

Forward-masked monaural and interaural intensity discrimination (L)

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Intensity-discrimination thresholds were measured for a 25-ms, 6-kHz pure tone for pedestal levels from 40 to 90 dB sound pressure level (SPL) with and without a forward masker (100-ms narrowband Gaussian noise, $N_0=70$ dB). When the masker was present, the masker and probe were separated by 100 ms of silence. Unmasked and masked thresholds were measured in a two-interval monaural procedure and, separately, in a single-interval interaural procedure in which the pedestal and incremented pedestals were presented simultaneously to opposite ears. While the monaural thresholds were elevated markedly by the forward masker for mid-level pedestals, interaural thresholds were nearly unaffected by the masker across pedestal levels. The results argue against the notion that the monaural elevation in forward-masked thresholds is due to degraded encoding of intensity information at early stages of auditory processing. © 2007 Acoustical Society of America. [DOI: 10.1121/1.2756167]

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I. INTRODUCTION

Zeng *et al.* (1991) reported that intensity-discrimination thresholds (or just-noticeable differences, JNDs) could be markedly elevated for mid-level standards when thresholds were measured in the presence of an intense forward masker. Intensity-discrimination thresholds for low- and high-level standards were relatively unaffected by the forward masker. Zeng *et al.* attributed this “mid-level hump” to differences between auditory nerve fibers with high and low spontaneous firing rates (SRs) in terms of their dynamic ranges and their recovery times from prior stimulation. Auditory nerve fibers can be categorized into two populations on the basis of their spontaneous rates (Liberman, 1978). Low-SR auditory nerve fibers have higher thresholds than high-SR fibers for a criterion increase in firing rate (Liberman, 1978). In addition, low-SR fibers have a slower recovery rate from prior stimulation than high-SR fibers (Relkin and Doucet, 1991). According to Zeng *et al.* (1991), for their mid-level standards, the high-SR, low-threshold fibers were saturated while the low-SR fibers, which would ordinarily encode the intensity of a mid-level stimulus, had not recovered from the prior stimulation of the masker. This resulted in degraded encoding of the intensity of mid-level stimuli across the two populations of fibers, which in turn produced elevated JNDs.

A number of studies have called into question the interpretation that the mid-level hump in forward-masked intensity discrimination can be attributed to degraded intensity information in two populations of auditory nerve fibers. For example, Plack and Viemeister (1992) found that a comparable mid-level hump in intensity-discrimination thresholds could be produced by a masker that followed the probe to be discriminated (a backward masker), which could not possibly affect the representation of the probe at the level of the

auditory nerve. However, Plack and Viemeister acknowledge that it is possible that the forward-masked and backward-masked results may be attributable to different mechanisms and that the explanation for the forward-masked results proposed by Zeng *et al.* (1991) may be tenable. Schlauch *et al.* (1997) found that a 10-ms forward masker produced a greater elevation in intensity discrimination thresholds than a 100-ms masker for a 10-ms probe. An explanation of the mid-level hump that depends on adaptation is inconsistent with the fact that auditory nerve fibers recover more slowly from adaptation with increasing duration of the adapting stimulus. Instead, Schlauch *et al.* proposed that the elevation in thresholds results from confusion caused by perceptual similarity of the masker and probe, e.g., when the masker and probe have similar durations. In support of this idea, Schlauch *et al.* also found that greater masking occurred when the masker and probe had similar spectra. While these data seem to argue against the auditory nerve as the source of mechanisms that produce the mid-level hump, Schlauch *et al.* note that their results do not rule out the cochlear nucleus as the site of origin of the effect, a possibility that was suggested by Zeng and Shannon (1995).

The present letter examines the notion that the mid-level hump in forward-masked intensity discrimination is attributable to effects occurring at levels of processing that precede the level at which binaural interaction occurs (superior olive). To this end, forward-masked intensity-discrimination thresholds were measured in a two-interval monaural task and a single-interval interaural task. Stellmack *et al.* (2004) argued that the two tasks present comparable amounts of information in each trial and they showed that monaural and interaural thresholds exhibit comparable Weber’s law behavior that is attributable to mechanisms at the auditory periphery that precede binaural interaction. In the present experiment, if a degradation of mid-level intensity-discrimination thresholds is not seen in the interaural intensity-

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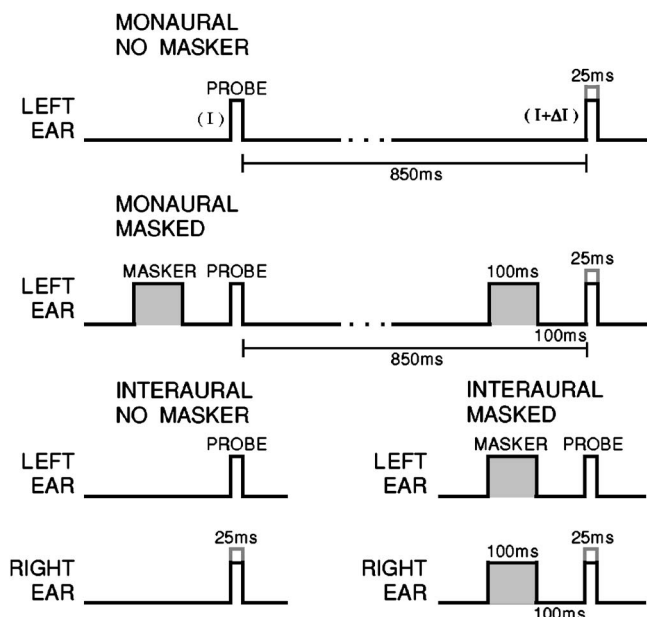


FIG. 1. A schematic illustration of the stimuli in the two-interval monaural and single-interval interaural conditions. In the two-interval monaural condition, the increment to be detected on the probe (ΔI) was presented randomly in either the first or second interval of each trial. In the single-interval interaural condition, the intensity increment was presented in either the left-ear or right-ear probe of each trial.

discrimination task, it would seem to rule out the auditory nerve and the cochlear nucleus as the sites of origin of the monaural effect.

II. METHODS

A. Stimuli

The timing of the stimuli in the two-interval monaural condition and single-interval interaural condition is illustrated in Fig. 1. The masker and probe levels and durations were similar to those of Plack and Viemeister (1992), as those parameters had been shown to produce a very large mid-level hump in monaural forward-masked intensity-discrimination thresholds. The probe (the stimulus whose intensity was to be discriminated) was a 6-kHz, 25-ms pure tone presented at a fixed (sine) starting phase. The forward masker was a narrowband of Gaussian noise (5.9–6.1 kHz) presented at a spectrum level of 70 dB and 100 ms in duration. Both the probe and masker were windowed with 5-ms raised-cosine on-off ramps.

Monaural and interaural intensity-discrimination thresholds were measured both with and without the forward masker. In the two-interval monaural task, the time between the offset of the probe in the first interval and the onset of the probe in the second interval was held constant (850 ms) across the masked and unmasked conditions as was done by Schlauch *et al.* (1997) in order to place similar demands on short-term memory across conditions. In the forward-masked conditions, the time between the offset of the masker and onset of the probe was 100 ms. Thus, the time between the offset of the probe in the first interval and the onset of the masker in the second interval was 650 ms. In the monaural conditions, the forward masker was identical in the two in-

tervals of a trial but an independent sample of Gaussian noise was generated for each trial. The listener's task in the monaural conditions was to select the interval containing the probe plus increment. In the "masked" condition, the masker was presented only to the left ear. (A "monaural-with-diotic-masker" condition, in which the probe was presented to the left ear but the masker was presented to both ears, was added to the design later. This condition is discussed further in the Results and Discussion section.)

In the single-interval interaural intensity-discrimination conditions, the forward masker was either identical in both ears (diotic) or consisted of independent samples of noise in the two ears (dichotic). The maskers in the two ears, were gated on and off simultaneously as were the probes in the two ears. As in the monaural conditions, there was 100 ms of silence between the offset of the masker (when present) and the onset of the probe. In the interaural conditions, the listener's task was to select the ear to which the probe plus increment was presented. Given the differential effects of diotic and dichotic forward maskers in detection tasks (Kohlrausch and Fassel, 1997), it is conceivable that the different interaural configurations of the maskers (diotic or dichotic) might produce different amounts of masking in this intensity-discrimination task. However, it will be seen that no such differences were observed in the present data.

Monaural and interaural intensity-discrimination thresholds were measured for probe pedestal levels from 40 to 90 dB sound pressure level (SPL). The range was chosen based on detection thresholds for the probe (see Sec. II B below) to ensure that all probe pedestals were above detection threshold in the discrimination tasks.

All stimuli were generated digitally in MATLAB. For the maskers, a 1-s broadband noise signal was generated in the frequency domain by drawing amplitudes from a Rayleigh distribution and starting phases from a uniform distribution for all components within the desired frequency range. A time-domain signal was produced by applying an inverse fast Fourier transform to the resulting spectrum. The resulting noise wave form was truncated to the desired length and windowed with 5-ms raised-cosine on-off ramps. The digital signals were generated and converted to analog signals at a 44.1-kHz sampling rate using a PC equipped with a high-quality, 24-bit sound card (Echo Audio Gina). Stimuli were presented over Sony MDR-V6 stereo headphones to listeners seated in a sound-attenuating chamber.

B. Procedure

Prior to measuring intensity-discrimination thresholds, monaural detection thresholds were measured in each ear so that an appropriate range of probe pedestals could be determined for each listener to ensure that all probes were above detection threshold in the discrimination task. Detection thresholds were measured in a two-alternative forced-choice task and using a three-down, one-up adaptive procedure designed to estimate the 79.4 percent-correct point on the psychometric function (Levitt, 1971). The step size was set to 2 dB until four reversals occurred and then the step size was reduced to 1 dB. A block of trials was terminated after 12

reversals and the probe levels at the final eight reversals were averaged to estimate threshold. Four such thresholds were measured for the probe in each ear, with and without the forward masker.

Intensity-discrimination thresholds were measured using the same three-down, one-up adaptive procedure as in the detection conditions. The intensity of the probe plus increment was adjusted in units of dB [$10 \log(\Delta I/I)$]. The intensity-discrimination procedure used the same step sizes and termination rule as in the detection conditions. The different conditions were run in the following order: monaural no masker, monaural masked, interaural no masker, interaural diotic/dichotic masker. Within each condition, each listener performed two adaptive runs at each probe pedestal level (with the probe pedestal levels presented in a random order) followed by two additional runs at each pedestal level. Blocks of trials in the interaural diotic/dichotic masker conditions were interleaved. Thus, each listener performed four adaptive runs in each condition, yielding four threshold estimates. The four threshold estimates were averaged to produce the final threshold estimate for each condition.

Each block of trials was initiated by the listener. On each trial, a “ready” light flashed on the computer screen for 250 ms followed by a 100-ms pause after which a trial was presented. The intervals were marked visually by lights on the computer monitor. Listeners entered their responses on the computer keyboard at which time the correct response was indicated on the screen. Listeners were run in 2-h sessions, during which approximately 10–12 blocks of trials were run, until all stimulus conditions were completed.

C. Subjects

The four listeners consisted of the first author and third author and two female undergraduate students from the University of Minnesota who were paid to participate in the study. All listeners had pure-tone thresholds of 15 dB hearing level (HL) or better at octave frequencies from 250–8000 Hz. All listeners had performed in intensity-discrimination experiments previously, therefore only a small number of practice trials were presented to familiarize the listeners with the stimuli prior to data collection.

III. RESULTS AND DISCUSSION

The general pattern of thresholds was similar for all listeners, therefore the thresholds were averaged across listeners and are shown in Fig. 2. In the upper panels of Fig. 2, intensity-discrimination thresholds are plotted in units of $10 \log(\Delta I/I)$ as a function of the probe pedestal level. Mean monaural and interaural thresholds are plotted in separate panels. The lower panels show the amount of masking, computed as the difference between the masked and unmasked thresholds.

Comparing the monaural and interaural unmasked thresholds in Fig. 2 (open symbols), the interaural thresholds show the same pattern across probe pedestal level as the monaural thresholds, but the interaural thresholds are a few

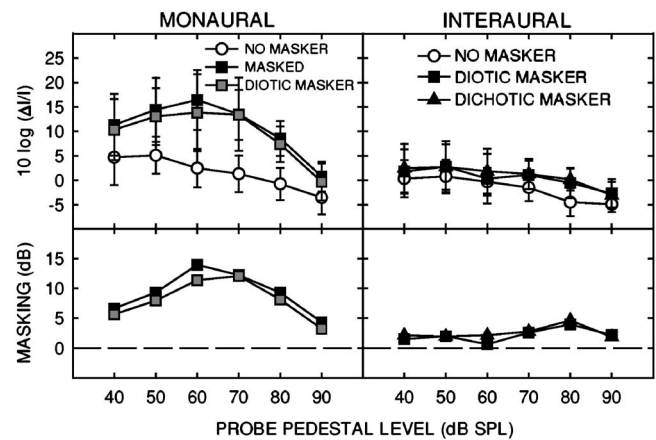


FIG. 2. Upper panels: Intensity-discrimination thresholds in dB [$10 \log(\Delta I/I)$] averaged across four listeners as a function of probe pedestal level in the monaural (left column) and interaural (right column) conditions. Open symbols show unmasked thresholds and filled symbols show masked thresholds, as indicated in the legend. Error bars represent \pm one standard deviation. Lower panels: Mean amount of masking in dB, computed as the difference between the masked and unmasked thresholds in the corresponding upper panels.

dB better than the monaural. This is consistent with the results reported by [Stellmack *et al.* \(2004\)](#) for unmasked monaural and interaural intensity discrimination.

In the monaural conditions, mean thresholds were higher when the forward masker was present relative to the unmasked conditions. In addition, the largest amount of masking (difference between the masked and unmasked threshold) occurred at an intermediate probe pedestal level (a mid-level hump). There were individual differences in terms of the probe pedestal level at which the greatest masking occurred, but for all listeners the greatest masking occurred at an intermediate pedestal level, such that all individual data exhibited a mid-level hump.

The mean monaural masked thresholds show the mid-level hump that has been reported in other studies (e.g., [Plack and Viemeister, 1992](#); [Schlauch *et al.*, 1997](#)). The amount of masking across probe level in the present study is very similar to that of [Plack and Viemeister \(1992\)](#) for comparable stimulus parameters. A one-way repeated-measures analysis of variance (ANOVA) performed on the amount of masking in the monaural condition (lower left panel of Fig. 2) confirms that the effect of probe pedestal level was statistically significant [$F(5, 15) = 1.29, p = .001$].

In contrast, the present interaural thresholds show no effect of either the diotic or dichotic masker across pedestal levels. A two-way repeated-measures ANOVA performed on the interaural data (with the factors masker configuration and probe pedestal level) confirmed that the main effect of the masker configuration (unmasked/diotic masker/dichotic masker) was not significant [$F(2, 6) = 4.88, p = .055$]. If the monaural mid-level hump was due to degraded intensity information at the level of the auditory nerve or cochlear nucleus, the interaural thresholds should exhibit a similar mid-level hump, but they do not. These results indicate that encoding of intensity information appears to remain nearly unaffected by forward masking across probe level at least to the level of the superior olive, the first opportunity for bin-aural interaction.

It is interesting that in the interaural condition the thresholds were similar with and without the masker. Assuming that the listeners were using a laterality cue to perform the task, the diotic masker might be expected to provide a strong centered reference. The listener could use this reference rather than a possibly unreliable “internal” reference to detect left-right deviations from a centered image. The similarity of the thresholds suggests that the masker was not used as a centering cue. This may be because the internal reference is sufficiently reliable to permit good performance: listeners may have a relatively noise-free representation of a centered image and do not need the reminder provided by the diotic masker.

The question remains as to the source of the mid-level hump in monaural intensity-discrimination thresholds. The idea that the effective levels or loudness of the masker and probe are combined, perhaps as a result of confusion due to perceptual similarity of the masker and probe (Schlauch *et al.*, 1997), remains a viable explanation. Perhaps the differences in perceived laterality that are introduced in the interaural condition permit the listener to perceptually segregate the masker and probe sufficiently to minimize the effects of the masker. In order to examine the effects of differential lateralization of the masker and probe, the masked monaural thresholds were measured again, but with the forward masker presented diotically (“monaural-with-diotic-masker”). All other stimulus parameters were the same as in the masked monaural conditions. In this case the masker is presumably lateralized in the center of the listener’s head while the probe is lateralized at the left ear.

The data from the monaural-with-diotic-masker conditions are plotted as gray squares in Fig. 2. If the absence of the mid-level hump in the original interaural conditions of the main experiment resulted from differential lateralization of the masker and probe, we might expect the mid-level hump to be eliminated in the monaural-with-diotic-masker conditions as well. However, it can be seen that thresholds were nearly identical to those in the purely monaural conditions (represented by the black squares). A difference between the monaural-with-diotic-masker and the interaural conditions is that in the former, although the masker and probe might be lateralized differentially, lateralization does not provide a cue to performing the intensity-discrimination task. The probe and incremented probe always will be lateralized at the same intracranial position and presumably the task must be performed on the basis of changes in the loudness of the probe. In the interaural condition, differential lateralization resulting from the incremented probe being presented to either the left or right ear provides a cue that would allow listeners to perform the task; that is, it is not necessary for the listener to discriminate loudness of the probe in the interaural task. Therefore, it is plausible that the forward masker interferes with some aspect of the perceived loudness of the probe, which will interfere with performance of the monaural task but not the interaural task.

How might the forward masker interfere with the perceived loudness of the probe? Plack and Viemeister (1992)

suggested a “referential coding” hypothesis, in which the masker degrades a “memory trace” for the probe, which interferes with the ability to make comparisons across temporally distinct intervals in both forward- and backward-masking situations. When a reference stimulus to which the probe can be compared is present within each interval, the system may switch to a “referential coding” mode, which does not require retention of a memory trace of the stimulus across intervals but rather encodes the stimulus on the basis of contextual relationships. Plack *et al.* (1995) showed that a fixed-level reference stimulus within each interval of a monaural forward- or backward-masked intensity-discrimination paradigm eliminates the mid-level hump. Presumably, the probe can be compared to the fixed-level reference in each interval, which facilitates encoding as a *change* in loudness within each interval. In the single-interval interaural task of the present experiment, the probe and incremented probe are presented simultaneously to opposite ears, which permits immediate comparison of the stimuli and removes any dependence on a representation in memory that might be degraded by the masker. Thus, the results of the present experiment are consistent with the referential coding hypothesis of Plack and Viemeister (1992). Although the source of the mid-level hump in monaural intensity-discrimination thresholds remains open to debate, the accumulating evidence, including that of the present letter, seems to indicate that it is not a result of processing that occurs at the auditory periphery.

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