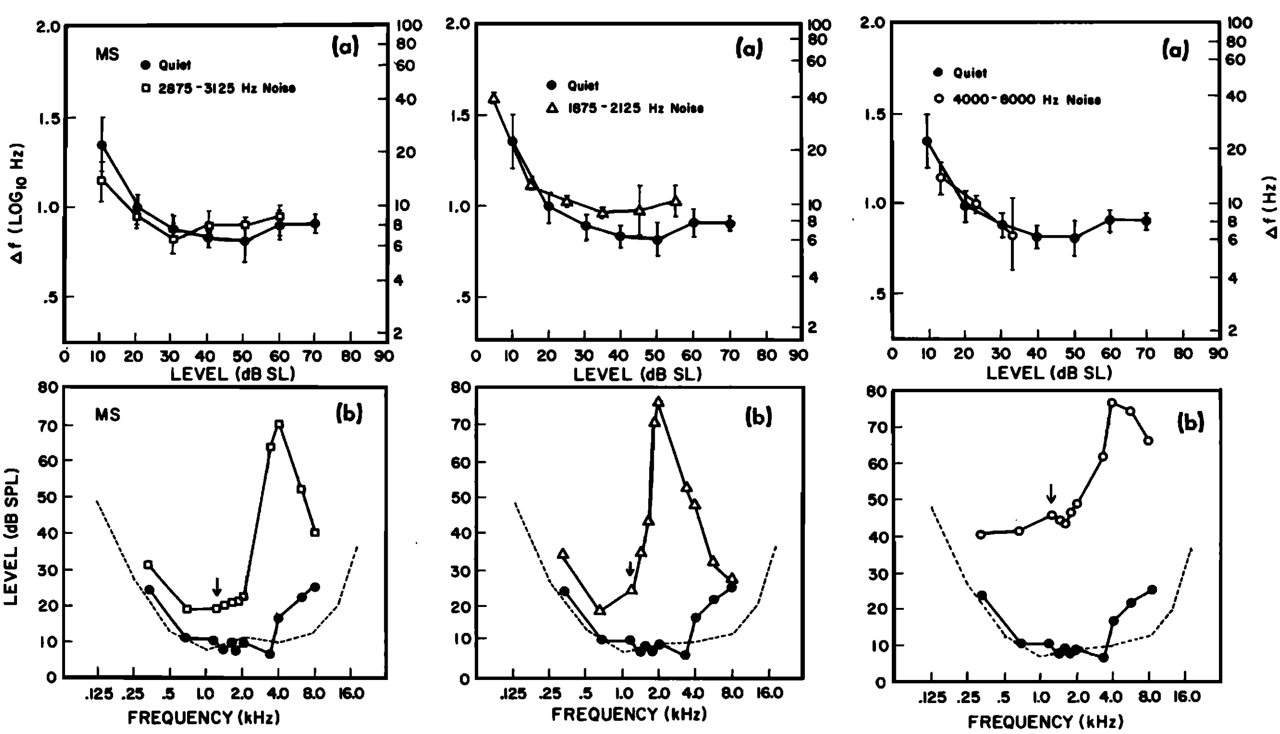

FIG. 4. DLF intensity functions and sensitivity thresholds from listener MS.

ing noises produced very little masking at 8000 Hz, it is possible that in both cases the more basal portions of the cochlea most sensitive to high frequencies at or above 8000 Hz could have contributed to the normal DLFs obtained in the presence of these masking noises. To test that notion, a third high-frequency masking noise (4000–8000 Hz, presented at 55 dB/Hz) was used, one that produced considerable masking at 8000 Hz. The results for this 4000–8000 Hz masking noise are shown in the right-most pair of panels in Figs. 3 and 4.

The off-band spectral components of this masking noise were only about 40 dB below the spectral components within the passband. Therefore considerable direct masking occurred at 1200 Hz and below. However, this 4000–8000-Hz masking noise did shift 8000-Hz thresholds by some 45 to 50 dB as desired. Despite the large amount of masking produced by this masking noise, the DLF intensity functions obtained in the presence of this noise were essentially the same as those obtained in the quiet listening condition. The standard deviations of the DLFs were also comparable to those obtained in quiet, with the exception of a rather large standard deviation at 32 dB SL from listener MS.

C. Learning effects

To evaluate the effect of practice upon DLFs in quiet and to ensure that sensitivity thresholds had not changed during the test sessions, DLFs and sensitivity thresholds were retested in the quiet listening condition. For both listeners, the DLFs and sensitivity thresholds remained essentially unchanged from the time of the original measures in a quiet listening condition to the final measures in a quiet listening condition.

III. DISCUSSION

One objective of this study was to provide evidence that would assist in the interpretation of previous findings that some listeners with high-frequency hearing loss obtained poor DLFs in regions of normal hearing sensitivity (Konig, 1957, 1969; McCandless, 1960; Turner and Nelson, 1981). Turner and Nelson (1981) suggested three possible interpretations: (1) Information from neural elements in basal regions of the cochlea normally contributes to acute DLFs at low and mid frequencies; therefore cochlear pathology in those basal regions of the cochlea, as indicated by high-frequency sensitivity losses, interferes with or eliminates that information. (2) Cochlear pathology responsible for high-frequency sensitivity losses may alter the mechanical properties of the traveling wave in the cochlea so as to affect frequency discrimination thresholds for low and middle frequencies, but not affect sensitivity thresholds for those frequencies. (3) Cochlear pathology exists in apical regions in the cochlea of high-frequency hearing-loss listeners, at frequency regions where sensitivity thresholds are normal but DLFs are not. Masking the high-frequency regions of the cochlea with high-frequency masking noise should interfere with or eliminate any response rate dependent contribution of basal regions of the cochlea to frequency discrimination at 1200 Hz. If that information were important, it was expected that 1200-Hz DLFs would be affected by the high-frequency masking bands. However, intense high-frequency masking noise had essentially no effect on frequency discrimination at 1200 Hz.

If one accepts the interpretation that the high-frequency masking noises employed here eliminated any essential contribution by high-frequency fibers to frequency discrimination at 1200 Hz, then Turner and Nelson's (1981) first explanation for abnormal DLFs in the presence of high-frequency hearing loss becomes less tenable. These results suggest that high-frequency hearing has little to do with acute frequency discrimination at low and middle frequencies. Their other two explanations remain quite tenable and cannot be differentiated from the results of this study.

ACKNOWLEDGMENTS

This report was based on Master's thesis research submitted to the University of Minnesota Graduate School by the second author. The authors wish to thank M.W. Cushing for her diligent efforts in preparing artwork for this manuscript. We also wish to thank Craig Wier for his thoughtful suggestions to an earlier version of this manuscript. This research was supported by research grants from NINCDS (NS 12125, NS 15451, and NS 00449).

[1]Estimates of DLFs at 1200 Hz for the Wier *et al.* (1977) study were made by interpolation using their fitting equation. Then transformations to 4IFC equivalent DLFs were accomplished by multiplying their 2IFC DLFs by the ratio of the expected d' at 70.7% correct in a 4IFC task (1.49) to the expected d' at 70.7% correct in a 2IFC task (0.78). That ratio was 1.49/0.78= 1.91.

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