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Intensity discrimination and loudness for tones in notched noise

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Fechner proposed that equally often noticed differences are subjectively equal. Parker and Schneider (1980) showed that a power-function representation for loudness was consistent with Fechner's proposal for auditory intensity discrimination when 1-kHz tones were presented in a quiet background. In the present experiment, (1) intensity-increment thresholds were determined for 1-kHz tones in notched noise, and (2) the intensities of 1-kHz tones in quiet which produced the same loudnesses as the tones in notched noise were obtained from the same subjects. Intensity-increment thresholds in notched noise could not be accounted for by either the loudness level of the tones in notched noise or by the Parker and Schneider model. A new model is developed in which the effects of notched noise on discrimination performance are related to the effects of notched noise on loudness.

Since 1860, when Fechner proposed that a just noticeable difference (jnd) corresponded to a constant increment in sensation, there have been many attempts to link differential sensitivity to sensation (e.g., see Falmagne, 1974; Luce & Green, 1974; McGill & Goldberg, 1968; Parker & Schneider, 1980; Rabinowitz, Lim, Braida, & Durlach, 1976; Zwislocki & Jordan, 1986). Consider, for example, loudness. It is now generally accepted that the loudness of pure tones grows as a power function of intensity (for intensities > 40 dB SPL); that is,

$$L = kI^p, \tag{1}$$

where L is loudness, I is sound intensity, and k and p are constants. It is also generally accepted (but see Rabinowitz et al., 1976) that a near-miss to Weber's law relates ΔI, the intensity difference at threshold, to the intensity of the standard tone; that is,

$$\Delta I = I_c - I_s = k'I_s^m, \tag{2}$$

where I_c is the value of the comparison stimulus at threshold, I_s is the intensity of the standard, and k' and m are constants. Equation 1 characterizes a large number of studies concerning the growth of loudness for pure tones, and Equation 2 describes how differential sensitivity changes as a function of intensity for the same pure tones. In a previous paper (Parker & Schneider, 1980), we were able to relate the two sets of empirical data for pure tones in quiet but did not discuss the relation of differential sensitivity to loudness in noisy backgrounds.

Consider, for the moment, how the loudness-difference model that we proposed (Parker & Schneider, 1980) relates the two sets of observations for pure tones in a quiet background. Equation 2 describes, for pure tones in quiet, how ΔI changes with intensity. However, if Fechner's assumption is correct, and a jnd corresponds to a constant increment in sensation, then the loudness difference between the standard and comparison tones, $L_c - L_s$, should be independent of the intensity of the standard stimulus; that is,

$$\Delta L = L_c - L_s = c \tag{3}$$

for all values of I_s, where ΔL is the constant loudness increment corresponding to jnd. Notice that this model assumes that intensity discrimination depends only on the loudness difference between the stimuli and ignores any other changes (such as pitch or timbre, etc.) that intensity increments might produce which could thereby contribute to discriminability.

For pure tones in quiet, Equation 1 governs the growth of loudness. Therefore, for intensity discrimination experiments in quiet,

$$\Delta L = I_c^{p'} - I_s^{p'} = c. \tag{4}$$

We use p' as the symbol for the discrimination exponent to allow for the possibility that it might differ from the exponent found in other loudness-judgment paradigms. Popper, Parker, and Galanter (1986) have shown that the values of the exponents that characterize individual sub-

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jects' loudness-difference judgments depend on the type of response employed. In general, the loudness exponent can vary with response scale and task (see Marks, 1979, for a review). Since it is not possible to specify a single exponent for loudness, we have allowed for the possibility that the exponent in discrimination, p', might differ from the exponent, p, that governs loudness of single tones in quiet backgrounds.

Equation 4 declares the loudness increment corresponding to a jnd in sensation to be constant. Note that this condition is satisfied when the variance of the ΔLs across levels or across conditions is zero. Therefore, Parker and Schneider (1980) determined the value of p' in Equation 4 that minimized the variance of ΔL. The variance of ΔL is at a minimum when

$$(\Sigma \Delta L)^2/n \Sigma \Delta L^2 \quad (5)$$

is at a maximum. Note that Formula 5 specifies the proportion of the total sum of squares ($\Sigma \Delta L^2$) due to the mean ($\Sigma \Delta L/n$) (see Graybill, 1961); hence, when all ΔLs are equal to their mean, Formula 5 equals 1.0. Formula 5 indexes goodness of fit of data to the constant-loudness-difference model; 1 minus the value of Formula 5 is the residual error variance. Parker and Schneider (1980) were able to find values of p' that successfully reduced the variance of the ΔLs to close to zero for a number of intensity-increment studies. The average discrimination exponent, p', was .11 (when determined as a function of sound intensity), which was quite close to the average value of the exponents found for suprathreshold loudness-difference judgments (see Parker & Schneider, 1980) but approximately ⅓ as large as the exponents found in magnitude estimation experiments in which the exponent relating loudness to sound intensity is about 0.3.

While the loudness-difference model can account for intensity-discrimination results in quiet, there is some question as to whether it can account for intensity discrimination results in noise. For example, Moore and Raab (1974) found that intensity-increment thresholds for pure tones in notched noise appear to follow Weber's law rather than a near-miss to Weber's law. (Notched noise is broadband noise from which energy in a narrow band of frequencies has been removed. It is also called band-reject noise.) Thus, we have a condition in which the intensity-discrimination function for tones in noise is different from that for tones in quiet. A reasonable conjecture is that notched noise, in addition to affecting the discrimination function for pure tones, might also affect their apparent loudnesses. When we began the study, there were no good data on the growth of loudness in notched noise (the data of Moore, Glasberg, Hess, & Birchall, 1985, were not yet published.) Therefore, we decided to study both the growth of loudness and intensity discrimination for pure tones in and out of notched noise in one set of subjects and attempt to connect these observations with our loudness-difference model.

EXPERIMENT 1A: LOUDNESS MATCHING

Subjects were asked to adjust the intensities of 1-kHz tones in quiet so that they matched the loudnesses of 1-kHz tones in notched noise. The notch spanned 2 octaves and was centered at 1 kHz.

Method

Subjects. Seven students and staff associated with the Psychology Department, Erindale Campus of the University of Toronto, served as subjects. Their ages ranged from 19 to 33 years. Four were female and 3 were male. None had any known auditory pathology. All were experienced psychophysical observers.

Apparatus and Stimuli. The masking noise was produced by a General Radio 1381 noise generator. The spectrum of the noise before filtering was flat up to 5 kHz and declined at a rate of 12 dB per octave thereafter. The output of the noise generator was sent through a band-reject filter (General Radio 1952) whose half-power points were 500 and 2000 Hz. The skirts of the band-reject filter declined at a rate of 30 dB per octave. The 1-kHz pure-tone signal, produced by a programmable Hewlett Packard Model 3325A function generator, had 10-msec rise and decay times. Programmable attenuators were used to set the level of the standard tone and of the noise. The spectrum level of the noise outside the notch was always set to 35 dB below the intensity of the standard tone, and thus rose and fell with the intensity of the standard. The comparison tone was produced by the same programmable function generator whose output level was under the subject's control. Stimuli were presented over TDH-49 earphones. Operations and timing were managed by a Commodore computer.

Procedure. The subject's task was to match the loudness of the 1-kHz tone presented in quiet to the loudness of the tone in the notched noise. Both tone in noise and tone in quiet were presented monaurally to the same ear. A trial consisted of alternate presentations of 750 msec of tone in noise and 750 msec of tone alone, separated by 750-msec silent interstimulus intervals. A trial began with the intensity of the tone in quiet set randomly from 1 to 7 dB below that of the tone in notched noise. The subject controlled the intensity of the tone in quiet by pressing either of two buttons, one of which increased its intensity by 1 dB and the other of which decreased it by the same amount. When satisfied with the match, the subject pressed a third button to end the trial. The next trial began 750 msec later. The intensity of the tone in quiet changed only during interstimulus intervals. The intensity of the tone in the notched noise remained unchanged throughout the trial.

During a session, seven levels (30, 40, 48, 58, 66, 76, and 84 dB SPL) of the tone in noise were presented a total of five times, for a total of 35 trials per session. The seven levels were permuted randomly within each of the five blocks.

Each of the 7 subjects participated in 12 sessions (6 for each ear), for a total of 30 matches at each intensity level for each ear. Averages were taken on the last five sessions for each ear.

Results and Discussion

Figure 1 plots the levels of the tones in quiet that matched in loudness the tones in notched noise for one ear of each of the 7 observers. Also shown is the average of the individual functions. (Recall that the spectrum level of the noise outside of the notch was always set 35 dB below the level of the tone, and thus rose and fell with tone intensity.) Notice that if tonal loudness were un-

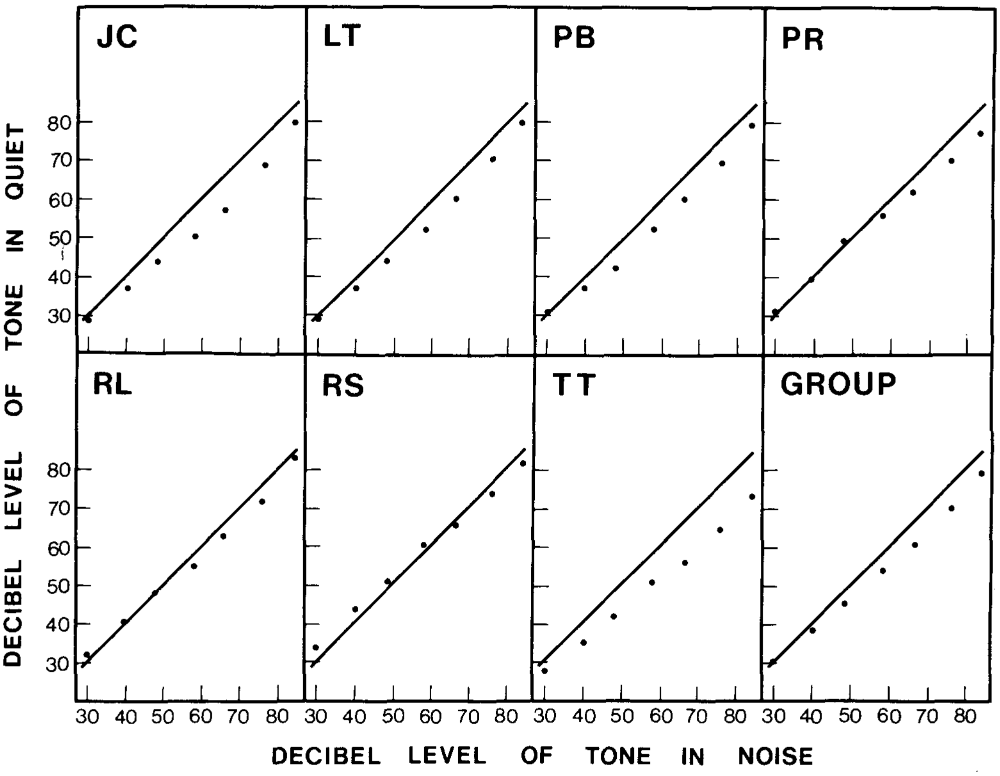

Figure 1. Intensity of tone in quiet that matches the loudness of a tone in notched noise for 7 subjects and for the group average. Signal-to-noise ratio is 35 dB.

affected by noise, the tone in quiet would be set to the same intensity level as that of the tone in noise. The positive diagonal represents this equal-loudness condition. If tonal loudness is reduced in notched noise, the intensity level of the adjusted tone should fall below this line. Except for Subject R.S., notched noise is shown to diminish the loudness of the tone at all but the lowest intensity levels. Four of the subjects (J.C., L.T., P.B., and T.T.) show a definite upward concavity, and this pattern is reflected in the group data. Note also that at least 1 subject (R.S.) shows signs of loudness enhancement (the tone in noise seems louder than the same tone in quiet), and that the group function does not show any loudness reduction at the lowest intensity (30 dB).

Loudness matches for the subjects' other ears are similar to the ones shown here. If the other ears are also included in the group average, the matching intensities change by .6, .25, .25, .4, .25, .25, and .1 dB for the seven intensities in increasing order. (The matching functions in Figure 1 were chosen to display the full range of individual differences.)

Concave upward patterns such as these were also found by Moore et al. (1985) for the loudness of tones in notched noise in which the spectrum level of the noise was 30 and 40 dB below that of the signal. (Since Moore et al. did not provide individual data, we cannot determine whether their individual differences were similar to ours).

EXPERIMENT 1B: LOUDNESS MATCHING AT OTHER SIGNAL-TO-NOISE RATIOS

To assess the extent to which loudness matching was affected by the ratio of the signal intensity to the spectrum level of the noise outside the notch, loudness matches were obtained for signal-to-noise ratios of 20 and 40 dB (15 dB less and 5 dB greater than the 35-dB signal-to-noise ratio used in Experiment 1A). The matches obtained at 20 dB were obtained from the same subjects using the same apparatus and procedures as in Experiment 1A. To change the signal-to-noise ratio from 35 to 20 dB, the tone intensities were reduced 15 dB below those in Experiment 1A while the noise spectrum levels were kept identical to those in Experiment 1A. For the 40-dB signal-to-noise condition, loudness matches were obtained only at the tonal intensities (30, 44, 57, 71, and 84 dB) used in Experiment 2 (to follow). Since only two of the original 7 subjects were available when this phase of Experiment 1B began, 4 new subjects were added. For these new subjects, and for the old, loudness matches were obtained with signal-to-noise ratios of both 35 and 40 dB.

Method

Subjects. The seven subjects in the 20-dB signal-to-noise condition were the same as in Experiment 1A. Of the 6 subjects in the

35- and 40-dB conditions, 2 (R.L. and L.T.) had been in Experiment 1A; the other 4 subjects were undergraduate students with no known auditory pathology.

Apparatus and Stimuli. For the 20-dB condition, the apparatus was identical to that in Experiment 1A. Signal levels were 15 dB below those used in Experiment 1A; noise spectrum levels were 20 dB below signal levels.

For the 35- and 40-dB conditions, the apparatus differed from that in Experiment 1A in that a Wavetek (System 716) Brickwall filter was employed to sharpen the roll-off of the noise above 5 kHz (the roll-off increased from 12 dB/octave in Experiment 1A to 115 dB/octave). Five tonal intensities (30, 44, 57, 71, and 84 dB SPL) were combined with notched noises whose spectrum levels were 35 and 40 dB below the signal levels.

Procedure. For the 20-dB condition, the procedures were identical to those in Experiment 1A.

For the 35- and 40-dB conditions, the only procedural change from Experiment 1A was that the button that diminished the intensity of the matching tone now produced a 2-dB reduction, rather than the 1-dB reduction it provided in Experiment 1A; intensity-increment step size remained at 1 dB, however.

Results

Figure 2 shows the loudness matches for the group of 7 subjects run at a signal-to-noise ratio of 20 dB. Data from Experiment 1A are included for comparison. It is clear that diminishing the signal-to-noise ratio by 15 dB has small effects on tonal loudness.

Figure 3 shows the average loudness matches for the group of 6 subjects run at 35 and 40 dB. Once again, little effect is seen on the intensity of the matching tone.

Discussion

Figures 2 and 3 indicate little change in the effect of notched masking noise on tonal loudness as signal-to-noise ratio varies from 35 dB either 15 dB down or 5 dB up.

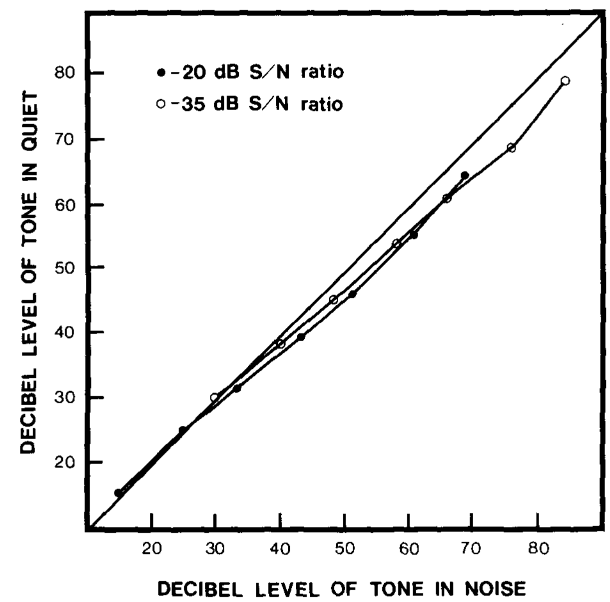

Figure 2. Group average intensity of tone in quiet that matches the loudness of a tone in notched noise at signal-to-noise (S/N) ratios of 20 and 35 dB.

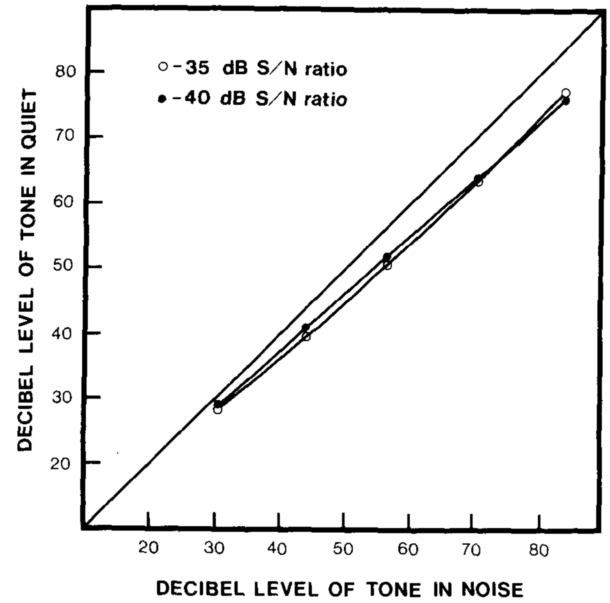

Figure 3. Group average intensity of tone in quiet that matches the loudness of a tone in notched noise at signal-to-noise (S/N) ratios of 35 and 40 dB.

Larger effects on tonal loudness induced by changed signal-to-noise ratios do appear in the work of Moore et al. (1985). The characteristics of the masking noises in the Moore et al. study and ours differ considerably, however. Moore et al.'s noise bands extended down to 0.2 kHz and up to 1.8 kHz, whereas ours extended down to 0.1 kHz and up to 5.0 kHz. More importantly, their broadest notch extended from 0.6 to 1.4 kHz, whereas ours extended from 0.5 to 2.0 kHz. They found that widening the notch diminished the effect of signal-to-noise ratio on the matching function. When notch width is narrowed to zero (as in broadband masking noise), effects of signal-to-noise ratio on the loudness-matching function are enlarged (as in Stevens & Guirao, 1967). Since the notch width in our noise was roughly twice that of the widest notch used by Moore et al., we regard our results as an extension of theirs. With our notched noise, signal-to-noise ratio had little impact on tonal loudness. The big effect on tonal loudness came from the presence of masking noise rather than its level, within the range of levels we studied.

EXPERIMENT 2: INTENSITY DISCRIMINATION

Intensity-increment thresholds were determined for five levels of the 1-kHz tone both with and without notched noise using a two-interval forced-choice procedure.

Method

Subjects. The same 7 people who were in Experiment 1A served as subjects.

Apparatus and Stimuli. Stimuli were generated in the same fashion as in Experiment 1A. The standard stimuli were at 30, 44, 57, 71, and 84 dB SPL. Note that these are within the range of the stimuli used in Experiment 1A but are not identical to them; they are identical to those in the high signal-to-noise conditions of Experiment 1B. For intensity-increment thresholds determined in notched noise, the spectrum level of the noise was 35 dB below the level of the standard tone. Comparison tones had levels that exceeded the standards by .5, 1.0, 1.5, 2.0, and 2.5 dB; the noise levels accompanying the comparison tones were identical to those accompanying the standard tones. Hence, the spectrum level of the noise was between 35.5 and 37.5 dB below the comparison-tone level, since it was always 35 dB below the standard-tone level.

Procedure. Stimulus presentation was monaural to the ears whose matching data are shown in Figure 1.

Each session consisted of 200 two-interval forced-choice trials involving one of the standard stimuli and one of the comparisons. Standard intensity was constant throughout a session. Standard and comparison tones appeared equally often in the first and second intervals in an otherwise random sequence, and the subject was instructed to indicate the interval containing the louder tone by pressing one of two buttons. Tone duration and interstimulus interval were both 750 msec. The subject pressed a button to initiate a trial. Feedback was provided by the illumination of one of two signal lights. Five standard and five comparison stimuli in all were tested, and the percentage correct for each combination was determined. The order of presentation of the 25 standard-comparison combinations was randomized for each subject. The pairs that bracketed 75% accuracy were retested. Threshold was the standard-comparison separation corresponding to 75% accuracy, and was estimated by linear interpolation between the two bracketing increments. Best performances were used for the interpolations. Intensity-increment thresholds were determined first for tones in notched noise and then for the same tones in a quiet background. The procedure for the same tones in quiet differed only in that the 2.5-dB increment was not used. For the few subjects whose performances with a .5-dB increment exceeded 75% accuracy, a .25-dB increment was added to the stimulus set.

Results and Discussion

The threshold increments in decibels for each subject (and the group average) at each standard intensity both in noise and in quiet are shown in Table 1. Notice that when there is no masking noise, the threshold increment shrinks as standard intensity grows; however, that pattern does not occur when there is masking noise. This is consistent with the occurrence of the "near-miss to Weber's law" for unmasked tones, but not for masked tones. That the threshold for masked tones exhibits no obvious trend is roughly consistent with Moore and Raab's (1974) claim that Weber's law governs discrimination of loudness for tones in notched noise.

Table 1
Intensity-Increment Thresholds in Quiet and in Notched Noise

		Intensity of Standard in Decibels				
Subject	Condition	30	44	57	71	84
J.C.	noise	0.93	0.63	0.81	0.80	0.55
	quiet	1.04	0.84	0.74	0.50	0.45
L.T.	noise	1.85	1.83	1.87	2.31	2.13
	quiet	1.00	0.94	0.80	0.47	0.50
P.B.	noise	1.45	1.71	1.95	1.95	1.06
	quiet	1.17	1.14	0.88	0.67	0.55
P.R.	noise	1.13	0.84	1.27	1.31	1.28
	quiet	1.14	1.29	1.15	0.89	0.72
R.L.	noise	1.54	1.79	1.56	1.68	1.86
	quiet	1.47	1.28	0.77	0.71	0.70
R.S.	noise	1.07	1.15	1.25	1.50	1.38
	quiet	1.58	1.33	0.95	0.55	0.61
T.T.	noise	1.12	1.08	0.97	2.00	1.85
	quiet	1.09	0.90	0.61	0.50	0.43
Group	noise	1.30	1.29	1.38	1.65	1.44
	quiet	1.21	1.10	0.84	0.61	0.57

Table 2
Values of p', ΔL, and Goodness-of-Fit Index for Tones in Quiet

Subject	p'	ΔL	Index
J.C.	.071	.0285	.9971
L.T.	.066	.0260	.9873
P.B.	.067	.0318	.9959
P.R.	.044	.0186	.9890
R.L.	.066	.0344	.9867
R.S.	.087	.0592	.9853
T.T.	.079	.0344	.9969
Group	.068	.0320	.9965

As in Parker and Schneider (1980), we interpret the near-miss as a manifestation of constant loudness difference at discrimination threshold. Following the procedure we described in the introduction, we determined values of the exponent of the power function, p', that maximized Formula 5 for the five levels of the tone in quiet. The value of the exponent, p', and the values of I_c and I_s can be used to generate estimates of the values of ΔL. Values of p' are shown in column 1 of Table 2. Notice that the values vary little over subjects—four of the subjects' values are bunched between .066 and .071. Column 2 of Table 2 gives the mean estimate of ΔL for every subject. The value of the threshold loudness difference varies from a low of .0186 to a high of .0592. Column 3 gives the proportion of total sum of squares due to the mean, the goodness-of-fit index used throughout this paper. Recall that a value of 1.00 indicates that the residual variance is zero and that the model fits the data perfectly. The index reaches 98.5% in all cases. Thus, for each subject and for the group, it was possible to select a value of p' that yielded ΔLs that were nearly equal. The values of p' deserve some discussion. In Parker and Schneider (1980), we found that values of p' near 0.11 allowed the constant-loudness-difference model to effectively capture the results of numerous intensity-increment studies on pure tones. There was some experiment-to-experiment variability in p', however (Parker & Schneider, 1980, Table 2; see also Jesteadt, Wier, & Green, 1977, Table IV). Our subjects here reliably produced a p' near the lower limit of those we found in others' data. We note that fact but have no account for it.

MODELS

The loudness-matching data obtained in Experiment 1 are similar to those of Moore et al. (1985), the intensity-increment thresholds for tones in notched noise obtained in Experiment 2 are similar to those obtained by Moore and Raab (1974), and the intensity-increment thresholds obtained in quiet replicate the near-miss function.

The failure to obtain a near-miss to Weber's law in notched noise has been attributed to masking of distortion products (Viemeister, 1972) and to the effects of notched noise on the excitation pattern on the basilar membrane (Florentine & Buus, 1981). In this paper, although we will not attempt to explain why the near-miss does not hold in noise, we will attempt to show that the change from the near-miss for intensity discrimination in quiet to something resembling Weber's law for tones in notched noise can be connected to the loudness reduction observed for tones in notched noise. To do this, we had to relax some of the restrictions of the constant-loudness-difference model. In Model 1, we assume that the effective intensities entering into Equation 4 when tones are presented in notched noise are the intensities of the tones in quiet that are equivalent to them in loudness. In Model 2, we make the discrimination exponent in noise vary as does loudness in noise. These two models will be compared with one (Model 0) that assumes no linkage between the discrimination of tones in quiet and the discrimination of tones in notched noise.

Model 0

For tones in quiet, Equation 4 (a constant-loudness-difference model) provides a good fit to the data. Suppose that Weber's law holds for tones in noise. Then the decibel difference between I_{cn} and I_s will be constant where I_{cn} is the intensity value of the comparison stimulus that provides 75% discrimination accuracy in noise. (This is the same as a constant-loudness-difference model in which loudness is a logarithmic function of intensity, although this is not the only possible interpretation of Weber's law.) In this case, we have

$$I_{cq}^{p'} - I_s^{p'} = k1$$

for the unmasked tones, where I_{cq} is the intensity of the comparison tone that provides 75% accuracy in quiet, and $\log(I_{cn}) - \log(I_s) = k2$ for the masked tones. Then, letting $k2/k1 = k$,

$$k(I_{cq}^{p'} - I_s^{p'}) = \log(I_{cn}/I_s). \quad (6)$$

Equation 6 specifies that the difference between the power-transformed comparison and standard intensities for tones in quiet must be proportional to the logarithmic difference between the analogous intensities in noise. Here, k is a free scale parameter. The values for p' were those that appeared in Table 2 and were estimated from the tones in quiet. We iteratively varied k and recorded the value of the goodness-of-fit index. The values of k that maximized that index, along with the index value, are listed for all 7 subjects and for the group in the first two columns of Table 3. This relation gives a good account of the results for all subjects but P.B. and T.T. Values of k vary by less than a factor of 4.

Note that this model does not mention the loudness-reduction data of Experiment 1, and in summarizing the intensity-discrimination data of Experiment 2 permits different discrimination functions in and out of noise. The remaining two models assume that intensity discrimination in noise is related to loudness in noise.

Table 3
Value of k and Goodness-of-Fit Index for Model 0

Subject	k	Index
J.C.	2.7	.9823
L.T.	7.7	.9892
P.R.	6.3	.9773
P.B.	5.3	.9835
R.L.	4.9	.9906
R.S.	2.1	.9852
T.T.	4.4	.9554
Group	4.4	.9940

Model 1

In Equation 4, the loudness difference between I_c and I_s is considered to be constant at threshold and loudness is assumed to be a power function of intensity. The simplest extension of this model to tones in noise is to suppose that the loudness difference at threshold between two tones in noise is not only constant but identical to the loudness difference at threshold for tones in quiet. Because we know from the matching data of Experiments 1A and 1B that the loudness of a tone in noise differs from the loudness of the same tone in quiet, we should use, in Equation 4, the intensity values of tones in quiet that are equivalent in loudness to the tones presented in noise. Since we used different intensity values in Experiments 1A and 2, we estimated the equivalent unmasked intensities by linear interpolation between the points in Figure 1. Thus, for any subject and masked standard intensity, I_s, we estimate its unmasked equivalent, $U(I_s)$. An estimate of the unmasked equivalent of I_{cn}, $U(I_{cn})$, is interpolated similarly, even though the relations between tone and mask are slightly different for I_{cn} and I_s. Since the spectrum level of the noise was always 35 dB below I_s and the comparison tones exceeded I_s intensities by 0.5 to 2.5 dB, the spectrum level of the noise ranged from 35.5 to 37.5 dB below I_{cn}. As Figures 2 and 3 show, the loudness reduction induced by signal-to-noise ratios of 35 and 40 dB are virtually identical, and those induced by signal-to-noise ratios of 20 and 35 dB are very close. Thus, Experiment 1A provides good estimates of loudness reduction, and hence of $U(I_{cn})$, for signal-to-noise ratios in the range of 35 to 37.5 dB.

To estimate the loudness difference between I_{cn} and I_s in notched noise, we raise $U(I_{cn})$ and $U(I_s)$ to the p'th power, where p' is the exponent taken from Table 2. Our model then is

$$I_{cq}^{p'} - I_s^{p'} = U(I_{cn})^{p'} - U(I_s)^{p'} = \Delta L. \quad (7)$$

Table 4 shows the goodness-of-fit index for the model, along with the estimates of the constant loudness differences. As Table 4 shows, except for Subject P.R., the

Table 4
Goodness-of-Fit Index and Loudness Difference for Model 1

Subject	Index	ΔL
J.C.	.9125	.0297
L.T.	.6787	.0503
P.B.	.8197	.0450
P.R.	.9686	.0181
R.L.	.7785	.0498
R.S.	.8620	.0704
T.T.	.6683	.0513
Group	.8286	.0425

fits are rather poor. Thus, the notion that notched noise alters the loudnesses of pure tones but has no effect on the intensity-discrimination process fares rather badly.

Model 2

Model 1's failure to fit the data shows that a constant-loudness-difference model cannot link loudness to discriminability in notched noise. This failure led us to search for other models that could provide such a linkage. The models that we explored abandoned the notion that the discrimination exponent and the loudness exponent were identical, but still attempted to link loudness to discriminability. One model, which does provide a good fit to the data, is described here. It assumes that the discrimination exponent is proportional to the relative loudness of the tone in notched noise to the loudness of the tone in quiet. We define

$$R = U(I)^p/I^p, \qquad (8)$$

where p, the exponent of the loudness function, is unknown and differs from p'. Thus, if L is the loudness of a tone in quiet, $L \cdot R$ is the loudness of that tone in noise. If the discrimination exponent in notched noise is proportional to R, then we have Model 2:

$$\Delta L = I_{cn}^{vR} - I_s^{vR}, \qquad (9)$$

where v is a constant. Note that in Model 2, when there is no loudness reduction, $R = 1$, and the discrimination exponent is unchanged; thus, the value of v should equal p', the discrimination exponent in quiet. When, however, loudness is reduced by notched noise, the effective discrimination exponent, vR, is lowered. The two parameters for Model 2 are p, the exponent of the loudness function, and v, the constant of proportionality. An iterative procedure was used to find best values of p and v for the 7 subjects and for the group data. These values and the goodness-of-fit index for the model are shown in Table 5. Note that the fit of the data to the model is extremely good. In fact, the fit is better than that for Model 0 for 4 of the 7 subjects and for the group data. Furthermore, the estimated parameters are quite reasonable. The estimates of the loudness exponent, p, range from .18 to .40, with a mean of .30. These are values typically found for loudness-estimation experiments (e.g., Marks, 1979). Note also that the values of the parameter, v, are very close to the p' values estimated for the discrimination exponents for tones in quiet. For 3 of the 7 subjects and for the group data, v and p' are virtually identical.

Table 5
Values of p, v, and Goodness-of-Fit Index for Model 2

Subject	p	v	Index
J.C.	.167	.080	.9886
L.T.	.327	.046	.9798
P.B.	.279	.061	.9921
P.R.	.242	.046	.9856
R.L.	.262	.048	.9736
R.S.	.354	.068	.9812
T.T.	.398	.103	.9914
Group	.351	.065	.9961

GENERAL DISCUSSION

The results of Experiments 1A and 1B and those of Moore et al. (1985) demonstrate that notched noise significantly affects the loudness of tones presented in the middle of the notch. In both sets of experiments, the ratio of the signal intensity to the spectrum level of the noise was held constant. Yet as Figure 1 shows, the amount of loudness reduction due to the notched noise varies, with maximal reduction occurring at intermediate intensity levels. Moore et al. (1985) show that this pattern occurs at several different signal-to-noise ratios. They entertain the thought that some combination of differential spread of excitation and suppression of both noise bands and signal as a function of intensity may account for the pattern. The available data do not permit a confident selection from among these possibilities. What is clear, however, is that the amount of loudness reduction is a function of something other than simply the signal-to-noise ratio.

The poor fit to Model 1 shows that Fechner's assumption cannot relate discriminability to loudness in notched noise. Model 2, however, does manage to link loudness and discriminability. It does so by giving up the assumption that the loudness exponent and the discrimination exponent are identical, proposing instead that the discrimination exponent is proportional to the relative loudness of the tone in and out of noise. Although Model 2 accounts for the results of the present study, further research is required to establish its generality. We do not know, for instance, whether Model 2 can provide equivalently good fits when (1) signal-to-noise ratios are varied substantially, (2) the notch is filled in, or (3) notch width is systematically varied.

In addition to providing a good fit to the present data, Model 2 accurately predicts the results reported by Hellman, Scharf, Teghtsoonian, Teghtsoonian, and Hellman (1985), who devised a method (using broad- and narrow-band noise maskers) for presenting masked tones whose loudness levels at one intensity were equal but whose loudness functions differed in steepness at that intensity. They found that the growth of tonal loudness with intensity was more rapid in narrow-band noise than in broadband noise. They plotted the two growth functions and found the intensity at which they crossed. At this intensity, the loudness of the tone in broadband noise was the same as the loudness of the tone in narrow-band noise, but the growth rates of tonal loudness with intensity were different. Tonal intensity-increment thresholds at this standard intensity proved to be equal in the presence of the two maskers. As a result, Hellman et al. (1985) concluded that intensity-increment thresholds were independent of the rate of change of loudness but, rather, depended on loudness itself. But notice that, in both cases, tonal loudness in masking was reduced by the same amount to the same level. Therefore, Hellman et al. (1985) equated not only loudness but also loudness reduction. Thus, Hellman et al.'s result is in accord with the findings for Model 2, since in Model 2 loudness reduction governs the size of the jnd. As we shall show below, in our data, equal-loudness levels do not produce equal jnds. Therefore, if notched, narrow-band, and broadband noises all work similarly, the Hellman et al. result is the consequence of their equating loudness reduction rather than of equating loudness per se.

Another report concluding that loudness level governs the size of the jnd is that of Zwislocki and Jordan (1986). They determined intensity-increment thresholds for two groups of listeners—one group of college students with normal hearing in both ears and a group of persons with monaural sensorineural hearing loss with loudness recruitment. Intensity-increment thresholds were determined at six levels for the normal subjects. For the subjects with hearing loss, dichotic loudness matches revealed the intensities that matched, for the abnormal ears, those six standard intensities presented to the good ears. Thus, Zwislocki and Jordan had six standard intensities for normal ears and the six intensities for abnormal ears which matched them in loudness.

Intensity-increment thresholds were determined for the six standard intensities in normal subjects; intensity-increment thresholds were determined for abnormal ears at the six intensities that matched in loudness the standard intensities presented to the normal ears. Thus, intensity-increment thresholds were determined for normal and abnormal ears at the same loudness levels. The main finding was that when loudness levels were equal, jnds were also equal. Zwislocki and Jordan (1986) concluded, therefore, that loudness level governed the size of the jnd.

We can apply their analytic procedure to our data. The results of Experiment 1A gave the intensity levels, $U(I_s)$, of tones in quiet that matched in loudness the standard intensities, I_s, used in Experiment 2 on intensity-increment thresholds in noise. Therefore, we can plot intensity-increment thresholds in notched noise as a function of the intensity levels of tones in quiet $[U(I_s)]$ that are equivalent in loudness. On the same axes, we can plot the jnds for tones in quiet as a function of the standard stimulus, I_s. The results for the group data of the 7 subjects are

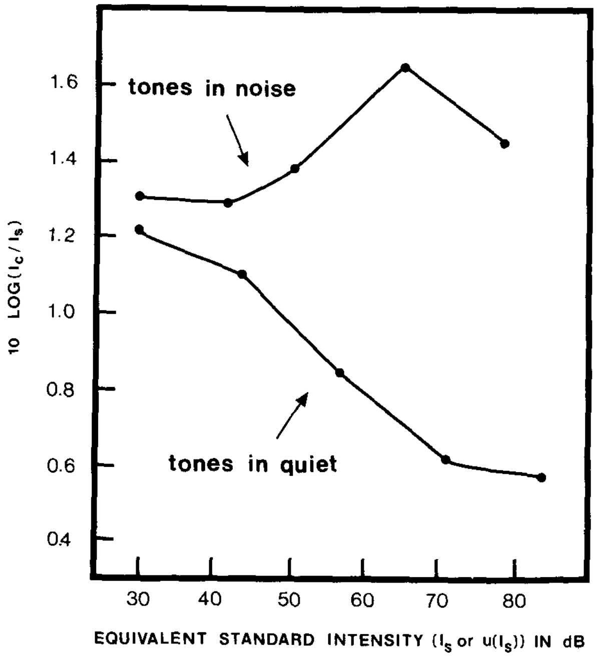

Figure 4. Group average intensity-increment thresholds for tones in quiet and in noise. Abscissa values are intensity levels of equally loud tones in quiet.

shown in Figure 4. Notice that the two functions are neither equivalent nor similar. Were our data to follow the Zwislocki and Jordan (1986) pattern, the functions should merge into one smooth curve. Inspection of Table 1 reveals that individual subjects would, like the group, produce two quite distinct functions. Thus, our data differ from those of Zwislocki and Jordan. This suggests that the loudness reduction induced by sensorineural hearing loss differs from that induced by band-reject masking noise. Loudness level alone does not govern intensity-increment threshold for tones in notched noise.

In summary, a constant-loudness-difference model (Fechner's assumption) cannot account for intensity-increment thresholds in notched noise. A model is proposed that successfully links loudness and discriminability for tones in quiet and tones in notched noise, and accurately predicts Hellman et al.'s (1985) findings on jnds for tones in narrow-band and broadband noise. It does so by assuming that discrimination is based on differences between power-transformed intensities. The model further assumes that the exponent that accounts for discrimination in notched noise is proportional to the relative loudness of the tone in noise to the loudness of the same tone in quiet. Further research is needed to test the validity of this assumption.

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