Frequency discrimination in forward and backward masking

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Frequency difference limens for pure tones preceded by a forward masker or followed by a backward masker were obtained across a wide range of signal levels. Relkin and Doucet [Hear. Res. 55, 215–222 (1991)] have shown that at a masker-signal delay of 100 ms, the thresholds of high-SR (spontaneous rate) auditory-nerve fibers are recovered, while the low-SR fiber thresholds are not. Therefore, forward-masked frequency discrimination potentially offers a method to investigate the role of low-SR fibers in the coding of frequency. It has been shown that when an intense forward masker is presented 100 ms before a pure-tone signal, intensity difference limens are elevated for mid-level signals [Zeng *et al.*, Hear. Res. 55, 223–230 (1991)]. However, Plack and Viemeister [J. Acoust. Soc. Am. 92, 3097–3101 (1992)] have shown that a similar elevation in the intensity difference limen is obtained under conditions of backward masking, where selective adaptation of the auditory neurons would not be expected to occur. A condition of backward-masked frequency discrimination was therefore included to investigate the role of interference resulting from adding additional stimuli to a discrimination task. For signals at 1000 and 6000 Hz, there was no effect of a forward masker upon frequency difference limens. For the backward-masked conditions, an elevation of the frequency difference limen was observed at all signal levels, demonstrating that the effects of forward and backward maskers upon frequency discrimination are dissimilar and suggesting that cognitive effects are present in backward-masked discrimination tasks. This difference between intensity and frequency discrimination supports the idea that intensity and frequency are encoded in different manners by the auditory system. The absence of an effect of forward masker on frequency discrimination suggests that the rate response of low-SR fibers does not contribute useful information to a frequency discrimination task.

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INTRODUCTION

Recent reports from our laboratory (Zeng *et al.*, 1991; Zeng and Turner, 1992) demonstrate that when pure-tone intensity discrimination is measured for signals presented 100 ms following an intense narrow-band forward masker a large midlevel increase in the Weber fraction is observed. For the combination of masker level (90 dB SPL) and masker-signal delay used in the studies, no shift in detection threshold was observed for signals at the test frequency. These same results were replicated by Plack and Viemeister (1992a). The results of these experiments were unusual in that an effect of a forward masker is demonstrated for suprathreshold tasks when the forward masker produces no elevation of the detection threshold. The choice of forward masker level and masker-signal delay in these experiments was designed to take advantage of the recent finding by Relkin and Doucet (1991), that at 100 ms following the adapting stimulus, low-SR (low spontaneous rate) eighth-nerve fibers were not completely recovered from adaptation (in terms of their rate response threshold), while the high-SR fibers were recovered. Zeng *et al.* (1991) and Zeng and Turner (1992) hypothesized that the high-SR fibers are therefore responsible for detection of signals near threshold, while low-SR fibers provide an important contribution to suprathreshold intensity discrimination at higher levels. Under certain conditions of forward masking these low-SR fibers are not completely recovered, thus leading to the observed deterioration in intensity discrimination performance following a forward masker.

The mechanism by which the auditory system encodes the frequency of a pure tone is uncertain. In terms of the auditory-nerve responses, both rate-place (excitation pattern) schemes (e.g., Bekesy, 1960; Zwicker, 1970) and phase locking schemes (e.g., Goldstein and Srulovicz, 1977; Wever, 1949) have been proposed as the relevant code, although each has theoretical limitations. For models based upon phase locking, it has been shown that the information provided by timing at low stimulus frequencies is precise enough to account for behavioral data (Siebert, 1970); however, it is also known that accurate phase locking is greatly diminished or absent at frequencies above 5000 Hz (Johnson, 1980). For models based upon rate-place codes, one limiting factor is the low sound levels at which the firing rate of high-SR neurons saturates, which would tend to reduce the sharpness with which the "excitation pattern" can be represented. Low-SR neurons do not saturate at these low sound levels, and therefore might provide an important contribution to place coding at higher stimulus levels. Shofner and Sachs (1986) have shown that the population of low-SR fibers maintains a sharp peak in the neural-rate population response to a 1500-Hz tone for high sound levels while high-SR fibers do not. Kim *et al.* (1991) have similarly shown that a neural response profile based upon rate response from a population of high-SR fibers loses its sharpness for a 1000-Hz tone at high levels, while the population of low-SR fibers maintains a sharp pattern. In contrast, Kim *et al.* showed that both the high-SR and low-SR neural response profiles maintain a sharp pattern even at high signal levels for a 5000-Hz tone. In particular, at 5000 Hz, the high-SR neurons show a sharp apical edge for the pattern across a wide range of signal levels.

In the first experiment described in this paper, we measured frequency discrimination of tone pairs, each member of the pair preceded by a forward masker presented 100 ms prior to the tone onset. Test frequencies were 1000 and 6000 Hz, to investigate the effects of selectively adapting low-SR fibers in frequency regions where temporal coding may and may not be important. Viewed in a straightforward manner, we were interested in determining if the effects of an adapting tone, one that does not alter a subject's sensitivity threshold, will have an effect upon the suprathreshold task of frequency discrimination. If not, such a result implies that there are fundamental differences between the way that intensity discrimination and frequency discrimination tasks are performed by a listener. At a more speculative level, since an adapting stimulus presented 100 ms before the test signal has been shown to lead to a differential recovery of the rate responses of low- and high-SR signals (Relkin and Doucet, 1991), this experiment would seem to offer an opportunity to investigate the role of the rate response of low-SR fibers in frequency discrimination.

A second experiment is also described, in which frequency discrimination of a tone pair, each followed by a backward masker, was investigated. This experiment was suggested following the recent report by Plack and Viemeister (1992b), that demonstrated that a midlevel elevation of intensity difference limens, similar in shape to the midlevel "hump" in forward-masked intensity discrimination described above, was obtained when the test stimuli were followed by a narrow-band-noise backward masker. Such a midlevel "hump" due to backward masking should not be the result of selective adaptation of certain auditory-nerve fibers; instead, a more central, or even cognitive, mechanism for the elevation of difference limens is indicated. It is of interest, then, to determine the degree to which forward- and backward-masked "humps" in discrimination experiments are related.

Massaro (1975) reported that a pure-tone backward masker presented up to 240 ms following a test stimulus produced a reduction in the percent correct obtained in a 2AFC frequency discrimination task. The masker frequency was similar to that of the test stimuli and both masker and test signals were presented at the same level (81 dB SPL). This effect was observed for signal-masker intervals from 0 to 240 ms, with the greatest reductions in performance occurring for shorter signal-masker intervals. Massaro attributed this effect to an interference with subjects' "auditory storage" memory. In contrast, Yost *et al.* (1976) found no effect of forward or backward maskers upon frequency discrimination when both the masker and signal were presented at 70 dB SPL using masker-signal intervals of 5 or 100 ms.

In a second experiment, we further examined this effect in a frequency discrimination task for backward-masked conditions. The Massaro (1975) data provides evidence that under some conditions a backward masker can have an effect upon frequency discrimination; it was of interest to determine the form of the frequency difference limen elevation obtained for the specific masking conditions used in our experiments. In the present experiments, we use the same masking conditions used by Zeng *et al.* (1991), Zeng and Turner (1992), and Plack and Viemeister (1992a,b) in their studies of intensity discrimination. Of even greater interest however, is the question of whether the similar "humps"

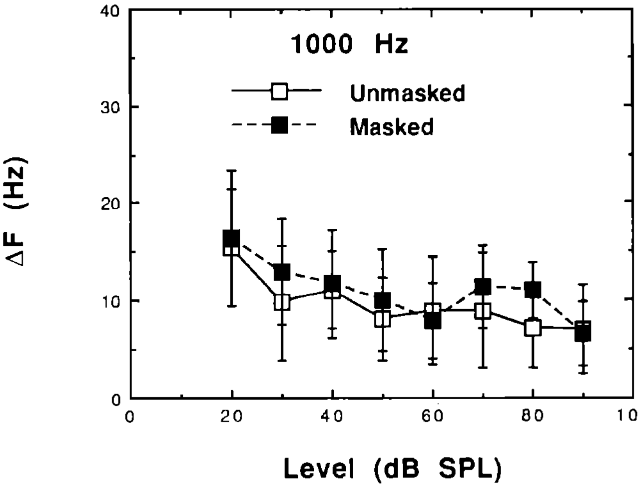

FIG. 1. Plot of the 1000-Hz frequency difference limens as a function of signal level for both the unmasked and narrow-band forward-masked conditions. Data points represent the mean of five normal-hearing listeners. Vertical bars indicate the standard deviation across the five listeners.

observed in intensity discrimination for both forward and backward masking, exist for both forward- and backward-masked conditions in frequency discrimination. If both forward and backward maskers produce the same effect for frequency discrimination, it is more likely that the elevation of the intensity difference limen originally observed in forward masking by Zeng *et al.* (1991) is not specifically related to auditory-nerve adaptation, but rather is a more general cognitive effect of adding additional stimuli to a discrimination task (e.g., Leek and Watson, 1988). On the other hand, if both maskers do not produce the same effect for frequency discrimination, this suggests that the effects of forward and backward masking are not related. Lutfi (1992) has shown that the final stimulus in a sequence presented to a subject has a uniquely disruptive effect upon intensity or frequency discrimination for a prior tone embedded in the sequence. Adding backward maskers to a discrimination experiment essentially adds a final interfering stimulus to the task, whereas in the forward-masked condition, the final stimulus is one of the test signals to be attended to.

I. EXPERIMENT 1: FORWARD-MASKED FREQUENCY DISCRIMINATION

A. Methods

1. Stimuli

Test signals were 25-ms (specified as the duration between the 0-voltage points) pure tones at either 1000 or 6000 Hz. Rise and fall times were 3-ms linear ramps. These signals were digitally generated by a Mac IIx computer in conjunction with a DigiDesign, 16-bit, digital-to-analog converter. The sampling rate was 44.1 kHz and signals were low-pass filtered at 20 kHz. Frequency difference limens were obtained at 10-dB steps for signal levels ranging from 20 to 90 dB SPL at 1000 Hz and from 20 to 80 dB SPL at 6000 Hz. The forward maskers were either a narrow band of noise centered at the test frequency (900–1100 Hz or 5600–6400 Hz) or in some cases, a wideband noise (low pass at 12 000 Hz). The noise maskers were 102 ms in duration, including 2-ms raised-cosine ramps. The maskers were generated by an analog random noise generator (MDF model 8156); narrow-band noises were bandpass filtered with rejection slopes of 90 dB/oct (Kemo model VBF 8). All signals were presented via Beyer DT-48 A.0 headphones and signal levels are expressed as the levels developed in an NBS-9A coupler.

The narrow-band maskers were presented at 90 dB SPL, while the wideband maskers were 100 dB SPL. In the forward-masked conditions, the masker preceded the test signal by 100 ms (masker offset to signal onset). Under these conditions, there was no threshold shift for the detection of a 25-ms test tone at the signal frequency. It should be noted that the masker and signal characteristics in the 1000-Hz narrow-band masker condition were identical to those employed by Zeng *et al.* (1991) with the exception that in the Zeng *et al.* study an increment in intensity was added to the signal in one listening interval whereas in the present study, an increment in signal frequency was added to one interval. An unmasked, control condition was also run at each test frequency and signal level.

2. Procedures

A two-interval two-alternative forced-choice listening paradigm (2IFC) was employed for the measurement of frequency discrimination. A silent interval of 500 ms was inserted between the two listening intervals of each trial. The subject responded by pressing a button corresponding to the interval containing the higher frequency tone. The correct answer was indicated via a small light following each trial. The stimuli for the following trial began 2200 ms after the subject's response.

A two-down, one-up adaptive tracking procedure controlled the frequency differences presented in an experimental run. This procedure tracks the 71%-correct point on the psychometric function (Levitt, 1971). For the 1000-Hz frequency discrimination experiment, the step size was 1 Hz, for 6000 Hz, the step size was 2 Hz. The procedure continued until 14 reversals were obtained. The frequency difference limen for each run was calculated as the mean of the final ten reversals. Subjects were run until performance was asymptotic and stable in each condition (minimum of six runs per condition). The final value for each data point for an individual subject was taken as the mean of the final six runs. A similar 2IFC procedure was employed for the measurement of detection thresholds for the 25-ms tonal signals under conditions of forward masking and in quiet. Under the conditions of 100-ms masker-signal interval and 90-dB narrow-band maskers, no threshold shift was observed (mean threshold shifts of 0.4 and 0.5 dB for 1000 and 6000 Hz, respectively). The same result was obtained for the wideband maskers presented at 100 dB SPL (threshold shifts of − 1.8 and 1.6 dB for 1000 and 6000 Hz, respectively). Five normal-hearing subjects participated in the narrow-band-masked conditions, a single normal-hearing subject completed the wideband-masked conditions.

B. Results

Figure 1 displays the frequency difference limens at 1000 Hz in the narrow-band masked condition as a function of signal level. Also plotted are the difference limens for the unmasked control condition. The individual data points represent mean values of the five normal-hearing listeners. The vertical bars indicate plus and minus one standard deviation across the five subjects in each condition at each signal level. There is essentially no difference between the frequency difference limens obtained under the masked and unmasked conditions in the group mean data; this same result was observed in each of the individual subjects' data. In particular, no midlevel elevation in the frequency difference limen was noted under forward masking, in contrast with the effect previously reported for intensity discrimination experiments.

Figure 2 displays the group mean frequency difference limens at 6000 Hz obtained from the same five normal-hearing listeners in the narrow-band masker condition. Both the unmasked control condition as well as the forward-masked condition are shown. The vertical bars indicate plus and minus one standard deviation across the five listeners. No data point is shown for the forward-masked frequency difference

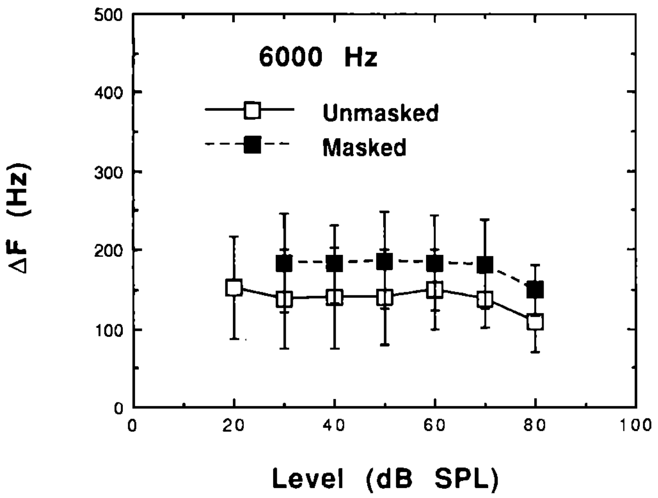

FIG. 2. Plot of the 6000-Hz frequency difference limens as a function of signal level for both the unmasked and narrow-band forward-masked conditions. Data points represent the mean of five normal-hearing listeners. Vertical bars indicate the standard deviation across the five listeners.

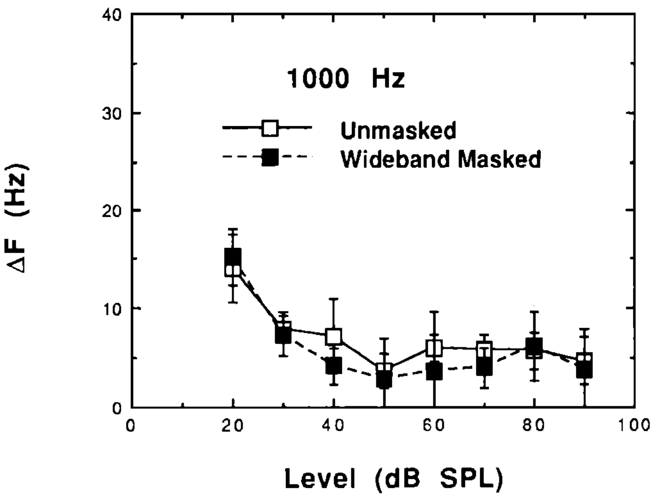

FIG. 3. Plot of the 1000-Hz frequency difference limens as function of signal level for both the unmasked and wideband forward-masked conditions. Data points are the results from one normal-hearing listener. Vertical bars indicate the standard deviation across the final six runs in each condition for the listener.

limens at 20 dB SPL because only three of the five subjects were able to reliably judge the pitch of the signal separately from the narrow-band masker when the signal was presented at such a low sensation level. However, the mean value for the remaining three subjects under these conditions was 230 Hz, which is similar to the other values on this function. The difference limens as a function of signal level under the forward-masked condition were parallel to, but slightly higher than, those of the control condition. As was the case for the 1000-Hz tones, no specific elevation of the difference limen at midlevels under the forward-masked condition is observed. Several listeners reported that the forward masked frequency discrimination task at 6000 Hz was more difficult at all signal levels than at 1000 Hz, due to the tonelike quality of the high-frequency narrow-band masker, which confused the listeners as to which portion of the masker-signal complex to judge in terms of pitch.

A wideband forward masker was then used in the remaining forward-masking-experiments. One rationale was to eliminate the confusing pitch cues that were present in the narrow-band maskers. In addition, because the results of the narrow-band masker experiments were negative, in that no midlevel elevation of frequency discrimination was noted in the forward-masked condition, the possibility existed that selectively adapting the rate response of low-SR fibers in a narrow frequency region surrounding the test tone was insufficient to disrupt accurate frequency coding. If the code for frequency involves looking at the entire neural response profile, rather than just the "peak" or the "edge" of the pattern, as suggested by the work of Emmerich *et al.* (1983), then adapting only a small group of low-SR fibers with the narrow-band maskers may not have been effective.

Figure 3 shows the results of the wideband masker condition for the single subject at 1000 Hz. Vertical bars indicate the standard deviation across runs for this subject. No midlevel elevation in the difference limen is observed. Figure 4 shows the results from the wideband masker at 6000 Hz. Again, no midlevel elevation is observed. In addition, the forward-masked frequency difference limens at 6000 Hz are no longer elevated with respect to the control condition, as was observed in the narrow-band masker case at 6000 Hz, indicating that the pitch confusion was successfully removed.

II. EXPERIMENT 2: BACKWARD-MASKED FREQUENCY DISCRIMINATION

A. Methods and procedures

We obtained frequency difference limens for short 1000-Hz tones under conditions of no masker and under condi-

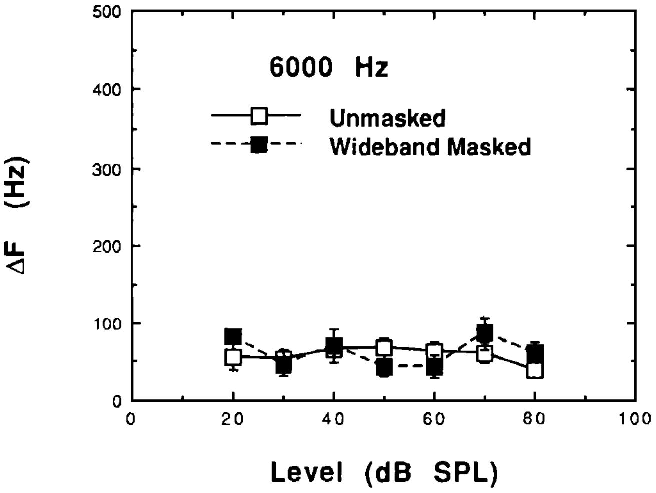

FIG. 4. Plot of the 6000-Hz frequency difference limens as function of signal level for both the unmasked and wideband forward-masked conditions. Data points are the results from one normal-hearing listener. Vertical bars indicate the standard deviation across the final six runs in each condition for the listener.

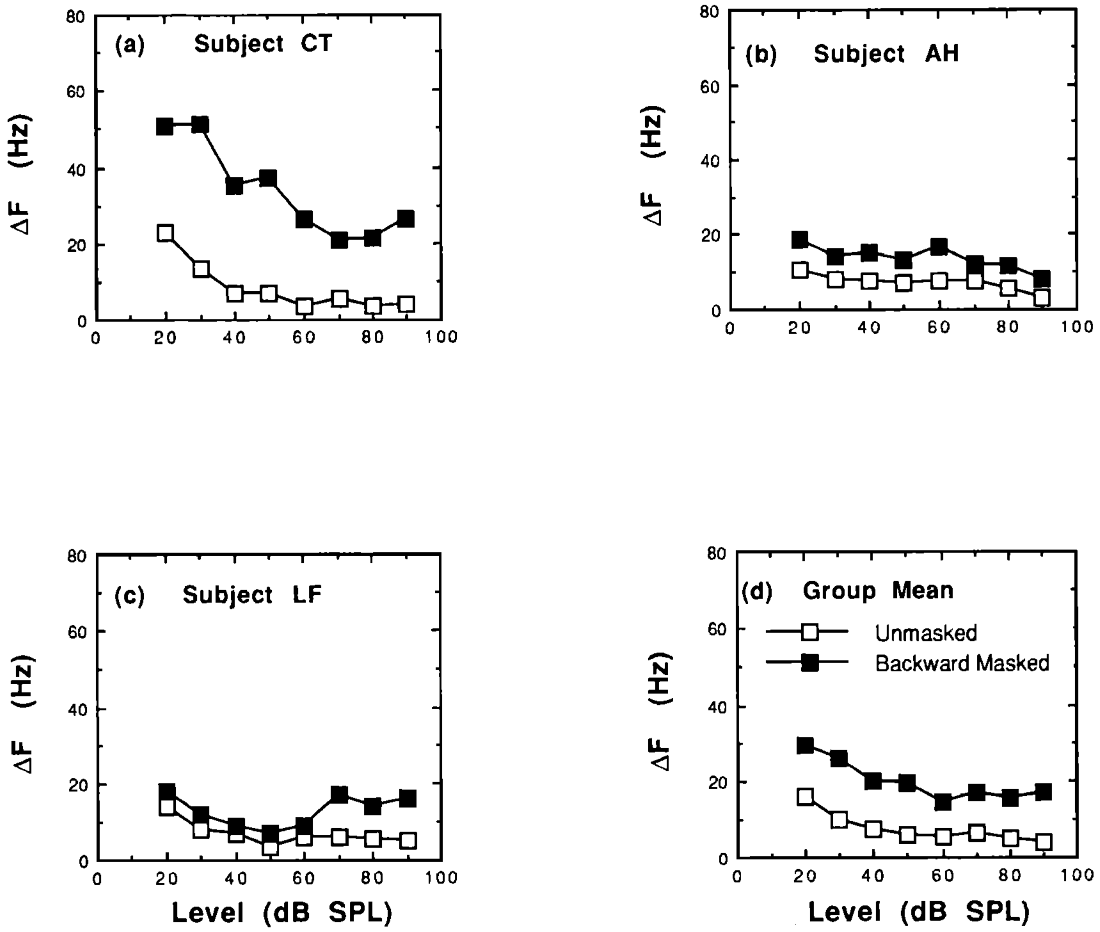

FIG. 5. Frequency difference limens at 1000 Hz for both the unmasked and narrow-band backward-masked conditions. Individual subjects' data are shown in (a)–(c). In (d), data points represent the means of the three normal-hearing listeners.

tions of backward masking by a narrow-band noise centered at 1000 Hz. The methods and stimuli for this experiment were identical to that described for the 1000-Hz narrow-band-masked frequency discrimination experiment described previously, with the exception that the masker was presented 100 ms after each member of the discrimination pair in the 2IFC task. Three normal-hearing subjects participated in the experiment, two of these subjects were also participants in experiment 1, the third was an experienced listener new to frequency discrimination experiments. In these subjects, the backward masker produced no threshold shift for a test tone at 1000 Hz (mean threshold shift of 0.7 dB).

B. Results

The four panels of Fig. 5 display the results of the backward-masked frequency discrimination experiments. Although the results of the three listeners showed the same trend, the magnitude of the effect of the backward masker differed among them. Therefore, (a)–(c) are provided showing the results of the three individual subjects, and (d) shows the group mean results. For subject CT [(a)], the backward masker produced a large elevation in frequency difference limens, while for the other two listeners [(b) and (c)], the elevation in difference limens was smaller. However, for all three subjects, the elevation in frequency difference limens was consistent and occurred for all signal levels as shown in the group mean data [(d)].

C. Discussion

The most important findings of this study are the differences between the effects of forward and backward masking upon frequency and intensity discrimination. Both a forward- and backward-masking intense narrow-band stimulus, separated from the signal by 100 ms, have previously been shown to affect the midlevel intensity coding of a tone. In contrast, the present experiments demonstrate that for frequency discrimination, neither a wide nor narrow-band forward masker affects the frequency coding of a tone (when pitch confusions are eliminated). However, the backward masker does produce an elevation in the frequency difference limen.

The reason for the forward-masking effect in intensity discrimination is not firmly established. The possibility exists that the relevant site of action is not peripheral as suggested by Zeng *et al.* (1991), but rather a more central or cognitive process, and therefore unrelated to the differential adaptation of low- and high-SR fibers. In particular, this possibility was suggested by the finding of Plack and Viemeister (1992b) that a backward masker produced a similar midlevel elevation of the difference limen. Our finding that only a backward masker and not a forward masker produces an elevation in frequency discrimination suggests that the effects of forward and backward masking upon discrimination tasks are unrelated. However, an elevation in frequency difference limens due to backward masking was observed in this study and was approximately equal for all signal levels. Plack and Viemeister (1992b) showed that the backward masker in their intensity discrimination task produced not only a constant elevation of the difference limen across all signal levels, but also an additional large elevation of the difference limen seen only for midlevel signals. Thus the effect of a backward masker upon discrimination tasks may consist of two components; first a general elevation of difference limens for both frequency and intensity tasks, and second, a midlevel elevation of the difference limen observed only for intensity discrimination.

The specific origins of these effects remain speculative at the present time, although a cognitive effect of either forward or backward maskers in discrimination experiments is certainly not ruled out. Recent data from our laboratory (Turner *et al.*, 1992) show that the effect of forward or backward maskers upon intensity discrimination depends upon the method used for obtaining the difference limens.

It is also not entirely straightforward how to interpret the lack of effect from a forward masker on frequency discrimination, even if one accepts the Zeng *et al.* (1991) hypothesis that the roles of differentially adapted high- and low-SR fibers are involved in forward-masked intensity discrimination. On one hand, it could be argued that the adaptation resulting from the 90-dB SPL forward masker employed here was not large enough to decrease the contribution of the low-SR fibers to the frequency discrimination task, but was sufficient to disrupt intensity coding. However, since both tasks are difference limen experiments, in which the smallest perceptible difference between two stimuli is determined, any disruption in coding of the relevant portion of the excitation pattern should result in a decrement in performance. Such a decrement in performance was not observed in this study, whereas such a decrement has been observed for intensity discrimination.

The absence of an effect of the forward masker upon frequency discrimination under the same stimulus conditions as those employed in previous forward-masked intensity discrimination experiments indicates that the two tasks are performed by the auditory system in fundamentally different manners. The results of the present frequency discrimination study, along with previous intensity discrimination studies (Zeng *et al.*, 1991; Zeng and Turner, 1992; Plack and Viemeister, 1992), would seem to contradict the general hypothesis originally put forth by Zwicker (1956) that both intensity and frequency are similarly encoded by the auditory nerve representation of the "excitation pattern" along the cochlea. Additional evidence against such a common mechanism has been presented by Moore (1992). The finding that a backward masker produces both a "midlevel hump" in addition to a general elevation in difference limens for intensity discrimination (Plack and Viemeister, 1992b), whereas the present study's finding that only the parallel elevation is observed for backward-masked frequency discrimination also suggests that the two discrimination tasks differ in mechanism.

It is known that the adapting stimuli used in these experiments selectively disrupts the rate response of low-SR fibers in chinchillas, elevating neural thresholds (Relkin and Doucet, 1991). The present results therefore suggest a role for phase-locking in the encoding of frequency at 1000 Hz, in view of the reports by Schofner and Sachs (1986) and Kim *et al.* (1991) that high-SR auditory-nerve fiber rate profiles for low frequencies are degraded in sharpness at higher signal levels. Selectively adapting the low-SR fibers in this experiment produced no elevation of the difference limen. Goldstein (1980) modeled frequency discrimination using rate responses from low- and high-SR fibers and concluded that if rate responses were important for behavioral performance, low-SR fibers are necessary for performance at high levels. At 6000 Hz, a role for phase-locking is not as strongly supported. First, as mentioned previously, the accuracy with which fibers can phase lock to a 6000-Hz tone is rather poor to begin with. Second, Kim *et al.*'s data suggest that low-SR fibers may not be necessary in coding high frequencies via a rate-place code. The "excitation pattern" for high-frequency stimuli transmitted by a population of high-SR fibers remains sharp even at high signal levels.

The present results then offer support to a dual-coding model of frequency discrimination, in which phase locking is used at lower frequencies and rate-place codes at higher frequencies. A similar mechanism has been proposed by others (e.g., Moore, 1973, 1989). However, the role of phase locking at even 6000 Hz cannot be completely ruled out, as the large frequency difference limens obtained at 6000 Hz in this experiment and others may still be compatible with the degraded phase locking at that frequency (Goldstein and Srulovicz, 1977).

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