The mid-level hump at 2 kHz[a)]

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Shortening the duration of a Gaussian-shaped 2-kHz tone-pip causes the intensity-difference limen (DL) to depart from the "near-miss to Weber's law" and swell into a mid-level hump [Nizami *et al.*, J. Acoust. Soc. Am. **110**, 2505–2515 (2001)]. For some subjects the size of this hump approaches or exceeds the size reported for longer tones under forward masking, suggesting that forward masking might make little difference to the DL for very brief probes. To test this hypothesis, DLs were determined over 30 to 90 dB SPL for a brief Gaussian-shaped 2-kHz tone-pip. DLs were obtained first without forward masking, then with the pip placed 10 or 100 ms after a 200-ms 2-kHz tone of 50 dB SPL, or 100 ms after a 200-ms 2-kHz tone of 70 dB SPL. DLs inflated significantly under all forward-masking conditions. DLs also enlarged under an 80 dB SPL forward masker at pip delays of 4, 10, 40, and 100 ms. The peaks of the humps obtained under forward masking clustered around a sensation level (SL) that was significantly lower than the average SL for the peaks of the humps obtained without forward masking. Overall, the results do not support the neuronal-recovery-rate model of Zeng *et al.* [Hear. Res. **55**, 223–230 (1991)], but are not incompatible with the Carlyon and Beveridge hypothesis [J. Acoust. Soc. Am. **93**, 2886–2895 (1993)] that nonsimultaneous maskers corrupt the memory trace evoked by the probe. © *2002 Acoustical Society of America.* [DOI: 10.1121/1.1485970]

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I. INTRODUCTION

The study of intensity-difference limens (DLs) has traditionally focused on stimuli of 50–500 ms duration, with which it has been shown (e.g., Jesteadt *et al.*, 1977) that the level-dependence of the DLs for pure tones follows the "near-miss to Weber's law" (McGill and Goldberg, 1968) and is uniform as a function of frequency. However, a mid-level hump in the DL, called the "severe departure from Weber's law," has been observed for tones of 6.5 or 8 kHz, having steady-state durations of 26 or 16 ms (Carlyon and Moore, 1984). A hump is also evident for 6-kHz tones of 25-ms steady-state duration (Plack and Viemeister, 1992a), for 6-kHz tones having 2-ms plateaus and 2-ms onset- and offset-ramps (Plack, 1998), and for 8- and 10-kHz tones of 500 ms duration (Florentine *et al.*, 1987). Data at lower frequencies are more limited and show a greatly reduced effect. Plack and Viemeister (1993) established DLs for pure tones of 1 or 4 kHz having plateau durations of 5 ms and 2-ms on- and off-ramps. Two of the three subjects show a marginal mid-level hump for the 1-kHz tone, perhaps a transition state between a mid-level hump, and the near-miss to Weber's law that was evident for the third subject. In contrast, all three subjects showed a clear mid-level rise for the 4-kHz tone.

A mid-level hump does, however, become evident for frequencies of less than 6 kHz, when the circumstances are right. In one circumstance, the level dependence of the DL shifts from the near-miss to Weber's law, to the mid-level hump, as the equivalent rectangular duration is shortened from 10 to 2.5 ms (Nizami *et al.*, 2001). In the second circumstance, a mid-level hump appears for 1-kHz tones having an equivalent rectangular duration D (see Baer *et al.*, 1999) of about 25 ms, if the pedestal or probe is preceded by a stimulus whose frequency spectrum contains the frequency of the pedestal (Zeng *et al.*, 1991; Zeng and Turner, 1992; Turner *et al.*, 1994; Plack *et al.*, 1995). Plack and Viemeister (1992b) and Plack *et al.* (1995) also found mid-level humps for 1-kHz tones under *backward* masking, a phenomenon whose relevance will be mentioned in Sec. VII.

Different models have been proposed for the mid-level hump seen for very brief Gaussian-shaped tone-pips (Nizami *et al.*, 2001), and for the mid-level hump seen for forward-masked stimuli (Zeng *et al.*, 1991; Carlyon and Beveridge, 1993), such that the effects of shortening a tone, and the effects of forward masking it, should be complementary. Thus the imposition of a forward masker should cause further inflation in the size of the mid-level hump seen by Nizami *et al.* (2001) for the non-forward-masked, very brief Gaussian-shaped 2-kHz tone-pip. If the DLs do not inflate, all the models will have to be reexamined. Thus it is important that DLs be obtained for the Nizami *et al.* tone-pip under forward masking. These measurements would also fill an information gap, as the literature contains no reports of DLs under forward (or backward) masking for any stimuli of $D < 10$ ms.

Careful DL measurements can also resolve a problem associated with the significance of mid-level humps. Inspec-

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tion of the literature reveals profound across-subject differences in whether or not a hump actually appears, what its magnitude is, and where its peak is located in dB SPL (see Zeng *et al.*, 1991; Plack and Viemeister, 1992a, b, 1993; Zeng and Turner, 1992; Carlyon and Beveridge, 1993). It is thus difficult to state definitively whether humps (or differences between humps) are genuine, no matter how self-evident they may appear, because the standard deviations associated with the within-subject averages of the forward-masked DLs or of the non-forward-masked DLs sometimes approach the size of the average DLs themselves. Also, the standard deviations associated with the across-subject average DLs, the data usually taken as the definitive summaries, can vary greatly from study to study. The standard deviations for the forward-masked DLs are less than 2 dB in Zeng *et al.* (1991), for example, but may exceed 4 dB in Turner *et al.* (1994), although both studies used identical stimulus conditions, similar methods, and show a similar hump, which reaches 6 dB. These differences must surely lead to differences in whether or not the effect is statistically significant.

Such problems can be mitigated by performing analyses of variance on the data, using the greatest number of subjects possible and the greatest number of probe levels possible, in order to improve statistical power. In the present series of experiments, the level-dependence of the DL was obtained for the discrimination of a 2-kHz tone-pip having an 8-ms Gaussian-shaped envelope that represents a D of 2.51 ms. This particular tone was chosen only because of its use in a previous paper. In that paper (Nizami *et al.*, 2001), a plot of the level-dependence of the DL shows a mid-level hump that is statistically significant, whose peak is the highest of those seen for the three tone durations for which group data are available (nine subjects, $D=1.25$, 2.51, 10.03). In the present work, the level-dependence of the DL was sampled at seven probe levels for nine subjects under three conditions of forward-masker level and postmasker delay. A fourth condition was provided by the non-forward-masked DLs. In the last experiment to be described here, three other subjects provided DLs at seven probe levels for an 80 dB SPL forward masker and four postmasker delays. The results are discussed within the framework of the models that were crafted to explain the effect of the forward masker on the level-dependence of the DL, viz., the model of Zeng *et al.* (1991) and the model of Carlyon and Beveridge (1993).

II. EXPERIMENTS 1, 3, AND 5: DIFFERENCE LIMENS WITHOUT FORWARD MASKING

Intensity-difference limens were obtained for the non-forward-masked tone-pip. This procedure was then repeated twice during the course of the study in order to check whether the subjects' experience of experiment 2 (forward-masked detection thresholds) or experiment 4 (forward-masked difference limens) influenced their non-forward-masked DLs. These checks were not employed in experiment 6, which had a different emphasis and used a different subject group.

A. Subjects

The nine listeners in experiments 1–5 were students from Creighton University, four male (average age=22) and five female (average age=19). All were paid volunteers, informed as to the method but not the expectations of the study. Subject DA had some previous experience as a laboratory listener. A different set of three subjects was employed in experiment 6 (as described later). All of the subjects' quiet thresholds were $\leqslant 20$ dB SPL at 500 Hz, 1 kHz, and 4 kHz in both the left and right ears for sinusoids having plateau durations of 200 ms.

B. Apparatus and stimuli

All stimuli were generated digitally at a sampling rate of 50 kHz using an array processor (TDT AP2). Signals were played through 16-bit digital-to-analog converters (TDT DD1). The pedestal or comparison tone was generated on channel 1 of the DD1, beginning at a positive-going zero crossing, while the increment was generated in quadrature phase on channel 2. The output of each channel was low-pass filtered at 10 kHz (TDT FT6) and attenuated (TDT PA4), then the outputs of the two channels were combined (TDT SM3) and presented to the listener though a headphone buffer (TDT HB6), a remote passive attenuator in the sound-proof chamber, and a Sennheiser HD 250 linear II headphone. Parallel use of multiple attenuators, summers, and headphone buffers made it possible to test as many as four listeners simultaneously. The subjects were thus assigned to groups, within which they remained.

All stimuli were presented to the left ear. To obtain quiet thresholds, only the increment channel was used. The tone-pips used as pedestals and increments were created by multiplying 2-kHz carriers by Gaussian envelopes that were smoothly reduced to zero amplitude at ± 4 standard deviations (σ), so that total stimulus duration was $8\sigma=8D/\sqrt{2\pi}\approx 3.19D$. The pip, whose total duration was 8 ms, can be thought of as consisting of a 4-ms half-Gaussian "up" ramp followed by a 4-ms half-Gaussian "down" ramp, with no steady-state portion. Stimulus levels are reported as dB SPL of the carrier.

C. Procedure

Estimates of the intensity DL were obtained using adaptive tracking of the level corresponding to 70.7% correct (Levitt, 1971). Each adaptive track consisted of 50 trials, each trial consisting of two successive observation intervals, both containing the pedestal. Within each block of trials, the increment was randomly distributed between the first and second intervals. Otherwise, the pedestal and the increment were of the same length, had the same Gaussian envelope, and appeared simultaneously whenever they occupied the same observation interval.

The subject's task was to identify which of the two listening intervals on each trial contained the more intense tone-pip. The starting level of the increment was typically set 15 dB higher than the level of the pedestal, allowing the subjects to easily identify the incremented tone on the first few trials. In each 50-trial block, 4-dB steps were followed by 2-dB steps after the fourth reversal. The reversal points for the 2-dB steps were averaged to obtain a threshold level of the increment. The DL was defined as $\mathrm{DL}=10\log_{10}[1+(\Delta I/I)]$ where $\Delta I/I=10^{\mathrm{Threshold}/10}/10^{\mathrm{Pedestal\ level}/10}$.

The subjects observed a 16-character message window at the top of a keypad small enough to be held in the hands. At the start of each trial, a small asterisk appeared in the message window to indicate impending stimuli. The first stimulus interval started after 400 ms and lasted 50 ms, with the stimuli starting at the beginning of the interval. There followed a 600-ms period of silence, followed by another 50-ms stimulus interval. The subjects then had all the time they desired to choose the interval that they believed contained the increment, indicated by pressing the button corresponding to the first interval or the button corresponding to the second interval. Typically, no more than a few seconds was required. There was then a feedback interval of 400 ms during which the message window displayed the identity of the interval, first or second, that had contained the increment. There then followed a 500-ms delay before the next trial. When more than one subject was tested at the same time, the feedback interval started at the time of the last response.

The subjects were given three blocks of 50 trials as training, for the 90 dB SPL pedestal, the 60 dB SPL pedestal, and the 30 dB SPL pedestal, in that order. Subjects showed proficiency at the task by the end of the third block. The subjects then completed two 50-trial blocks at each pedestal level, moving from 30 to 90 dB SPL in steps of 10 dB. Between the 40 and 50 dB SPL pedestal levels, two blocks were inserted to measure quiet threshold. The entire sequence was then repeated in reverse order, and then the whole cycle was repeated once more, providing a grand total of eight measurements of the DL at each pedestal level, and a grand total of eight measurements of the quiet threshold. Arithmetic averages and standard deviations were then computed.

D. Results

The subjects' absolute detection thresholds ranged from 16.9 to 35.3 dB SPL with an arithmetic average of 22.6 dB SPL. A subject's DLs were considered valid only when the subject's quiet threshold was more than 5 dB below the level of the pedestal, a criterion found elsewhere to be reliable (Nizami *et al.*, 2001). Subjects AL, KG, and NH had quiet thresholds of 28.2, 28.5, and 35.3 dB SPL, respectively, and so the DLs were not computed for AL, KG, and NH for the 30 dB SPL pedestal, and the DL was not computed for NH for the 40 dB SPL pedestal.

The size of the DL and its pattern of level-dependence were found to vary greatly across subjects, as noted earlier (Nizami *et al.*, 2001). Meaningful patterns can nonetheless be found. Figure 1 (upper panel) presents the across-subject arithmetic average DLs and their standard deviations. The level-dependence of the DL shows a clear mid-level hump whose peak is situated somewhere between 40 and 60 dB SPL. This pattern can also be seen not only in Nizami *et al.* (2001) but in Plack (1998, 6-kHz tone, $D\approx 3$ ms).

Experiment 1 was followed by experiment 2, forward-masked detection thresholds. Experiment 1 was therefore subsequently repeated as experiment 3 in order to examine whether the experience gained in experiment 2 affected the mid-level hump that was demonstrated for the non-forward-masked tone-pip in Nizami *et al.* (2001) and in experiment 1. Experiment 3 employed the same subjects, apparatus, stimuli, and procedure as used in experiment 1, with the

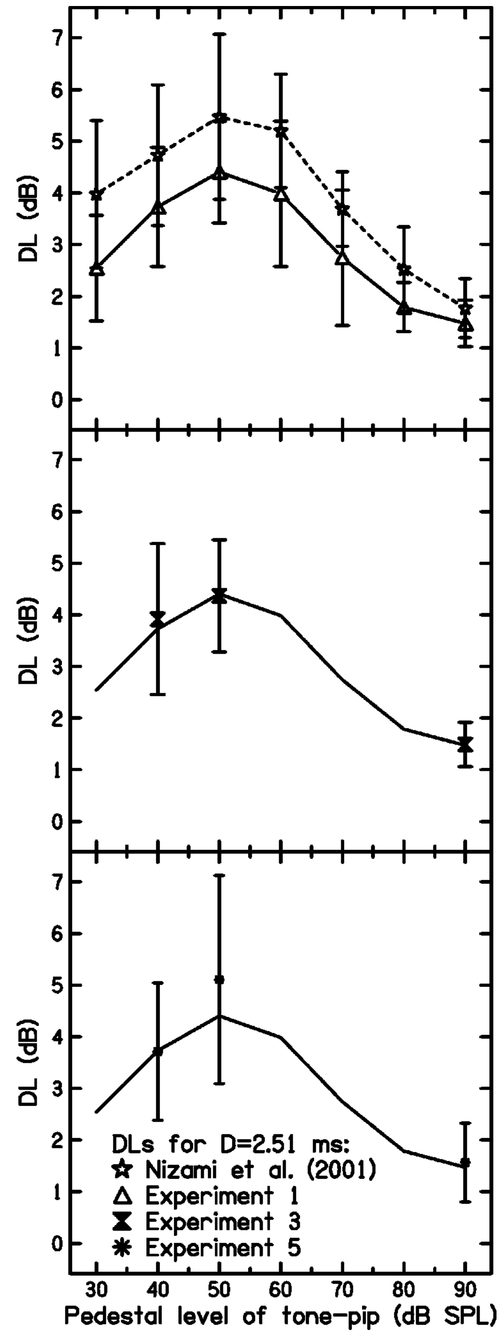

FIG. 1. Difference limens for a 2-kHz Gaussian-shaped tone-pip, averaged over nine subjects (data of experiments 1, 3, and 5). The error bars are standard deviations. Three of the subjects could not provide DLs at 30 dB SPL and one subject could not provide DLs at 40 dB SPL (see text). (Upper panel) Results of experiment 1. Provided for comparison are average DLs over nine other subjects for the same stimulus, from Nizami *et al.* (2001). (Middle panel) Results of experiment 3, the first replication of experiment 1 (same nine subjects). DLs were obtained only at 40, 50, and 90 dB SPL. The solid line connects the group DLs from the upper panel. (Lower panel) Results of experiment 5, the second replication of experiment 1 (same nine subjects). DLs were obtained only at 40, 50, and 90 dB SPL. The solid line connects the group DLs from the upper panel.

exception that, due to time constraints, the pedestal levels were restricted to 40, 50, and 90 dB SPL. The middle panel of Fig. 1 shows that there was no notable drift in the quiet thresholds, or in the DLs.

Experiment 3 was followed by experiment 4, forward-masked level discrimination. Experience gained in experiment 4 could conceivably help the subjects improve their discrimination for the non-forward-masked stimulus. Thus experiment 5 was done, in which non-forward-masked DLs were again obtained at 40, 50, and 90 dB SPL. Quiet thresholds were not obtained due to lack of time. The lower panel of Fig. 1 shows that the DLs at 40 and 90 dB SPL did not notably differ from those obtained in experiment 1. The group-average DLs at 50 dB SPL were worse than before and the standard deviations were larger, reflecting poorer performance by just two of the subjects, who produced DLs that were notably larger than before, probably due to inattention.

III. EXPERIMENT 2: FORWARD-MASKED DETECTION THRESHOLDS

In order to obtain meaningful forward-masked DLs, the level of the pedestal must be far enough above the forward-masked detection threshold that the tone-pip can be heard clearly on both intervals of any trial. In order to establish what pedestal levels could be heard under what circumstances of forward masking, forward-masked detection thresholds were obtained for the 2-kHz Gaussian-shaped tone with a variety of forward-masker levels and postmasker delays.

A. Subjects, apparatus, stimuli, and procedure

The apparatus, stimuli, and procedure were the same as used in experiments 1, 3, and 5, with the following exceptions. The 2-kHz Gaussian-shaped tone-pip was presented only on channel 2, previously used for the "increment." Channel 1 now contained only a 2-kHz forward masker. The forward masker was ramped up using the 4-ms-long rising portion of the same Gaussian envelope used for the probe. The forward masker was ramped down using the 4-ms-long falling portion of the Gaussian envelope used for the probe. In between, the profile was flat, with a duration of 200 ms, for a total forward-masker duration of 208 ms. The forward masker preceded the tone-pip by either 3, 10, 30, or 100 ms, as measured from the end of the forward masker to the start of the tone-pip. This gap was fixed for any given block of trials. Each trial consisted of two stimulus intervals each lasting 500 ms, with the stimuli starting at the beginning of each interval.

The subject's task was to identify which of the two listening intervals contained the tone-pip. The starting levels for the tone-pip were high enough to allow the subjects to choose unambiguously which interval contained the tone-pip for the first few trials. A complete set of detection thresholds was established as a function of forward-masker level at the 3-ms delay before proceeding on to the 10-ms delay, then to 30 ms, then to 100 ms. At the start of each new delay condition, the subjects were given three blocks of 50 trials as training, one for the 90 dB SPL forward masker, one for the

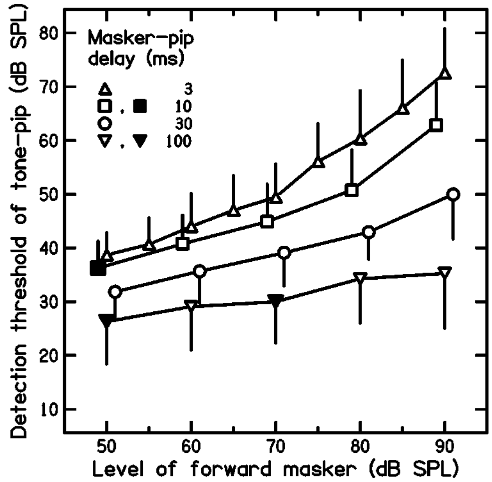

FIG. 2. Detection thresholds for a 2-kHz Gaussian-shaped tone-pip presented 3, 10, 30, or 100 ms following a 200-ms, 2-kHz tone whose level is indicated on the abscissa (experiment 2). These are the across-subject averages for the same nine subjects whose DLs appear in Fig. 1. The error bars are standard deviations. The thresholds representing the conditions chosen for experiment 4 are shown as solid symbols. For the sake of clarity, the plot for the 10-ms delay has been shifted to the left by 1 dB, and the plot for the 30-ms delay has been shifted to the right by 1 dB. The subjects' absolute detection thresholds for the Gaussian-shaped tone-pip ranged from 16.9 to 35.3 dB SPL with an arithmetic average of 22.6 dB SPL.

70 dB SPL forward masker, and one for the 50 dB SPL forward masker, in that order. Subjects showed proficiency by the end of the third block. For each delay condition, the subjects completed two 50-trial blocks at each forward-masker level, moving from 50 to 90 dB SPL in steps of 10 dB. Steps of 5 dB were used for the 3-ms delay. [Forward-masker levels of <50 dB SPL were not used because they have little effect on forward-masked DLs (Zeng and Turner, 1992), at least for 100-ms narrow-band maskers centered at 1 kHz.] Once the forward-masker level reached 90 dB SPL, the data-gathering process was repeated in reverse order, and then the whole cycle was repeated once more, providing a grand total of eight forward-masked pip-detection thresholds per subject at a given delay.

B. Results

For any given masker-probe delay, there was substantial variation between individuals in the shift in detection threshold caused by the forward masker's presence, and in the rates of increase of the detection thresholds with increase in forward-masker level (the slope of the growth-of-forward-masking curve). Nonetheless, common patterns emerged. Figure 2 presents the across-subject arithmetic averages and standard deviations. These curves resemble those for 4-kHz tone-pips of 10-ms total duration preceded at 0, 10, or 30 ms by 4-kHz 200-ms tones (Oxenham and Plack, 2000; Schairer *et al.*, 2001).

IV. EXPERIMENT 4: DIFFERENCE LIMENS UNDER FORWARD MASKING

The group-average detection thresholds in Fig. 2 were used to select combinations of forward-masker level and probe delay for which the tone pedestals should be clearly audible despite the presence of the forward masker. Delays of 10 and 100 ms were chosen in order to confirm the apparent rise of the DL as the masker-probe delay increases from 12.5 to 100 ms (Plack *et al.*, 1995). At the 10-ms delay only the lowest masker level tested, 50 dB SPL, appeared to guarantee that the subjects could provide real DLs at the lowest of the desired pedestal levels, 30 and 40 dB SPL. At the 100-ms delay, masker levels of 50 and 70 dB SPL were chosen.

A. Subjects, apparatus, stimuli, and procedure

The apparatus, stimuli, and procedure were the same as used in experiment 1, with the following exceptions. Channel 1 now contained both the 200-ms 2-kHz forward-masker described under "experiment 2," and the pedestal, both of which were presented at a fixed level in both intervals of every trial. Channel 2 contained the increment in quadrature phase, presented randomly in either interval 1 or interval 2. The forward masker preceded the pedestal (also in channel 1) and the increment (channel 2) by 3, 10, 30, or 100 ms, as measured from the end of the masker to the start of the tone-pip. This gap was fixed for any given block of trials. Each trial consisted of two stimulus intervals lasting 500 ms, with the stimuli starting at the beginning of each interval.

The subject's task was to identify which of the two listening intervals contained the more intense tone-pip following the forward masker. Starting levels for the increment were set high enough that the subjects could choose unambiguously which interval contained the incremented tone-pip, for the first few trials. A complete set of DLs was established as a function of pedestal level for the 70 dB SPL forward masker and the 100-ms delay. The DLs were then obtained for the 50 dB SPL forward masker and the 100-ms delay, followed by the 50 dB SPL forward masker and the 10-ms delay. At the start of each new masker-level/probe-delay condition, the subjects were given three blocks of 50 trials as training, one block for the 90 dB SPL pedestal, one block for the 60 dB SPL pedestal, and one block for the 30 dB SPL pedestal, in that order. For each masker-level/probe-delay condition, the subjects completed two 50-trial blocks at each pedestal level, moving from 30 to 90 dB SPL in steps of 10 dB. This process was then repeated in reverse order, and then the whole cycle was repeated once more, providing a grand total of eight measurements of the forward-masked difference limen for a given masker-level/probe-delay condition.

B. Results and analysis

Despite the efforts made to take detectability into account, there were still instances in which the pedestal level of the tone-pip was less than 5 dB above the forward-masked detection threshold. In those cases the pedestal tended to fade in and out of hearing range, so that a difference limen could not be resolved. Those data were not used. This problem happened for all the subjects when the 30 dB SPL tone-pip followed the 50 dB SPL forward masker at 10 ms, and it happened for all but three subjects for the 40 dB SPL tone-pip under the same forward-masking conditions. It happened for four subjects when the 30 dB SPL tone-pip followed the 50 dB SPL forward masker at 100 ms, and still happened for one of those subjects at the 40 dB SPL pedestal level. Finally, the pedestal level of the tone-pip was less than 5 dB above the forward-masked detection threshold for six subjects when the 30 dB SPL tone-pip followed the 70 dB SPL forward masker at 100 ms. One of those subjects could still not always hear the pedestal repeatedly when its level was raised to 40 dB SPL.

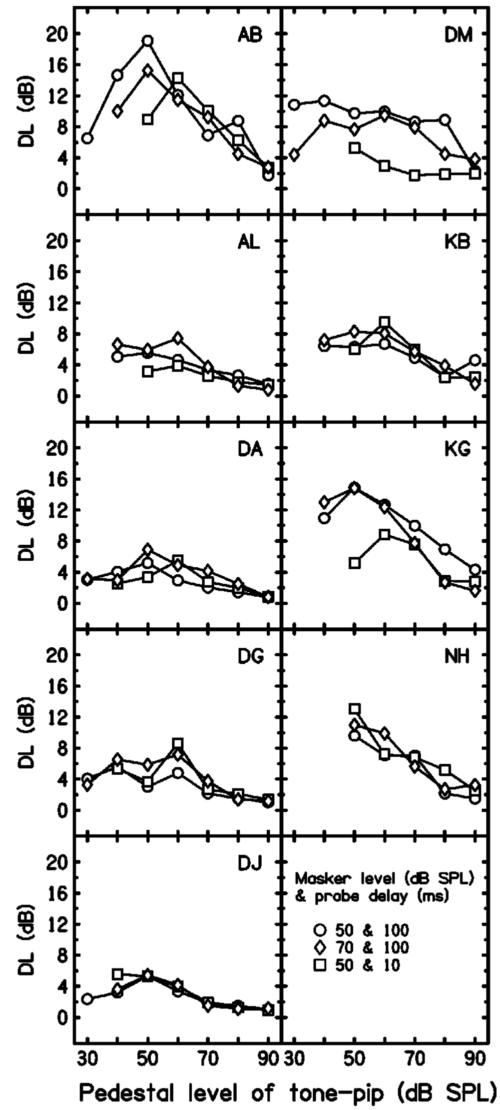

FIG. 3. Forward-masked difference limens for each of the nine subjects (experiment 4). Each frame shows one subject's forward-masked DLs for three conditions: 50 dB SPL forward-masker and 10 ms delay (open squares), 50 dB SPL forward-masker and 100 ms delay (open circles), and 70 dB SPL forward-masker and 100 ms delay (open diamonds).

Figure 3 shows DL versus pedestal level for each subject at each of the three masker-level/probe-delay conditions. Figure 4 presents across-subject arithmetic averages and standard deviations. For the 100-ms delay, the DLs appear to peak at 50 dB SPL, just as found for the non-forward-masked DLs, regardless of forward-masker level. The DLs for the 70/100 and 50/100 masker-level/probe-delay conditions do not appear to substantially diverge. The level-dependence of the DLs for the 50/10 masker-level/probe-delay condition appears to peak at a higher pedestal level.

In order to lend some rigor to these assertions, the data

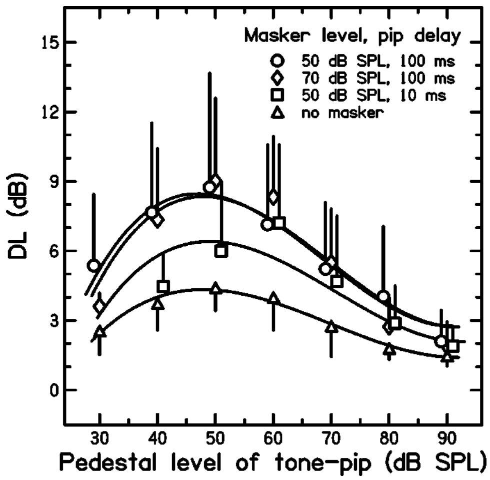

FIG. 4. The forward-masked difference limens (Fig. 3) averaged across the nine subjects. The error bars are standard deviations. For the sake of clarity, the plot for the 50 dB SPL forward masker and 100-ms delay has been shifted 1 dB to the left and the plot for the 50 dB SPL forward masker and 10-ms delay has been shifted 1 dB to the right. Also shown are the non-forward-masked DLs from the upper panel of Fig. 1. The smooth curves represent regression-fitted polynomials described in the text.

used to construct Fig. 4 were subjected to a two-way ANOVA (forward-masking condition by pedestal level), using the interaction with subjects as the error term. Four forward-masking conditions were stipulated: 50 dB SPL masker and 100-ms delay, 50 dB SPL masker and 10-ms delay, 70 dB SPL masker and 100-ms delay, and no forward masker. None of the DLs for the two lowest pedestal levels (30 and 40 dB SPL) were used, because not all subjects were able to provide DLs at those levels (see above). Significant effects were found for forward-masking condition [$F(3,24)=6.240$, $p<0.01$], pedestal level [$F(4,32)=40.764$, $p<0.001$], and the interaction of forward-masking condition with pedestal level [$F(12,96)=7.711$, $p<0.001$].

These significant effects were explored with further tests. Figure 4 shows large standard deviations that might render illusory any apparent differences between points on a given curve. Consequently, a separate one-way ANOVA was completed for each forward-masking condition, and the linear, quadratic, and higher-order components of the level effect were evaluated (see Keppel, 1991, pp. 141–161). These components are orthogonal and provide a means of describing the nature of a significant effect of pedestal level. The linear component represents a pattern in which the DL varies as a function of level but can be described by a straight line with nonzero slope, as in a ''near miss to Weber's law,'' while the quadratic component provides a measure of the significance of deviation from that linearity in the form of a single peak or trough, as in a mid-level hump. There were significant effects of pedestal level, and a significant linear component, for each of the four masker-level/probe-delay conditions, 50/100 {[$F(4,32)=14.085$, $p<0.001$], and [$F(1,8)=22.267$, $p<0.01$], respectively}, 50/10 {[$F(4,32)=13.629$, $p<0.001$], and [$F(1,8)=41.777$, $p<0.001$], respectively}, 70/100 {[$F(4,32)=36.899$, $p<0.001$], and [$F(1,8)=47.071$, $p<0.001$], respectively}, and no-forward-masker {[$F(4,32)=24.961$, $p<0.001$], and [$F(1,8)=22.267$, $p<0.001$], respectively}. The consistent lack of a quadratic component presumably reflects the exclusion of DLs at 30 and 40 dB SPL.[1]

The drop in DL with increasing pedestal level, with or without forward masking, is apparently genuine. However, the overall effect could conceivably have been due to the inclusion of the non-forward-masked DLs in the initial analysis. Consequently, ANOVAs were done in which the non-forward masked DLs were excluded. The DLs for the 50 dB SPL forward masker were analyzed with a two-way ANOVA [delay (10 or 100 ms) by pedestal level], using the interaction with subjects as the error term. Pedestal level was significant [$F(4,32)=22.015$, $p<0.001$], but delay was not, suggesting no difference between the two plots for the 50 dB SPL forward masker for pedestal levels from 50 dB SPL onwards.

The DLs for the 100-ms delay were also analyzed with a two-way ANOVA [forward-masker level (50 or 70 dB SPL) by pedestal level], using the interaction with subjects as the error term. Pedestal level was significant [$F(4,32)=27.070$, $p<0.001$], but forward-masker level was not. There was a significant interaction between forward-masker level and pedestal level [$F(4,32)=2.834$, $p<0.05$].

The four curves in Fig. 4 appear to converge to a common DL for a pedestal level somewhere just above 90 dB SPL. This impression was confirmed by a set of ANOVAs in which pedestal level was held constant and the effect of forward-masking condition was examined. The effect of forward-masking condition was significant at 50 dB SPL [$F(3,24)=6.353$, $p<0.005$], at 60 dB SPL [$F(3,24)=6.020$, $p<0.005$], at 70 dB SPL [$F(3,24)=4.196$, $p<0.05$], and at 80 dB SPL [$F(3,24)=3.066$, $p<0.05$]. At 90 dB SPL, the effect of forward-masking condition was not significant, i.e., there was no significant difference between the DLs.[2]

The ANOVAs indicate that the DLs obtained in the presence of the forward masker for pedestal levels of 50–90 dB SPL are greater than those obtained in the masker's absence. Figure 4 also shows smooth curves, the lowest of which was obtained by fitting a third-order polynomial to DLs obtained in the absence of the forward masker. The three upper functions were obtained by multiplying the lowest function by 1.955 for the 50/100 condition, 1.927 for the 70/100 condition, and 1.478 for the 50/10 condition. With these multipliers, the three polynomials account for 96.3%, 90.6%, and 73.0% of the variance, respectively. The smaller percentage for the 50/10 condition perhaps reflects the shift of the peak to the right. Overall, however, the DLs obtained in the presence of a forward masker are proportional to those obtained in the absence of a forward masker across all pedestal levels and the DLs obtained in the presence of one forward masker are proportional to those obtained in the presence of another. This does not necessarily mean that forward-masked and non-forward-masked DLs have the same origin. The proportionality rule cannot be general, in view of the incidents in which there is no mid-level hump in the absence of the forward masker (e.g., Zeng *et al.*, 1991; Zeng and Turner, 1992). Several studies do show mid-level humps in the absence of a forward masker and apparently larger DLs in the presence of a forward masker (e.g., Carlyon and Beveridge, 1993, Fig. 1; Plack and Viemeister, 1992a, Fig. 3; Schlauch *et al.*, 1997, Figs. 3 and 6), and this data was examined in the same manner as that of Fig. 4. While simple multiplication works very well in some cases, such as S3 in Fig. 3 of Schlauch *et al.* (1997), it does not work in the majority of cases, primarily because the hump in the absence of the forward masker is too low to account for the hump seen under forward masking.

V. EXPERIMENT 6: DIFFERENCE LIMENS UNDER AN 80 dB SPL FORWARD MASKER

This experiment was actually completed before experiments 1–5, but is presented last for continuity of logic.

A. Subjects, apparatus, stimuli, and procedure

The subjects were LN (the first author, age 41), and two female students from Creighton University, SWO (age 22) and AS (age 21), paid volunteers informed as to the method but not the expectations of the study. The two students had no previous experience as psychophysical listeners.

The apparatus, stimuli, and procedure are the same as described under experiment 4, with the following exceptions. The level of the 200-ms 2-kHz forward masker was 80 dB SPL. The masker preceded both the pedestal (channel 1) and the increment (channel 2) by 0, 10, 40, or 100 ms. A complete set of DLs was first established as a function of the tone-pip's pedestal level for the 40-ms probe delay. A complete set of DLs was then obtained for the 10-ms delay, followed by the 100-ms delay, and finally the 0-ms delay. For each delay condition, the subjects performed a forward-masked detection task between doing the DLs for the 40 dB SPL pedestal condition and the DLs for the 50 dB SPL pedestal condition. In this detection task, the subjects completed two 50-trial blocks in which only the increment tone appeared (as in experiment 2). Thus for each delay the subjects provided a grand total of eight measurements of the forward-masked difference limen for each pedestal level, and a grand total of eight measurements of the forward-masked pip-detection threshold.

After forward-masked DLs and forward-masked detection thresholds were obtained, non-forward-masked DLs and quiet thresholds were obtained, as done in experiment 1.

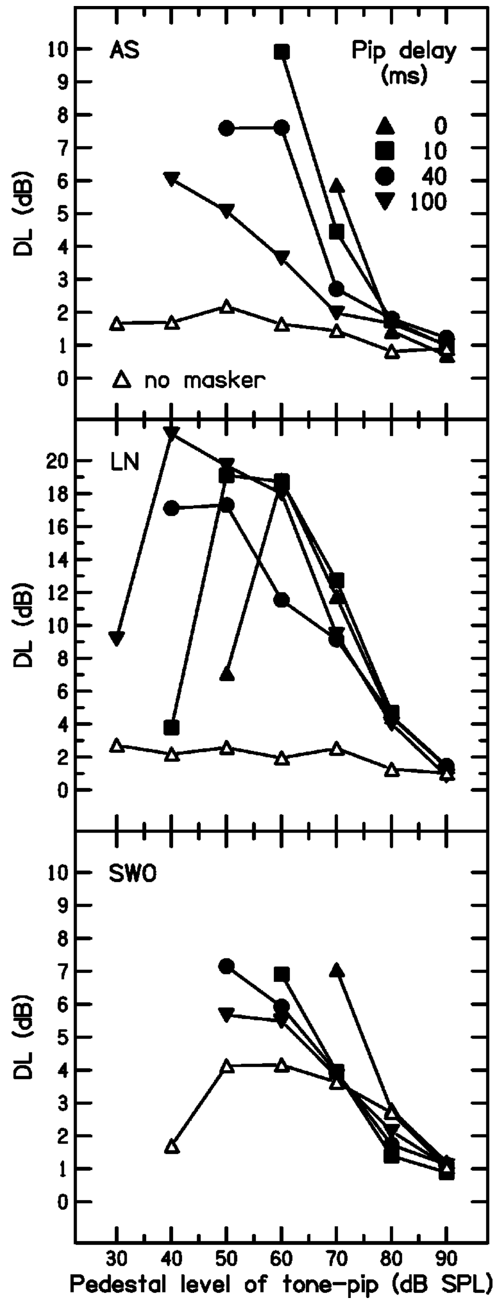

FIG. 5. Difference limens for a 2-kHz Gaussian-shaped tone-pip presented 0, 10, 40, or 100 ms following an 80 dB SPL, 200-ms, 2-kHz tone (experiment 6). The three subjects were not part of the group of nine subjects used earlier. Note the different vertical scale used for LN.

B. Results and analysis

Figure 5 presents the within-subject average DLs found with and without forward masking. The standard deviations have been omitted for the sake of clarity, but for the forward-masked DLs, the standard deviations have the same orders of magnitude and same dependence on pedestal level as seen for the group averages of Fig. 4, and for the non-forward-masked DLs, the standard deviations have the same orders of magnitude and same dependence on pedestal level as seen for the group averages of Fig. 1. Forward-masked DLs were rejected if the forward-masked detection threshold was less than 5 dB below the level of the pedestal, just as in the analysis for experiment 4. Similarly, non-forward-masked DLs were rejected if the quiet threshold was less than 5 dB below the level of the pedestal, just as in the analysis for experiment 1. The non-forward-masked DLs for subject LN were anomalously flat compared to the previous performance of this subject for this stimulus (Nizami *et al.*, 2001), and so LN was retested with pedestals at 30, 60, and 90 dB SPL. The resulting DLs followed the peaked pattern seen in Fig. 1, reconfirming the mid-level hump for this subject.

At the delays of 0, 10, 40, and 100 ms, respectively, the subjects' forward-masked detection thresholds were 43.7, 34.5, 28.1, and 23.8 dB SPL (subject LN); 62.4, 50.7, 41.8, and 36.9 dB SPL (subject SWO); and 58.7, 47.4, 37, and 28.2 dB SPL (subject AS). The subjects' quiet thresholds were 20.8 dB SPL (LN), 27.3 dB SPL (SWO), and 20.5 dB SPL (AS), numbers that are well within the range found for

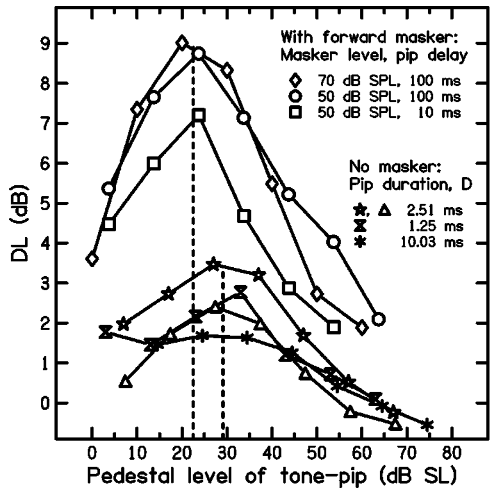

FIG. 6. The forward-masked DLs of Fig. 4, presented in SL scales that were constructed as described in the text. Error bars have been omitted for clarity. Also shown, but offset 2 dB downwards for clarity, are the non-forward-masked DLs for the Gaussian-shaped 2-kHz tone-pip of $D=2.51$ ms (open triangles, as in Fig. 1), as well as the DLs for the Gaussian-shaped 2-kHz tone-pips of $D=1.25$ ms, $D=2.51$ ms (open stars, as in Fig. 1), and $D=10.03$ ms, from Nizami *et al.* (2001). The *x*-intercept of the left-hand vertical line was determined by averaging the SLs at which the three upper curves appear to peak, and the *x*-intercept of the right-hand vertical line was determined by averaging the SLs at which the humps for the one curve for $D=1.25$ ms and the two curves for $D=2.51$ ms appear to peak.

the other nine subjects (experiment 1). Only subject LN had forward-masked detection thresholds low enough to obtain forward-masked DLs at low pedestal levels, revealing a return from the mid-level hump to the lower DLs seen at high SPLs. The other subjects' forward-masked DLs suggest a peak somewhere in the range of 40–60 dB SPL, the same range seen for the position of the peak for the forward-masked DLs at the 100-ms delay for the nine subjects of experiment 4.

VI. SL ANALYSIS OF EXPERIMENTS 1-6

Experiments 1, 3, and 5 confirmed the mid-level hump for 2-kHz Gaussian-shaped tone-pips for $D=2.51$ ms, that had first been observed by Nizami *et al.* (2001). In that study, the level-dependence of the DL had been determined for non-forward-masked 2-kHz Gaussian-shaped tone-pips of $D=1.25$, 2.51, and 10.03 ms. The resulting level-dependence curves achieved closer mutual alignment when plotted using SL scales. A common SL scale had been made for each D by subtracting the group average quiet threshold at each D from the pedestal level. For $D=2.51$ ms, this average threshold was 23.0 dB for the Nizami *et al.* (2001) DLs (nine subjects) and 22.6 dB for the present DLs (nine different subjects). Figure 6 shows all these DLs, past and present, in SL scales. Because the peaks of the two level-dependence curves for $D=2.51$ ms align in SPL scales (top panel, Fig. 1), the similarity of the group average thresholds allows them to also align in SL scales.

Comparing Fig. 6 to Fig. 4 shows that the peaks in the level-dependence plots for the forward-masked DLs are in closer alignment when plotted in an SL scale. The peaks of the non-forward-masked DLs, including those of Nizami *et al.* (2001), occur at a level that is 6.6 dB higher, a significant difference ($t=2.877$, $p<0.05$, two-tailed t-test, $df=4$). Thus the mid-level hump in the forward-masked DLs, and that in the non-forward-masked DLs, may have different origins.

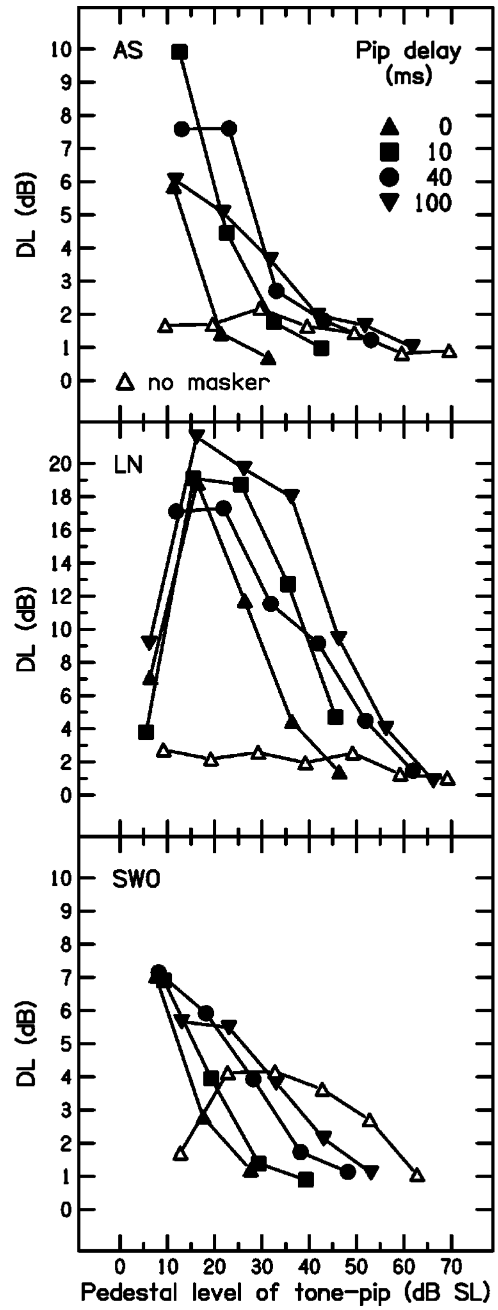

FIG. 7. Difference limens for a 2-kHz Gaussian-shaped tone-pip presented 0, 10, 40, or 100 ms following an 80 dB SPL, 200-ms, 2-kHz tone (data of Fig. 5), displayed using SL scales constructed as described in the text.

Figure 7 shows the effect of an SL transform on the DLs from experiment 6 (that was seen in Fig. 5). The subjects' individual forward-masked detection thresholds were used to make the SL scales for the forward-masked DLs, and the subjects' individual quiet thresholds were used to make the SL scales for the non-forward-masked DLs. The forward-masked DLs of LN, where peaks are well defined, come into alignment, suggesting a peak at 20 dB SL, similar to the forward-masked DLs in Fig. 6. The largest forward-masked DLs of the other two subjects also fall into respective alignment. These alignments suggest that each subject's level-dependence curve has a peak somewhere in the range of 10–20 dB SL.

VII. DISCUSSION

A. Absence of learning effects on the non-forward-masked mid-level hump

The group-average DLs for the non-forward-masked 2-kHz Gaussian-shaped tone-pip (Fig. 1, upper panel) did not improve with extensive experience at forward-masked detection of the probe, or with extensive experience at forward-masked discrimination of level changes in the probe (Fig. 1, middle and lower panels, respectively). It appears that the mid-level hump is not an artifact that can be removed through training.

B. The Zeng *et al.* (1991) model of the mid-level hump under forward masking

Zeng *et al*. (1991) were the first to note the emergence of a mid-level hump under forward masking. They used probe delays of 100 ms to obtain their principal data, and the literature (including the present work) has followed suit. Zeng *et al*. explained the forward-masked mid-level hump by noting that at their probe delay of 100 ms, neurons of different spontaneous firing rates (and hence, on average, different thresholds) would be in different states of recovery from the diminishing effect that the forward masker is known to have on the neuronal response to a probe. High-spontaneous-rate neurons would have recovered from the influence of the masker, but would fire at their saturation firing rates in response to a mid-level probe. In contrast, low-spontaneous-rate neurons would not be recovered at all; due to the forward masker, their dynamic ranges would still be shifted upwards in the intensity dimension. Consequently, the auditory periphery is not as sensitive to changes in probe level at moderate probe levels as at lower or higher probe levels.

Our review of the current data and of the published data suggests two problems with the Zeng *et al*. model. The first problem concerns probe delay. Zeng *et al*. (1991) obtained DLs as a function of probe delay using, for each subject, the pedestal level at which that subject had shown a maximal DL for the 100-ms delay (40, 50, or 60 dB SPL). In this manner, they found a monotonic decrease in the size of the DL with increasing delay, which they assumed reflected the relatively slow recovery of low-spontaneous-rate neurons, supporting their model. Plack *et al*. (1995) investigated the delay-dependence of the DL using a probe of the same frequency as Zeng *et al*. (1 kHz) but with longer ramps (5 vs 2 ms) and a shorter steady state (20 vs 25 ms). The level of the probe was 50 dB SPL and the level of the 1-kHz forward masker was 80 dB SPL. Plack *et al*. (1995) found that the DLs actually increased as the probe delay increased from 12.5 to 50 ms, and continued to rise at a slower rate as delay increased to 200 ms. This finding moves opposite in direction to that of Zeng *et al*. (1991).

It is at first tempting to blame this inconsistency on the differences in the stimuli used in the two studies. The forward maskers used by Plack *et al*. were shorter (30 vs 100 ms), and for nonsimultaneous masking Plack *et al*. had used 1-kHz tones whereas Zeng *et al*. (1991) had chosen a 200-Hz narrow-band noise centered at 1 kHz, the frequency of the probe. Plack *et al*. (1995) interpreted the inconsistency between their DLs and those of Zeng *et al*. (1991) as a reflection of referential coding, in which the random amplitude fluctuations of the narrow-band masker used by Zeng *et al*. would reduce its usefulness as a reference relative to the forward masker used by Plack *et al*. (1995), that had the same frequency, duration, and ramping as the probe. Indeed, Zeng *et al*. had chosen a narrow-band masker specifically because it did *not* sound like the 1-kHz probe, whereas the forward masker used by Plack *et al*. (1995) introduces a potential confound, that of "perceptual similarity" (Schlauch *et al*., 1997, 1999). But if perceptual similarity is a problem, then the DLs of Plack *et al*. should have been larger than those of Zeng *et al*. (1991), not smaller as observed. Perceptual similarity is also contraindicated by the dependence of the size of the forward-masked DL on the center frequency of the narrow-band-noise masker (Zeng *et al*., 1991).

The present data suggest an explanation for the different delay-dependences found by Zeng *et al*. (1991) and by Plack *et al*. (1995). Experiment 4 provides DLs for the probe tone at two delays following the 50 dB SPL forward masker, 100 and 10 ms. Figures 4 and 6 show that the DL at the peak of the level-dependence curve, the plotting parameter used by Zeng *et al*. (1991, Fig. 3), is lower for the 10-ms delay than for the 100-ms delay, in accord with Plack *et al*. (1995), regardless of whether plotted using SPL scales or SL scales. The DLs of experiment 6 qualify this relation. In experiment 6, DLs had been obtained at various durations following an 80 dB SPL forward masker at the probe frequency (2 kHz). Those DLs (Fig. 5) seem to become smaller with increasing delay, in accordance with Zeng *et al*. (1991). The data points cluster together at high pedestal levels, however, making interpretation difficult, and suggesting that the trend may depend on the pedestal level. Therefore the DLs of Fig. 5 were replotted as a function of delay, subject-by-subject, for pedestal levels of 50, 60, and 70 dB SPL. These levels were chosen because Fig. 5 shows that, above 70 dB SPL, there seems to be little difference in the DL with level, and, below 50 dB SPL, only one subject of the three could detect the pedestal. The DLs for subjects AS and SWO, shown in Fig. 8, generally decline with increasing delay for the 50 and 60 dB SPL pedestals, but flatten out for the 70 dB SPL pedestal. The DLs for LN, the oldest of the three subjects, actually rise over 50 to 100 ms postmasker. In sum, although the data of Fig. 8 do not allow us to unambiguously choose between the delay-dependence found by Zeng *et al*. and that found by Plack *et al*., there is a hint nonetheless that those delay-dependences may differ according to pedestal level.

Our second issue with the Zeng *et al*. model is the effect of forward-masker level. For the 100-ms delay, the present experiments provide DLs for three levels of the forward-masker, 50, 70, and 80 dB SPL. Although the DLs obtained in the presence of the 80 dB SPL forward masker appear to be slightly larger than the others at low pedestal levels and slightly smaller at high pedestal levels, the variability asso-

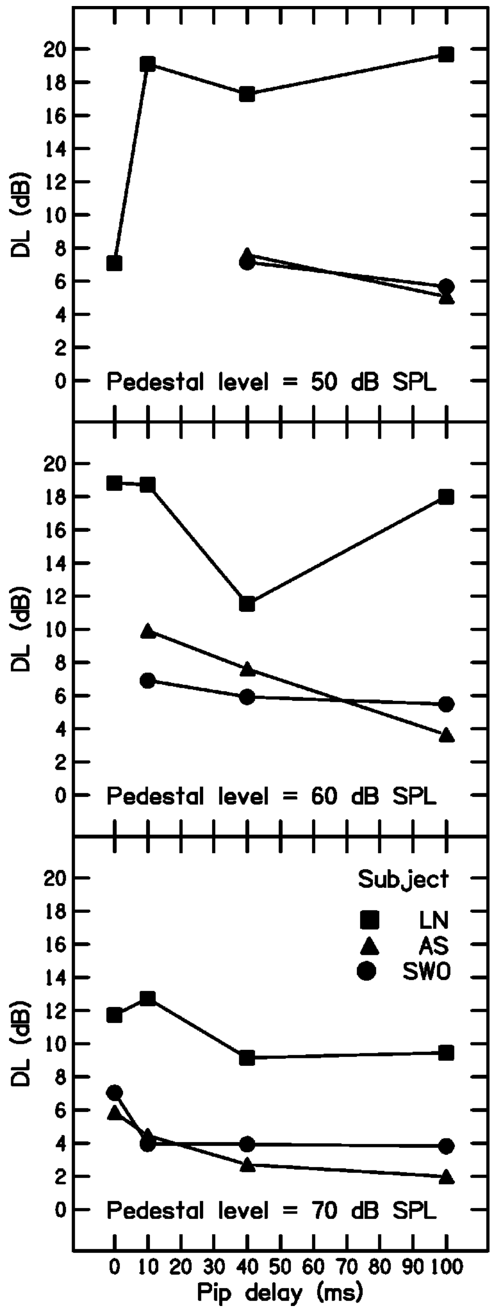

FIG. 8. The difference limens of Fig. 5, plotted as a function of tone-pip delay with the pedestal level of the tone-pip as the parameter.

ciated with these points is high and the number of subjects is lower than for the other two forward maskers. In general, masker level appears to have no effect. This result stands in stark contrast to the only published report of the effect of forward-masker level on the size of the mid-level hump. Zeng and Turner (1992) noted a general increase in the size of the average DL as a function of forward-masker level for levels 40 dB SPL and above, from about 2 dB at 40 dB SPL to about 7 dB at 90 dB SPL. In their study, the masker-probe delay was 100 ms and the stimuli were centered at 1 kHz. The units used for the DL were the same as used here. Zeng and Turner (1992) hypothesized that the elevation of the DL at moderate levels of the probe was only substantial at high levels of the forward masker because afferents of low spontaneous rate have high thresholds, so that high forward-masker levels are required to cause a significant forward-masking effect. Presumably, within the context of their model, Zeng and Turner meant that only high forward-masker levels would shift the dynamic ranges of the low-spontaneous-rate afferents enough to open up a substantial encoding gap. [Increasing a forward-masker's intensity does increase the threshold shift of the primary afferents, and lengthens the duration required for recovery (Smith, 1977; Harris and Dallos, 1979).] The present finding of a substantial mid-level hump for the 100-ms delay condition when the forward-masker level is only 50 dB SPL, and the lack of an effect of the forward-masker level on the size of the mid-level hump, run counter to the Zeng *et al.* (1991) model.

C. Context-coding models of the mid-level hump under forward masking

Plack and Viemeister (1992b) demonstrated that a profound rise in the DL is found when the masker *follows* the probe, for the stimuli and masker-probe interval originally used by Zeng *et al.* (1991). Plack *et al.* (1995) confirmed this result for ipsilateral and contralateral backward-maskers. The unlikelihood of a peripheral interaction in backward masking implies a central mechanism in which the representation of the backward masker and the pedestal or pedestal +increment overlap in a temporal window. A central interaction of some kind is also implied by the existence of contralateral effects of forward masking on intensity discrimination (e.g., Plack *et al.*, 1995; Zeng and Shannon, 1995; Schlauch *et al.*, 1999), because the left- and right-ear inputs do not have the opportunity to interact below the level of the brainstem (Irvine, 1986).

The longer integration times and contralateral effects can be accounted for in models that incorporate assumptions concerning memory. Carlyon and Beveridge (1993) provided the first such account, based on the two modes of intensity coding described by Durlach and Braida (1969). It is generally assumed that subjects in an intensity discrimination task rely on traces of the sounds in auditory memory, but Durlach and Braida described an alternative coding strategy based on context coding and verbal labeling that would generally be less accurate, but that would become the optimum strategy when the memory trace was poor. They noted that context coding was better in the proximity of perceptual anchors and that the top or bottom of the stimulus range, marked by threshold and discomfort, respectively, served as natural anchors (Braida *et al.*, 1984). Carlyon and Beveridge (1993) suggested that the forward or backward masker might be expected to interfere with memory for the tones to be discriminated, but that the effect of this might not be as observable for tones presented at low or at high levels, because the subjects would be able to fall back on context coding in those cases. At moderate levels, however, context coding would be poor, and either coding strategy would result in elevated DLs. Plack has interpreted the results of more recent studies in terms of context coding or referential coding (Plack *et al.*, 1995; Plack, 1998) and has shown that conditions that would be expected to alter referential coding have an impact on the magnitude of the mid-level hump. The occurrence of mid-level humps at comparable levels in conditions with and without forward maskers presents problems for context-coding models. We review those issues in the following sections, following a brief review of the data.

The high correlation between the position of mid-level humps obtained at high frequencies with and without a forward masker (Carlyon and Beveridge, 1993; Plack and Viemeister, 1992a), together with the stronger relationship shown in Fig. 4, suggest a common mechanism underlying mid-level humps observed with and without nonsimultaneous maskers. Plack (1998) has argued that referential coding results in better performance in all cases and thus may be the common mechanism. The argument is based on the observation that notched noise presented with the pedestal reduces the mid-level hump at high frequencies (Plack, 1998), as well as in the presence of nonsimultaneous maskers (Plack and Viemeister, 1992a,b), combined with the assumption that the notched noise has a beneficial effect because it provides an intensity reference. The effect of notched noise is heavily dependent, however, on temporal parameters that would not be expected to interfere with referential coding (e.g., Oxenham and Moore, 1995). In order for the notched noise to result in better performance through referential coding, we must assume that the probe-evoked memory trace has been corrupted at mid levels and that the auditory system has fallen back on context coding. But there is no *a priori* reason to suppose that shortening the tone's duration from $D = 25$ ms to $D = 2.51$ ms or increasing its frequency from 1 to 6 kHz would weaken a memory trace. Thus we still lack an explanation for why mid-level humps occur under some conditions, but not others.

The role of context coding is debatable, but the present data do not contradict the notion that the probe evokes a memory trace that is corrupted by a forward or backward masker. The latter notion is compatible with results reported by Turner *et al.* (1994). They obtained forward-masked and non-forward-masked DLs using the stimulus conditions of Zeng *et al.* (1991) but using three different experimental methods: two-alternative forced-choice, two-alternative forced-choice with multiple looks at the stimuli, and the method of adjustment, in which subjects adjust the incremented tone to achieve equal loudness with the pedestal tone. (Each DL is then taken as the standard deviation of eight such adjustments.) Turner *et al.* found that the two-alternative forced-choice trials produced the mid-level hump, but the method of adjustment did not result in any visible divergence from the near miss to Weber's law, in the same group of subjects. Turner *et al.* then obtained non-masked, forward-masked, and backward-masked DLs using the same stimuli, with the adjustment procedure only, and another subject group. This group also showed no mid-level hump. Turner *et al.* concluded that the method of adjustment measures "a fundamentally different quantity than that measured by forced-choice procedures." It might also be thought that the method of adjustment allows the memory trace to stay uncorrupted.

Plack (1998) notes that if providing a reference or context eliminates mid-level humps of all kinds, then they cannot be assumed to have a peripheral component. If not, a two-stage model remains, in which peripheral factors of the type described by Nizami *et al.* (2001) might account for mid-level humps in the absence of forward or backward masking, and a central factor associated with the masker might lead to a further reduction in performance in some conditions. Explication of the underlying processes requires knowing more about what conditions cause a mid-level hump in the absence of nonsimultaneous masking.

VIII. SUMMARY AND CONCLUSIONS

There is a change in the level-dependence of the intensity-difference limen (DL) of a tone when that tone is forward masked by a stimulus of 50 dB SPL or higher, whose frequency is centered at the frequency of the probe. For 1-kHz probes, the near miss to Weber's law develops into a mid-level hump (Zeng *et al.*, 1991; Zeng and Turner, 1992; Plack and Viemeister, 1992b; Turner *et al.*, 1994; Plack *et al.*, 1995; Schlauch *et al.*, 1997, 1999); for higher frequencies, where the DLs show a mid-level hump even in the absence of a forward masker (e.g., Carlyon and Moore, 1984; Florentine *et al.*, 1987; Plack, 1998), the hump apparently enlarges under forward masking (Plack and Viemeister, 1992a; Carlyon and Beveridge, 1993). Although the effect observed by Zeng *et al.* (1991) is large, a hump just as big can appear for mid-frequency tones in the absence of forward maskers, if the equivalent rectangular duration of the tone is shortened to less than 10 ms (Nizami *et al.*, 2001). Because this hump could be as large as some of those seen under forward masking, it was predicted that the imposition of a forward masker would make little further difference in the size of the hump.

First, the present results confirmed the mid-level hump found by Nizami *et al.* (2001) for a 2-kHz Gaussian-shaped tone-pip having an equivalent rectangular duration D of 2.51 ms. Then a 200-ms 2-kHz sinusoid was placed in each interval of the two-interval forced-choice task in order to forward mask the Gaussian-shaped tone-pip. The masker-level/probe-delay conditions used were 50 dB SPL/10 ms, 50 dB SPL/100 ms, and 70 dB SPL/100 ms. The level-dependence of the DL showed a mid-level hump significantly larger than that found without forward masking. The DLs obtained under forward masking were found to be a constant multiple of those obtained without forward masking, so that the inflating effect of the forward masker weakened with further rises in pedestal level, the DLs converging at the highest level used (90 dB SPL). When tone-pip intensities were expressed as sensation levels, the mid-level humps found under forward masking lined up. The mid-level humps for the non-forward-masked 2-kHz Gaussian-shaped tone-pips of Nizami *et al.* (2001) also align in SL scales, but at a different SL, suggesting a different mechanism for those humps.

Zeng *et al.* (1991) were the first to note a mid-level hump under forward masking. They used masker-probe delays of 100 ms, and they explained the hump as a result of the different recovery rates of peripheral afferents from the adapting effects of the forward masker. Later, Zeng and Turner (1992) noted a dependence of each subject's maximum DL on the level of the forward masker. The present experiments provided DLs at a delay of 100 ms for forward-masker levels of 50, 70, and 80 dB SPL. Masker level made no difference in the pedestal-level-dependence of the DLs. Further, the finding of a mid-level hump with a forward masker of only 50 dB SPL contradicts the Zeng *et al.* (1991) model.

Carlyon and Beveridge (1993) have suggested that non-simultaneous masking acts by disrupting the memory trace evoked by the probe, causing a reliance on context coding, providing poor discrimination at mid-levels. The present data do not contradict the notion of a corruptible memory trace.

ACKNOWLEDGMENTS

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[1]Regarding the 50 dB SPL masker and the 100-ms delay: the significant linear component reflects a nonzero slope to the curve, but does not tell us which of the DLs differ significantly from each other. For that we use pairwise comparisons. There are ten pairs of DLs to be compared, representing all possible pairs of points on the curve for pedestal levels $\geqslant 50$ dB SPL. All but three differed at $p<0.05$ or better. The three nonsignificant pairings were the DLs for 50 and 60 dB SPL, the DLs for 70 and 80 dB SPL, and the DLs for 80 and 90 dB SPL. Regarding the 50 dB SPL masker and the 10-ms delay, pairwise comparisons revealed differences at $p<0.05$ or better between all but three pairs of DLs for pedestal levels $\geqslant 50$ dB SPL: the DLs for 50 and 60 dB SPL, the DLs for 50 and 70 dB SPL, and the DLs for 80 and 90 dB SPL. Regarding the 70 dB SPL masker and the 100-ms delay, pairwise comparisons revealed differences at $p<0.05$ or better between all but one pair of DLs for pedestal levels $\geqslant 50$ dB SPL: the DLs for 50 and 60 dB SPL. Finally, regarding the non-forward-masked DLs, pairwise comparisons revealed differences at $p<0.05$ or better between all but two pairs of DLs for pedestal levels $\geqslant 50$ dB SPL: the DLs for 50 and 60 dB SPL, and the DLs for 80 and 90 dB SPL.

[2]This analysis also yielded paired comparisons, the results of which will only be mentioned for the highest and lowest SPLs used, for which the results are most telling. For the 50 dB SPL pedestal, the DL for the 50/100 masker-delay condition differed significantly from the DL for the non-forward-masked tone-pip, the DL for the 50/10 masker/delay condition differed significantly from the DL for the 70/100 masker/delay condition, and the DL for the 70/100 masker/delay condition differed significantly from the DL for the non-forward-masked tone-pip. For the 90 dB SPL pedestal, pairwise comparisons revealed no significant differences between DLs.

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