Intensity discrimination in forward masking

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A nonmonotonic intensity discrimination function was recently reported in which a midlevel hump occurred for 25-ms sinusoidal standards ranging from 20 to 100 dB SPL and presented 100 ms after an intense narrow-band noise forward masker [F.-G. Zeng *et al.*, Hear. Res. **55**, 223–230 (1991)]. This paper provides additional data on how the midlevel hump is affected by three factors of forward masking: signal delay, masker level, and frequency. Specifically, just-noticeable differences (jnd's) in intensity were obtained at signal delays of 50, 200, and 400 ms. Results show that at the midlevels the forward-masked intensity jnd's did not recover to their unmasked values, even at the 400-ms signal delay. The longer the signal delay, the smaller this midlevel hump. This slow recovery of the midlevel jnd's is consistent with the finding that low-spontaneous rate (SR) neurons have a slow recovery from forward masking [E. M. Relkin and J. R. Doucet, Hear. Res. **55**, 215–222 (1991)]. The large midlevel effect decreased sharply as masker level was reduced from 90 to 60 dB SPL, and disappeared for masker levels less than 40 dB SPL. A frequency selectivity effect for the large midlevel jnd effect was also observed, as maskers with frequency components 2 to 3 oct away from the signal frequency did not affect the jnd's. Overall, the present data are consistent with the hypothesis of Zeng *et al.* (1991) that low-SR neurons are involved in the midlevel hump of intensity discrimination in forward masking.

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INTRODUCTION

The term forward masking is used to describe the effect of a preceding sound upon the detection and discrimination of a following sound. Most previous studies have focused on the effect of forward masking on the detection threshold of a signal (e.g., Zwislocki *et al.*, 1959; Elliott, 1962; Smiarowski and Carhart, 1975; Zwislocki, 1978; Jesteadt *et al.*, 1982; Carlyon, 1988). Since there is essentially no threshold shift in forward masking at 100 to 200 ms signal delay, the assumption that the effect of forward masking is limited to 100 to 200 ms has been widely accepted.

Intensity discrimination refers to the ability of a listener to detect changes in intensity. For pulsed tones, intensity can be reliably discriminated over a dynamic range of at least 100 dB, and Weber's fraction, expressed as ($\Delta I/I$), approaches 0.1 at high intensities (e.g., Rabinowitz *et al.*, 1976; Viemeister and Bacon, 1988). This large psychophysical range contrasts with the 20- to 30-dB range in the majority of primary auditory neurons (e.g., Kiang *et al.*, 1965). Recent attempts to model this dynamic range discrepancy have utilized the contribution of the minority of auditory neurons possessing low spontaneous activity and high thresholds (Liberman, 1978).

Intensity discrimination in forward masking has rarely been investigated. Widin *et al.* (1986) compared the effects of forward and simultaneous masking on the intensity discrimination of a 20-ms, 1000-Hz tone. Carlyon and Moore (1984) used a similar forward masking paradigm in one condition of their experiment to control the contribution of the onset response of a 26-ms tone to intensity discrimination. In both studies, the delay between the offset of the forward masker and the onset of the signal was 5 ms. Both studies showed that the jnd's in intensity were greater than expected on the basis of a sensation level shift. This finding implies that suprathreshold discrimination in forward masking cannot be predicted by the recovery of absolute threshold detection from forward masking. However, because of the significant amount of threshold shift at the 5-ms delay, these two studies did not directly challenge the widely accepted assumption that a masker that does not change the threshold of a signal also has no suprathreshold consequences.

The findings of Zeng *et al.* (1991) directly challenged this notion by showing that forward masking produces a nonmonotonic intensity discrimination function with a midlevel hump for a 25-ms sinusoidal stimulus presented 100 ms after an intense narrow-band noise. At this 100-ms delay, there was essentially no threshold shift. Their interpretation was that the midlevel hump on the forward-masked intensity discrimination function was due to the slower recovery of threshold from forward masking of the low-SR neurons as compared to the high-SR neurons, and that the recovered threshold at the 100-ms delay was due to the fast recovery of the high-SR neurons (Relkin and Doucet, 1991). Thus the study of Zeng *et al.* may have provided long-sought psychophysical evidence for the involvement of low-SR neurons in intensity coding.

If Zeng *et al.* are correct that the effect of the midlevel jnd hump is related to the slow recovery of low-SR neutrons, then this effect should follow other aspects of physiological properties of low-SR neurons. For example, the high threshold of low-SR neurons (e.g., Liberman, 1978) would suggest that a high masker level is necessary to cause a significant midlevel hump; the frequency selectivity of low-SR neurons would result in a differential effect of the masker frequency on the midlevel hump. The present paper specifically aims to investigate the effects of signal delay, masker level, and masker frequency on intensity discrimination in forward masking.

I. METHODS

A portion of these data were originally reported in an earlier article (Zeng *et al.*, 1991). The experimental design and methods are briefly described here.

Three normal-hearing listeners, 20 to 27 yr old, served as subjects. Subject FG was the first author, and subjects AY and RB were paid for their participation.

Figure 1 shows the temporal paradigm of the stimuli. Two intervals were presented, each of which contained a masker followed by a standard. In one of the intervals, the standard contained an increment in amplitude relative to the standard. The subject was instructed to identify the interval with the increment. All stimuli had 2 ms, cosine-squared onset and offset ramps. The masker was a narrow-band noise with a duration of 100 ms, generated by passing a white noise (MDF Inc., Model 8156) through a Kemo (Type VBF 8) low- and high-pass filter. The filter attenuation slopes were 90 dB/oct (modified Butterworth responses). The 1000 Hz, 25-ms probe tone was synthesized and stored on a Macintosh IIx computer. All the test tones were output by a 16-bit digital-to-analog converter (South Accelerator-Digidesign) at a sampling rate of 44.1 kHz. The synthesized tones were smoothed by a 20 kHz low-pass filter and presented to the subject via a Beyer DT 48 A.0 headphone. The amplitude increment was produced by adding an in-phase version of the standard. The level of this in-phase addition was controlled by a Wilsonics programmable attenuator.

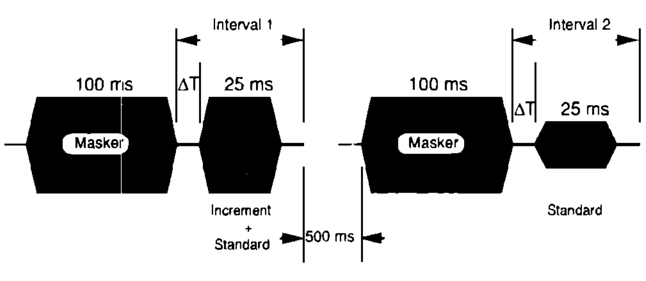

FIG. 1. Temporal paradigm of the acoustical stimuli in one trial of forward-masked intensity discrimination. All ramps were 2 ms, cosine squared. Interval 1 contains the incremental tone (signal), which was randomly presented in either interval 1 or in interval 2 during the experiment. Both warning and feedback lights were presented before and after each trial. The interval was marked by a signal light following the masker.

A standard 2-down, 1-up, two-interval, forced-choice adaptive procedure tracking the 70.7% level of correct response was employed in the intensity discrimination experiment (Levitt, 1971). Subjects received trial-by-trial feedback on the correct response. The intensity jnd in each run was estimated from the arithmetic mean of the last 10 reversals in a 14-reversal sequence. The reported jnd values were the average of 6 such runs. The data are presented as a logarithmic form of the relative jnd in intensity: $10 \text{ Log } (1 + \Delta I / I)$.

II. RESULTS

A. Effects of signal delay

Figure 2 plots forward-masked intensity discrimination functions at signal delays of 50, 200, and 400 ms. The data for the 100-ms delay (open circles) and for the unmasked condition (closed circles) have been presented previously (Zeng *et al.*, 1991). The masker level was 90 dB SPL.

Panels AY, FG, and RB in Fig. 2 show the individual jnd data. Note the large individual differences among subjects, particularly at low intensity levels. Nevertheless, examination of the group mean data (the lower right panel in Fig. 2) indicates that suprathreshold intensity discrimination did not recover to the unmasked values even at the 400-ms signal delay, except at the highest standard levels. There were large differences between the jnd's in the presence and absence of forward masking for midlevel standards at each measured signal delay, as shown by Zeng *et al.* (1991). Also, this midlevel hump effect decreased as the signal delay was increased.

Figure 3 plots the average data of Fig. 2 on different coordinates, with the jnd's at each standard level replotted as a function of signal delay. Two forms of the intensity jnd recovery functions are presented. The upper panel shows recovery functions for the jnd for tones of different standard levels. The forward-masked recovery functions for high standard levels—80, 90, and 100 dB SPL, the lowest three curves in the upper panel of Fig. 3—show that the 90 dB SPL forward masker had little effect on these high-level tones, as their jnd's were essentially unchanged across the entire range of signal delays. A different recovery pattern occurs between the low-level (20 and 30 dB SPL) and the midlevel (40 to 70 dB SPL) tones: the low-level tones appear to recover at a faster rate than the higher level tones between the 50 and 100-ms signal delays.

The rate of recover for the jnd recovery functions in the upper panel of Fig. 3 are difficult to compare across different standard levels, because they have different values at the 50 and 400-ms delays. The lower panel of Fig. 3 shows a normalized form of the jnd recovery functions. The jnd's at the shortest delay (50 ms) are normalized by assigning to them a value of 0% recovery, and, the value of 100% recovery is taken as the unmasked jnd from the control condition (see in Fig. 2). The linear relative jnd's $(1 + \Delta I / I)$ are used to calculate the recovery function. By such a definition, 100% represents complete recovery from forward masking. Since the 90-dB SPL masker has little effect upon the jnd's of the high-level standards, the relative recovery functions for

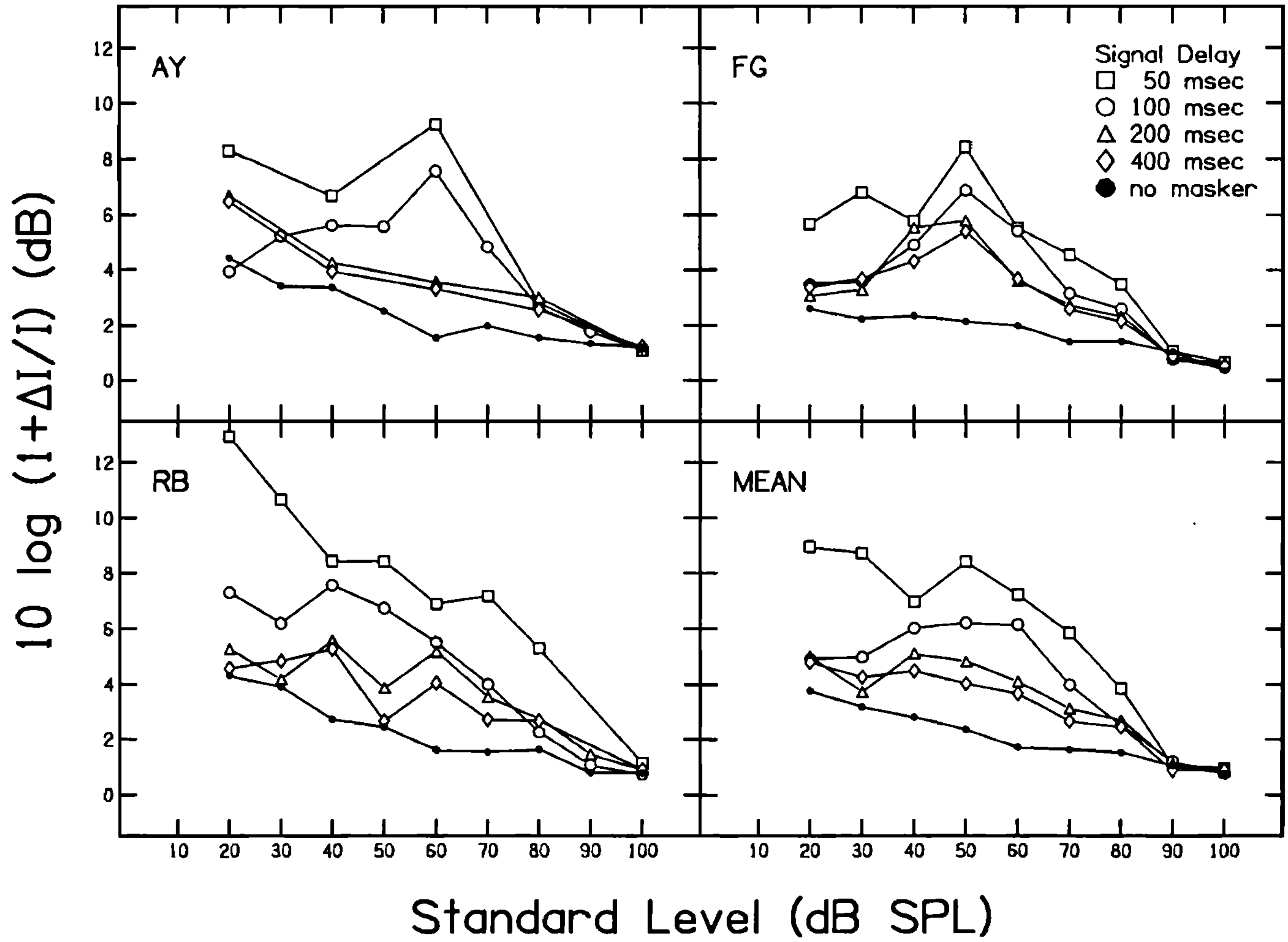

FIG. 2. Individual forward-masked intensity jnd functions (panels AY, FG, and RB) and their mean jnd function at various signal delays. The open squares, circles, triangles, and diamonds represent the forward-masked jnd's at 50-, 100-, 200-, and 400-ms signal delay, respectively. The data were obtained for a 25 ms, 1000-Hz tone following a 90-dB SPL noise masker at the above 4 signal delays. For comparison, the jnd functions in the absence of masking are also plotted as the closed circles.

standard levels of 80, 90, and 100 dB SPL are not included in this plot, as they are essentially straight horizontal lines corresponding to 100% recovery. For comparison, the detection threshold for a 25-ms signal (Zeng *et al.*, 1991) in forward masking is normalized in the same way and included as a dashed line in the lower panel of Fig. 3. The normalized jnd recovery functions at 20 and 30 dB SPL (solid circles and squares) appear to be a two-stage process: an initial fast recovery from 50 to 100 ms followed by an asymptote at about 80% recovery level up to 400 ms. Also note that the first recovery stage is similar to the threshold recovery functions from 50 to 100 ms. In contrast to the two-stage recovery at low levels, the midlevel jnd's (from 40 to 70 dB SPL, all open symbols) appear to have only a single recovery process. The midlevel relative recovery functions follow a straight line on a logarithmic time scale. At the 400-ms signal delay, the normalized jnd recovery levels for tones of 40, 50, 60, and 70 dB SPL were 65%, 79%, 71%, and 80%, respectively.

B. Effects of masker level

To investigate the effects of masker level upon intensity discrimination, we chose the standard level at which each subject had the largest jnd at the 100-ms signal delay. The standard level showing maximum effects was 60, 50, and 40 dB SPL for subjects AY, FG, and RB, respectively (see Fig. 2). The signal delay was fixed at 100 ms in this experiment.

Figure 4 shows the effect of masker level upon the large midlevel jnd's. The standard deviations across runs for each subject are shown by vertical bars on each data point. The group means (dashed line) show that, for masker levels lower than 40 dB SPL, there was essentially no masking effect on the jnd's compared to the unmasked condition (solid line with an arrow head). The jnd increased for masker levels greater than 40 dB SPL, but a large effect was not observed until masker levels reached 70 dB SPL and higher.

C. Effects of masker frequency

We measured the effect of masker frequency upon the large midlevel jnd's at 100-ms signal delay. The same stimulus parameters as in the preceding masker level experiment were used, except that the independent variable was the masker frequency and the masker level was fixed at 90 dB SPL. For noise maskers with center frequencies of 125, 250, and 500 Hz, the bandwidth was 100 Hz; for those with center

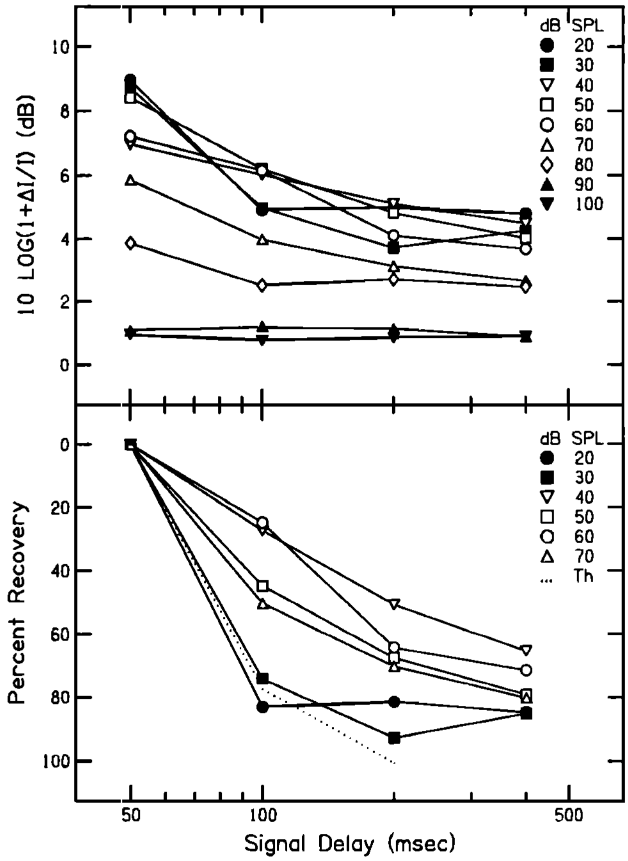

FIG. 3. Relative (upper panel) and normalized (lower panel) intensity discrimination recovery functions for different standard levels (different symbols in upper right corner). The normalized threshold recovery function is also included as the dashed line on the lower panel.

frequencies of 1000, 1500, and 2000 Hz, the bandwidth was 200 Hz; for the 4000-Hz masker, the bandwidth was 400 Hz.

Figure 5 shows how the midlevel jnd's change as a function of the masker center frequency. The mean jnd's (dashed

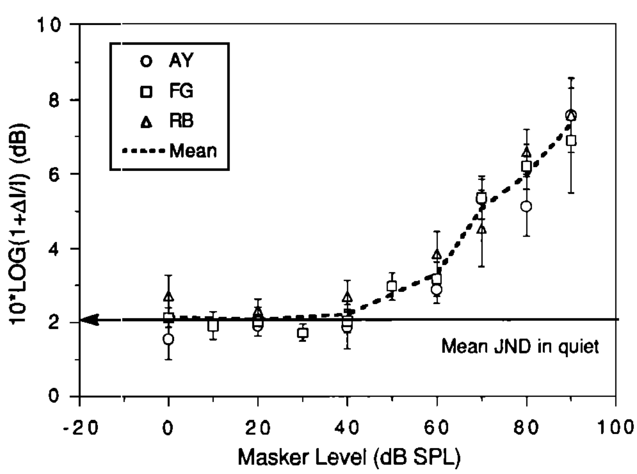

FIG. 4. Effects of masker level. Here, jnd's from each subject are plotted as a function of masker level. The signal delay was fixed at 100 ms. The standard deviations across runs for each subject are expressed by the vertical bars on each data point. The group mean data are expressed as a dashed line. The group mean jnd in the absence of masking is plotted as the line with an arrow head.

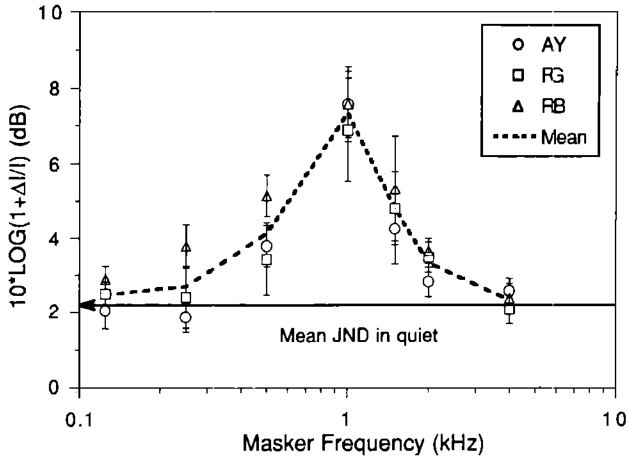

FIG. 5. Effects of masker frequency. Here, jnd's for each subject are plotted as a function of masker frequency. The forward masking conditions were the same as in Fig. 4, except that the masker level was fixed at 90 dB SPL and the independent variable was the masker frequency.

line) indicate that the large midlevel jnd's occurred when the center frequency of the masker and the signal frequency were close. The effect of masker frequency decreased gradually to zero over 2 to 3 octaves for lower masker frequencies; for higher masker frequencies, the decay appeared to be more rapid on a logarithmic frequency scale.

III. DISCUSSION

A. Summary of results

The data reported by Zeng *et al.* (1991) were expanded upon by presenting additional forward-masked intensity discrimination functions at signal delays of 50, 200, and 400 ms. Results show an elevation on the forward-masked intensity discrimination function at all delays, and the function becomes nonmonotonic (with a "hump") at midlevels for signal delay of 100 ms. This midlevel hump decreases at longer signal delays (Fig. 2). A normalized plotting procedure shows that there may be differential recovery from forward masking between low-level (20 and 30 dB SPL) and midlevel (40 to 70 dB SPL) intensity discrimination. The low-level jnd's have an initially fast recovery function, which is similar to the threshold recovery from 50 to 100 ms, after which there is a second asymptote indicating a slowly recovering residual process. The fast recovery for the low-level jnd's may be due to the high-SR neurons, which, correspondingly, have a narrow dynamic range of approximately 30 dB. The midlevel jnd recovery functions, on the contrary, appear to have only a single slower recovery process. The slow recovery of the midlevel jnd is also consistent with the physiological finding of slow recovery of low-SR neurons from forward masking (Relkin and Doucet, 1991).

We speculate that the asymptote of the low-level jnd's at long signal delays may be related to the high masker level (90 dB SPL) in the present study. Young and Sachs (1973) showed that the long-term recovery of discharge rate from an intense forward masker is related to the intensity of the forward masker rather than to the number of spikes generated by that masker [Fig. 2(b) and 7 in their study]. This physiological process is similar to temporary threshold shift or fatigue and seems different from short-term adaptation (which depends mostly upon the discharge rate). In other words, although both the 50 and 90 dB SPL maskers produce the same discharge rate in the high-SR neurons, due to saturation, the long-term recovery from these two levels may be different. This hypothesis can be tested using a low-level (50 dB SPL) masker to obtain the forward-masked intensity jnd's at 20 and 30 dB SPL. If the hypothesis is true, then the asymptote at long delays should disappear.

The effects of masker level and frequency on the large midlevel jnd's were also investigated at a single signal delay of 100 ms. The data show that the large midlevel jnd's occur only when the masker has a high intensity level. This finding is consistent with physiological data that low-SR neurons generally have high thresholds which, in turn, require high-level maskers to produce a significant forward masking effect. The data also show that maskers of different frequency affect the large midlevel jnd's differentially: masker frequencies of 2 to 3 oct away from the signal frequency have no effect. Such a frequency selectivity suggests that the large midlevel jnd's may be due to some physiologically based forward masking effect rather than a general psychological distraction factor resulting from the loud masker.

B. Origins of the midlevel hump

To fully understand the origins of the midlevel jnd hump in forward masking, we need to know the physiological mechanisms involved in forward masking. Unfortunately, they are not clear at the present time. The data of the present paper and that of Zeng *et al.* (1991) are only suggestive. We hope that the discussion of the following three issues will serve as a starting point to understand the origins of the midlevel jnd hump in forward masking.

The first issue concerns threshold versus suprathreshold measurement. The present comparison between psychophysical and physiological data is indirect in that we attempt to relate psychophysical suprathreshold discrimination in forward masking to the threshold recovery of low-SR neurons. Zeng (1990) showed that assuming only a threshold shift for low-SR neurons at 100-ms signal delay predicts a much narrower midlevel hump on the intensity jnd function than obtained in psychophysical data. This discrepancy suggests that the physiological threshold-shift data (Relkin and Doucet, 1991) are not sufficient to account for the suprathreshold intensity discrimination. Discharge rate and its variance as a function of the standard level and signal delay for both high- and low-SR neurons are needed for a more realistic model of foward-masked intensity discrimination. Abbas (1979) reported that, even at a 10-ms delay, low- and high-SR neurons may have different rate-intensity (RI) functions in forward masking: the RI slope of low-SR neurons seemed to decrease at low levels. This RI slope difference may be larger at a 100-ms delay in light of the threshold difference between low- and high-SR neurons (Relkin and Doucet, 1991). If so, both the threshold difference and the suprathreshold RI difference between low- and high-SR neurons would contribute to the midlevel jnd hump in forward masking.

The second issue concerns a single-nerve versus whole-nerve coding scheme. Increasing evidence indicates that the brain may not process neural information in an optimal manner. For example, if the brain were optimally to use information from each peripheral neuron, not only would intensity discrimination be much better than the psychophysical data suggested (Winter and Palmer, 1991), but also the recovery from forward masking would be much shorter (Relkin and Turner, 1988). On the other hand, a better correlation has been found between psychophysical data and some form of less optimally combined whole-nerve data, such as the compound action potential (Abbas and Gorga, 1981; Relkin and Smith, 1991) and the auditory nerve neurophonic (Snyder and Schreiner, 1985). Auditory-nerve neurophonic represents the spatially summed, phase-locked response of auditory neurons and can be recorded with low-frequency, long-duration tones (Chimento and Schreiner, 1990). In a similar forward masking paradigm, Snyder and Schreiner (1985, Fig. 11) measured the neurophonic response to a 40-dB SPL tone following a 85-dB SPL tone masker and found two stages of recovery from forward masking. The first stage consists of rapid recovery, with at time constant of about 20 ms, and the second stage consists of slow recovery, with a longer time constant of 200 ms or more. This two-stage process may provide a whole-nerve representation combining the recovery of high- and low-SR neurons from forward masking. Such a representation might possibly be an alternative way to compare psychophysical and physiological forward-masked discrimination data. Understanding how the brain uses available information at the peripheral level is the next step in reconciling the present discrepancies between physiological and psychophysical data.

The third issue concerns peripheral versus central mechanisms. Forward masking has been hypothesized to be due to residual neural excitation (Luscher and Zwislocki, 1947; Zwislocki, 1960; Plomp, 1964; Houtgast, 1972), peripheral adaptation at the synaptic level (Duifhuis, 1973; Smith, 1970; Kidd and Feth, 1982; Meddis, 1986), and adaptation along with axonal transmission or more central mechanisms (Javel *et al.*, 1987; van den Honert and Stypulkowski, 1987; Chimento and Schreiner, 1991). Recent psychophysical data also showed that cochlear and brainstem implant listeners have a similar threshold recovery time from forward masking as do normal-hearing listeners, suggesting the involvement of more central mechanisms in forward masking (Shannon, 1990; Shannon and Otto, 1990). However, it is not clear whether the midlevel relative jnd hump in forward masking is due to peripheral or central mechanisms or both. This problem requires further investigation.

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Abbas, P. J. (1979). "Effects of stimulus frequency on adaptation in auditory-nerve fibers," J. Acoust. Soc. Am. **65**, 162–165.

Abbas, P. J., and Gorga, M. P. (1981). "AP responses in forward-masking paradigms and their relationship to responses of auditory-nerve fibers," J. Acoust. Soc. Am. **69**, 492–499.

Carlyon, R. P. (1988). "The development and decline of forward masking," Hear. Res. **32**, 65–80.

Carlyon, R. P., and Moore, B. C. J. (1984). "Intensity discrimination: A severe departure from Weber's law," J. Acoust. Soc. Am. **76**, 1369–1376.

Chimento, T. C., and Schreiner, C. E. (1990). "Time course of adaptation and recovery from adaptation in the cat auditory-nerve neurophonic," J. Acoust. Soc. Am. **88**, 857–864.

Chimento, T. C., and Schreiner, C. E. (1991), "Adaptation and recovery from adaptation in single fiber responses of the cat auditory nerve," J. Acoust. Soc. Am. **90**, 263–273.

Duifhuis, H. (1973). "Consequences of peripheral frequency selectivity from nonsimultaneous masking," J. Acoust. Soc. Am. **54**, 1471–1488.

Elliott, L. L. (1962). "Backward and forward masking of probe tones of different frequencies," J. Acoust. Soc. Am. **34**, 1116–1117.

Houtgast, T. (1972). "Psychophysical evidence for lateral inhibition in hearing," J. Acoust. Soc. Am. **51**, 1885–1894.

Javel, E., Tong, Y. C., Shepard, R. K., and Clark, G. M. (1987). "Response of cat auditory nerve fibers to biphasic electrical current pulses," Am. Otol. Rhino. Laryngol. **96**, Suppl. 128, 26–30.

Jesteadt, W., Bacon, S. P., and Lehman, J. R. (1982). "Forward masking as a function of frequency, masker level, and signal delay," J. Acoust. Soc. Am. **71**, 950–962.

Kiang, N. Y. S., Watanabe, T., Thomas, E. C., and Clark, L. F. (1965). *Discharge Patterns of Single Fibers in the Cat's Auditory Nerve* (MIT, Cambridge, MA), Research Monograph No. 35.

Kidd, G., and Feth, L. L. (1982). "Effects of masker duration in pure-tone forward masking," J. Acoust. Soc. Am. **72**, 1384–1386.

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

Liberman, M. C. (1978). "Auditory-nerve response from cats raised in a low-noise chamber," J. Acoust. Soc. Am. **63**, 442–455.

Luscher, E., and Zwislocki, J. J. (1947). "The decay of sensation and the remainder of adaptation after short-tone impulses on the ear," Acta Oto-Laryngol. **35**, 428–445.

Meddis, R., (1986). "Stimulation of mechanical to neutral transduction in the auditory receptor," J. Acoust. Soc. Am. **79**, 702–711.

Plomp, R. (1964). "Rate of decay of auditory sensation," J. Acoust. Soc. Am. **36**, 277–282.

Rabinowitz, W. M., Lim, J. S., Braida, L. D., and Durlach, N. I. (1976). "Intensity perception. VI. Summary of recent data on deviations from Weber's law for 1000-Hz tone pulses," J. Acoust. Soc. Am. **59**, 1506–1509.

Relkin, E. M., and Doucet, J. R. (1991). "Recovery from prior stimulation. I. Relationship to spontaneous firing rates of primary auditory neurons," Hear. Res. **55**, 215–222.

Relkin, E. M., and Smith, R. L. (1991). "Forward masking of the compound action potential: Thresholds for the detection of the N_1 peak," Hear. Res. **53**, 131–140.

Relkin, E. M., and Turner, C. W. (1988). "A reexamination of forward masking in the auditory-nerve," J. Acoust. Soc. Am. **84**, 584–591.

Shannon, R. V. (1990). "Forward masking in patients with cochlear implants," J. Acoust. Soc. Am. **88**, 741–744.

Shannon, R. V., and Otto, S. R. (1990). "Psychophysical measures from electrical stimulation of the human cochlear nucleus," Hear. Res. **47**, 159–168.

Smiarowski, R. A., and Carhart, R. (1975). "Relations among temporal resolution, forward masking, and simultaneous masking," J. Acoust. Soc. Am. **57**, 1169–1174.

Smith, R. L. (1970). "Adaptation, saturation, and physiological masking in single auditory-nerve fibers," J. Acoust. Soc. Am. **65**, 166–178.

Snyder, R. L., and Schreiner, C. E. (1985). "Forward masking of the auditory nerve neurophonic (ANN) and the frequency following response (FFR)," Hear. Res. **20**, 45–62.

van den Honert, C., and Stypulkowski, P. H. (1987). "Temporal patterns of single auditory nerve fibers elicited by periodic electrical stimuli," Hear. Res. **29**, 207–222.

Viemeister, N. F., and Bacon, S. P. (1988). "Intensity discrimination, increment detection, and magnitude estimation for 1-kHz tones," J. Acoust. Soc. Am. **84**, 172–178.

Widin, G. P., Viemeister, N. F., and Bacon, S. P. (1986). "Effects of forward and simultaneous masking on intensity discrimination," J. Acoust. Soc. Am. **80**, 108–111.

Winter, I. M., and Palmer, A. R. (1991). "Intensity coding in low-frequency auditory-nerve fibers of the guinea pig," J. Acoust. Soc. Am. **90**, 1958–1967.

Young, E. D., and Sachs, M. B. (1973). "Recovery from sound exposure in auditory-nerve fibers," J. Acoust. Soc. Am. **54**, 1535–1543.

Zeng, F.-G. (1990). "Intensity discrimination in the presence of forward masking," Ph.D. dissertation, Syracuse University.

Zeng, F.-G., Turner, C. W., and Relkin, E. M. (1991). "Recovery from prior stimulation. II. Contribution to intensity discrimination," Hear. Res. **55**, 223–230.

Zwicker, E. (1961). "Subdivision of the audible frequency range into critical bands," J. Acoust. Soc. Am. **33**, 248.

Zwislocki, J. J., Piroda, E., and Rubin, H. (1959). "On some poststimulatory effects at the threshold of audibility," J. Acoust. Soc. Am. **31**, 9–14.

Zwislocki, J. J. (1960). "Theory of temporal auditory summation," J. Acoust. Soc. Am. **32**, 1046–1060.

Zwislocki, J. J. (1978). "Masking: Experimental and theoretical aspects of simultaneous, forward, backward and central masking," in *Handbook of Perception, Vol. IV: Hearing*, edited by E. C. Carterette and M. P. Friedman (Academic, New York), pp. 283–336.