Effects of external noise on detection of intensity increments^{a)}

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The detection of an intensity increment in a longer duration sinusoid or pedestal is often used as a measure of intensity resolution, but the decision processes underlying this measure are poorly understood. Thresholds were obtained for detection of an increment in a 370-ms, 4-kHz pedestal in quiet or in noise to determine the relative contributions of background noise level and pedestal level, the effect of increment duration, and the effect of different noise spectra. Increment detection thresholds expressed in units of $\Delta L[10 \log(1 + \Delta I/I)]$ decreased as pedestal levels increased. At low pedestal levels, increment detection was limited by the masking effect of the noise and was similar across noise conditions for pedestals of equal sensation level. At high pedestal levels, the noise had no effect and increment detection was determined by the pedestal level in dB SPL (sound pressure level). Increment detection improved with increasing increment duration and was altered less by a noise band above the pedestal/increment frequency than by a broadband noise that produced equal masking at the pedestal/increment frequency. The quadratic-compression model described by Neely and Jesteadt [(2005). *Acta Acust. Acust.* **91**, 980–991] provided a better approximation to the data than a model based on excitation patterns.

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I. INTRODUCTION

Increment detection (detection of an intensity increment when the standard or pedestal is longer in duration than the increment or signal) and intensity discrimination (when the increment and pedestal are the same duration) are two well-established measures of intensity resolution that appear to rely on different decision processes. One line of evidence indicating different underlying processes is that interval-to-interval variation in overall level has little effect on increment detection (Jesteadt *et al.*, 2003) but has a predictable effect of degrading intensity discrimination (Jesteadt *et al.*, 2005). A second line of evidence indicating different underlying processes is that background noise has been shown to have a significant effect in limiting increment detection (Glasberg *et al.*, 2001; Oxenham, 1997) but less effect on intensity discrimination (Jesteadt *et al.*, 1977; Neff and Jesteadt, 1996). The present study explores the effects of noise on increment detection over a wide range of levels to determine the factors that contribute to those effects.

Two previous studies have examined increment detection in quiet and in noise. Oxenham (1997) obtained thresholds for detection of both increments and decrements in a 4-kHz, 500-ms pedestal. The pedestal was presented at 55 dB SPL (sound pressure level), with noise at –20, –10, 0, 10, or 20 dB spectrum level, plus a no-noise condition. Increments or decrements had steady-state durations ranging

from 2 to 198 ms with 2-ms raised-cosine ramps. Only noise levels of 0-dB spectrum level and higher had an impact on increment detection, and the effect was greater at shorter increment durations. In a second experiment, Oxenham obtained thresholds for detection of increments and decrements using the same pedestal, with 10-dB spectrum level noise that was either low-pass filtered at 4.4 kHz, high-pass filtered at 3.6 kHz, or band-reject filtered to create a notched noise with cutoff frequencies of 3.6 and 4.4 kHz. Increment detection was best in low-pass noise, suggesting that the primary effect of the noise was to mask upward spread of excitation of the pedestal and pedestal plus increment. The effect of low-pass noise compared to no noise, however, suggested that noise played some role beyond limiting excitation. Additional conditions ruled out any effect of spectral splatter.

Oxenham (1997) evaluated a multi-stage temporal window model that has been used frequently in modeling increment and decrement detection (e.g., Peters *et al.*, 1995) and found that it predicted little or no effect of noise, although the data indicated that noise had a significant effect on increment detection and an even larger effect on decrement detection. Oxenham noted that the noise might interfere with modulation detection as well as limiting spread of excitation.

Comparing increment detection in quiet and in noise, Glasberg *et al.* (2001) repeated some of the detection-in-noise conditions used in earlier studies (Peters *et al.*, 1995; Moore *et al.*, 1996, 1999; Moore and Peters, 1997) and included corresponding conditions for increment and decrement detection in quiet. The pedestal was a 0.25-, 1-, or 4-kHz tone presented 18 dB above masked or quiet threshold [i.e., at 18 dB SL (sensation level)]. The noise maskers were chosen such that the output of an auditory filter centered on

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the pedestal would be 56.6 dB. Thus, only one noise level (and one corresponding signal-to-noise ratio) was tested in each masking condition. As in earlier studies, increment detection thresholds for conditions with noise maskers decreased with increasing increment duration and with increasing pedestal frequency. In conditions without noise, increment detection thresholds showed a similar effect of duration but were either constant or increased with increasing pedestal frequency. Increment detection at 4 kHz was poorer in quiet than in noise for pedestals that were 18 dB SL in both conditions. Glasberg *et al.* suggested that this unusual result might indicate that external noise had a smaller effect on performance than fluctuations in internal noise. A second experiment used only 4-kHz, 70-dB SPL pedestals presented in quiet or in three noise conditions: a narrow-band noise centered at either 4 or 7 kHz or with both bands together. To determine whether the interaction of noise and frequency effects in the first experiment was due to differences in the bandwidth of the noise at the output of auditory filters at 0.25, 1, and 4 kHz, the bandwidth of the noises in the second experiment varied from 0.05 to 0.4 kHz. This range was chosen to include the equivalent rectangular bandwidth (ERB) of the auditory filter at 0.25 kHz but to stop short of the 0.456 kHz ERB at the 4-kHz pedestal frequency used in the experiment. The effect of noise at 7 kHz was small, either alone or in combination with noise at 4 kHz, and the effect of noise bandwidth was small as well, with slightly better performance at the widest bandwidth.

The model used by Glasberg *et al.* (2001) was similar to the model described by Oxenham (1997), with the addition (after the temporal integrator) of a log transform, an internal noise, and a decision device based on a template-matching mechanism (Moore *et al.*, 1999). The decision process was based on a comparison (cross correlation) of the internal representation of the incoming stimulus with a template or pattern of levels across time that was created by averaging internal representations of more audible stimuli. Moore *et al.* (1999) and Glasberg *et al.* (2001) noted that template matching has elements in common with modulation detection, as described by Dau *et al.* (1996, 1997).

Oxenham (1997) and Glasberg *et al.* (2001) found evidence that background noise influenced increment detection both by limiting spread of excitation and by introducing modulation that might interfere with template matching or modulation detection. Oxenham emphasized the first interpretation, whereas Glasberg *et al.* emphasized the second. The effect of spread of excitation was reduced in these studies by the use of a limited range of levels. When pedestal level is varied over a wide range in quiet, the effect of level is larger than the effects of frequency, of increment duration, or of the other parameters that have been manipulated in studies of increment detection (e.g., Viemeister and Bacon, 1988). Thus, it is important to understand the origins of the level effect and how to control it.

To obtain a more complete picture of the effect of spread of excitation on increment detection and of the role of noise in reducing that effect, thresholds for increment detection were obtained at a number of different noise spectrum levels, with multiple pedestal-to-noise ratios for each noise level.

The effect of increment duration was explored across three experiments. A fourth experiment explored the effect of varying the bandwidth of the noise masker.

II. EXPERIMENT 1: EFFECT OF PEDESTAL SL AND NOISE SPECTRUM LEVEL (60-MS INCREMENT)

In experiment 1, the range of conditions was expanded beyond previous studies. Increment detection thresholds were obtained over a range of noise and pedestal levels to compare increment detection as a function of pedestal level in both dB SPL and dB SL. The goal was to determine if the effects of noise on increment detection across a range of levels could be accounted for by assuming that the noise limited the spread of excitation or whether it was necessary to assume that an additional factor such as envelope fluctuation was involved.

A. Subjects

Four paid volunteers (1 male and 3 females), ages 19–21 years, participated. All were college students and two have previous experience with an intensity discrimination task. Hearing had been screened at 0.5, 1, 2, and 4 kHz within the past year using a two-interval-forced-choice (2IFC) adaptive procedure. Thresholds were ≤ 18 dB SPL for all test frequencies bilaterally for all subjects.

B. Apparatus

Stimuli were generated digitally at a sampling rate of 50 kHz using an array processor [Tucker Davis Technologies (TDT) AP2] and 16-bit digital-to-analog converters (TDT DD1). The pedestal and noise were generated on one channel of the DD1; the increment was generated on the other. The output of each channel was low-pass filtered at 20 kHz (TDT FT6) and attenuated (TDT PA4), and then the outputs were combined (TDT SM3) and presented to the listener through a headphone buffer (TDT HB6), a remote passive attenuator in the sound-treated chamber, and a Sennheiser HD 250 Linear II headphone. Stimuli were delivered to the left ear. With parallel attenuators, summers, and headphone buffers, up to four listeners were tested simultaneously. The same equipment was used in all experiments.

C. Procedure

Adaptive thresholds were estimated in a 2IFC task. Each trial consisted of a 300-ms warning interval, two 390-ms observation intervals separated by 560 ms, and a 100-ms feedback interval following the response of the final subject. A 400-ms pause preceded the beginning of the next trial. Visual markers for the warning and observation intervals and correct-interval feedback were given on a message window at the top of the keypad used to indicate responses. The increment was presented at an initial level well above threshold, decreased after two consecutive correct responses, and increased after one incorrect response to estimate the 71% correct point on the psychometric function (Levitt, 1971). Initial step sizes were 4 dB until the fourth reversal, and then 2 dB. Threshold was calculated as the average level of the

TABLE I. Parameters of stimuli used in the experiments.

Expt.	Pedestal level	Signal duration (ms)	Noise level (dB N_0)	Noise band
1	15, 25, 35, 45, 55, 65, and 75 dB SPL	60	0, 10, or 20	8 kHz low pass
2	-5, 0, 5, 10, 15, 20, 25, 30, 40, 55, 70, and 85 dB SL	10	0, 10, or 20	8 kHz low pass in all conditions; 16 kHz low pass in 40 dB SL pedestal, 0 dB N_0 condition
3	0, 5, 10, 20, 40, and 80 dB SL	20, 40, or 60	20	8 kHz low pass
4	10, 20, 30, 40, and 50 dB SL	10	20	4.8–16 kHz bandpass; 5.6–16 kHz bandpass; 7.2–16 kHz bandpass; 16 kHz low pass

Note: Pedestal and signal were 4 kHz and pedestal and noise durations were 370 ms in all conditions. The 0, 10, and 20 dB N_0 values correspond to 39, 49, and 59 dB overall level. For pedestal level specified in SL, the reference is the mean threshold across subjects for the pedestal in quiet or in noise.

reversal points after the fourth reversal for 100-trial blocks. The number of blocks per condition is specified below.

D. Stimuli and conditions

The pedestal was a 4-kHz, 370-ms tone with 5-ms $\cos^2$ ramps, presented in different conditions at 15, 25, 35, 45, 55, 65, and 75 dB SPL (not all pedestal levels were presented in each noise condition). The increment was a 4-kHz, 60-ms tone with 5-ms $\cos^2$ ramps, adapted in level to estimate threshold. The onset of the increment was 205 ms after the onset of the pedestal (0-voltage points). These temporal parameters resulted in a 200-ms steady-state segment of the pedestal preceding and a 100-ms segment following the increment, the same stimulus configuration used by Glasberg *et al.* (2001). The background noise, when present, was low-pass filtered at 8 kHz, was turned on and off with the pedestal, and was presented at 0, 10, and 20 dB spectrum level (N_0) in different conditions. These spectrum levels correspond to 39, 49, and 59 dB overall level. The stimulus parameters are summarized in Table I.

In addition to estimates of the threshold of the increment in the presence of the pedestal, for pedestals presented in quiet and in noise, estimates of thresholds were obtained for the increment without the pedestal and for the pedestal itself (i.e., a 60-ms, 4 kHz tone and a 370-ms, 4 kHz tone presented in quiet and in each of the three levels of noise). When the increment and pedestal were presented together, initial pedestal phase was fixed at 0° , and increment phase was tied to the pedestal in quadrature. When the tones were presented individually, the initial phase was random. In increment detection conditions for pedestals presented in noise, a different range of pedestal levels was used for each noise level. In 0-dB N_0 conditions, increment detection was measured using a range of pedestal levels from 25 to 55 dB SPL. The ranges were 35–65 dB SPL in 10-dB N_0 noise and 45–75 dB in 20-dB N_0 noise. In the absence of noise, increment detection was measured for pedestal levels from 15 to 75 dB SPL. Two estimates of threshold were obtained for the short and long duration 4-kHz tones in quiet after all other

data collection was complete. Threshold estimates in each of the remaining conditions were based on two repetitions of two blocks each in a counterbalanced order.

E. Results and discussion

Mean thresholds for the pedestal in quiet and in noise are shown in Table II for this experiment and for conditions used in later experiments. Increment detection results for experiment 1 are shown in Fig. 1, where the pedestal level ($10 \log I$) and increment level at threshold ($10 \log \Delta I$) have been converted to $\Delta L(10 \log(1 + \Delta I/I))$ and plotted on a log axis (Buus and Florentine, 1991). Geometric mean ΔL across subjects is shown as a function of pedestal level in dB SPL in the left panel and in dB SL (re thresholds for detection of the pedestal in quiet or in noise, from Table II) in the right panel. Because threshold for detection of the pedestal in quiet is close to 0 dB SPL, there is little shift in the data for the

TABLE II. Mean threshold for detection of the pedestal in quiet and in noise for conditions in experiments 1–4. Threshold values are means across subjects in dB SPL. Four subjects participated in experiment 1. Another group of three subjects participated in experiments 2–4.

	Threshold in dB SPL	Standard deviation
Experiment 1		
Quiet	5.1	6.32
0 dB N_0 , 8 kHz low pass	25.1	2.15
10 dB N_0 , 8 kHz low pass	34.0	1.81
20 dB N_0 , 8 kHz low pass	43.9	2.40
Experiments 2 and 3		
Quiet	-0.6	5.42
0 dB N_0 , 8 kHz low pass	19.4	0.58
10 dB N_0 , 8 kHz low pass	33.7	1.29
20 dB N_0 , 8 kHz low pass	42.4	1.13
0 dB N_0 , 16 kHz low pass	21.8	4.07
Experiment 4		
20 dB N_0 , 4.8–16 kHz	21.0	9.14
20 dB N_0 , 5.6–16 kHz	10.3	2.05
20 dB N_0 , 7.2–16 kHz	4.5	5.75
20 dB N_0 , 16 kHz low pass	43.5	2.67

FIG. 1. Geometric mean values of ΔL across four subjects for experiment 1. ΔL was calculated as $10 \log(1 + (\Delta I/I))$. The 4-kHz, 60-ms increment was presented 205 ms after the onset of a 4-kHz, 370-ms pedestal. Increment detection was measured in conditions without noise (filled squares) or with 0- (circles), 10- (up triangles), or 20-dB (down triangles) spectrum level (N_0) noise that was low-pass filtered at 8 kHz and gated on and off with the pedestal. The data are plotted as a function of pedestal level in dB SPL on the left and in dB SL (based on thresholds for detection of the pedestal in quiet and in noise) on the right. For clarity, error bars representing ± 1 standard deviation are shown only on the left panel.

no-noise condition, but the effects of noise are different in the two panels. In dB-SPL coordinates, mean values of ΔL are higher in noise for a given pedestal level than in the no-noise condition, and mean ΔL increases with noise level. In dB SL coordinates, results are similar across noise levels, and the difference between noise and no-noise conditions is small. Compared to the no-noise condition, there is an improvement in threshold in the highest pedestal-level and noise-level conditions. Also, there is the appearance of a notch in the data around 10 dB SL. Error bars have been plotted in the left panel but omitted in the right panel to make the data points more visible.

The use of different pedestal-level ranges for different noise conditions was efficient but made statistical analyses more difficult. For this and later experiments, a within-subjects analysis of variance (ANOVA) was conducted on the log ΔL values for pedestal levels that were in common across noise levels. Effects are reported as significant for $\alpha < 0.05$. An ANOVA for the four subjects that was restricted to the three pedestal levels (45, 50, and 55 dB SPL) used at all three noise levels indicated significant effects of pedestal level [$F(2, 6) = 9.085$] and noise level [$F(2, 6) = 22.656$] but no interaction. A second ANOVA of six pedestal levels approximately equated in dB SL indicated a significant effect of pedestal level [$F(5, 15) = 46.319$], a marginally significant effect of noise level [$F(2, 6) = 5.470$], and a significant interaction. The large effect of noise level evident in the first analysis and in the left panel of Fig. 1 is all but eliminated when the pedestal levels are grouped by SL as in the right panel of Fig. 1.

As suggested by Oxenham (1997), the main effect of the noise is to restrict the spread of excitation. The area under the excitation pattern is relatively constant across noise levels for a constant-SL pedestal, and increment detection is relatively constant as well. Increment detection improves as the signal-to-noise ratio of the pedestal increases at a given noise level. This appears to be due to increased spread of excitation rather than increased distance from the fluctua-

tions in the noise wave form because the same degree of improvement with pedestal level can be seen in the absence of noise. The notch at 10 dB SL is reminiscent of the notch in intensity discrimination near threshold (Hanna *et al.*, 1986) but is small and occurred at a higher SL than the notch reported by Hanna *et al.*

III. EXPERIMENT 2: EFFECT OF PEDESTAL SL AND NOISE SPECTRUM LEVEL (10-MS INCREMENT)

Results of experiment 1 suggested that the effect of noise on increment detection was to restrict spread of excitation rather than to introduce modulation that would interfere with detection of a brief change in the level of a longer duration pedestal. Because the increment duration was relatively long, however, any independent effects of the noise alone, such as effects due to envelope fluctuations, might have been missed. This issue was addressed in experiment 2 by use of a shorter, 10-ms increment. To explore the possible near-threshold notch in greater detail, pedestal levels were equated in dB SL and were extended to -5 dB SL in the noise conditions.

A. Subjects

Three volunteers (1 male, 2 females, ages 31–33 years) participated in experiment 2 and in the two subsequent experiments. One subject was paid for his participation. Two of the subjects (one of the authors and a college student) had previous experience with an intensity discrimination task, while the third subject (a new laboratory assistant) did not. Hearing thresholds were tested using standard clinical procedures within the 6 months prior to the experiment. Thresholds were ≤ 15 dB HL (hearing level) at all audiometric test frequencies from 0.5 to 8 kHz bilaterally for all subjects. Air-bone gaps were no greater than 5 dB.

B. Stimuli and procedures

The 4-kHz pedestal was the same as in experiment 1, except that pedestal levels in quiet ranged from 10 to 85 dB SL (re mean threshold across subjects for the pedestal-in-quiet condition) and pedestal levels in noise ranged from -5 to 40 dB SL (re the mean threshold across subjects for the pedestal in the presence of each of the three noise levels). The background noise properties were the same as in experiment 1. An additional single condition was run with a 16-kHz low-pass noise in the 0-dB N_0 , 40-dB SL pedestal condition to determine whether additional noise in the 8–16 kHz range would influence increment detection thresholds by masking off-frequency listening or spread of excitation at higher frequencies. The increment was the same as in experiment 1, except that the duration was 10 ms with 5-ms $\cos^2$ ramps (i.e., no steady state). Stimulus parameters are summarized in Table I.

Two consecutive 100-trial blocks were completed for conditions in which the pedestal was presented without noise at 85, 70, 55, 25, and 10 dB SL and for the 16-kHz low-pass noise conditions. Four 100-trial blocks were completed for all other conditions. Masked thresholds were obtained for the increment and the pedestal in the 0- and 20-dB N_0 , 8-kHz

FIG. 2. Geometric mean values of ΔL across three subjects for experiment 2 plotted as in Fig. 1. Error bars representing ± 1 standard deviation are shown only on the left panel. The increment duration was 10 ms. All other stimulus parameters, except for specific pedestal levels, were the same as in experiment 1. The asterisk in each panel represents increment detection measured in the presence of a 0-dB spectrum level noise that was low-pass filtered at 16 kHz, with the pedestal at 40 dB SL (re mean threshold across subjects for the pedestal in the 16-kHz low-pass noise).

low-pass noise conditions, followed by increment detection thresholds in those two noise conditions. Absolute thresholds for the increment and the pedestal and increment detection thresholds in quiet were then measured, followed by masked thresholds and increment detection thresholds in 10-dB N_0 , 8-kHz low-pass conditions. Finally, masked thresholds and increment detection thresholds were measured in the 20-dB N_0 , 16-kHz low-pass noise.

C. Results and discussion

The results are shown in Fig. 2 in a form that parallels Fig. 1. The asterisk in each panel indicates the data point obtained at the lowest noise level and highest pedestal level using noise low-pass filtered at 16 kHz. Results for this condition were consistent with the other data, suggesting that subjects were not using information above the 8-kHz cutoff of the low-pass noise in the main set of conditions.

As in experiment 1, the large effect of noise that is apparent when the data are plotted as a function of pedestal level in dB SPL is greatly reduced when the data are plotted in dB SL. Unlike experiment 1, there is no notch at low levels. Results are similar across noise levels. The difference in results between no-noise and noise conditions is small, except at high SLs where ΔL for increment detection in quiet is larger than ΔL in noise for pedestals equal in dB SL. The shapes of the functions differ for no-noise and noise conditions. The no-noise function becomes shallower at higher levels, whereas the noise functions become steeper with a greater effect of noise at higher noise levels.

Data were available for the quiet conditions and the three noise levels at pedestal levels of 5, 10, 15, 20, and 40 dB SL. An ANOVA of the log ΔL values for the three subjects showed significant effects of pedestal SL [$F(4,8) = 441.432$], noise level [$F(3,6) = 7.104$], and a significant interaction [$F(12,24) = 11.502$]. ANOVAs conducted at individual pedestal levels showed a significant effect of noise level only at 40 dB SL [$F(3,6) = 23.676$]. *Post hoc* comparisons of means at 40 dB SL did not show a significant difference between any two conditions. The analyses support the

FIG. 3. Mean thresholds for the increment in dB SPL across three subjects as a function of pedestal level in dB SPL for experiment 2 with error bars representing ± 1 standard deviation. Symbol definitions are the same as in Fig. 2. Data points on the far left show thresholds for detection of the increment in the absence of the pedestal in quiet and in the three levels of noise. Increment detection thresholds are limited by the noise at low pedestal levels and converge on a single value in dB SPL at high pedestal levels.

conclusion that there is an effect of noise level at high pedestal levels even when pedestal levels are equated in SL.

Given that both the noise and the pedestal can be viewed in some sense as maskers, it is informative to re-plot the data as masked thresholds for the increment, as shown in Fig. 3. Thresholds for the increment in quiet and in noise are shown on the left of the figure. At low pedestal levels, thresholds for the increment approach thresholds for the pedestal as a limit. At high pedestal levels, the noise ceases to have any effect on increment threshold. As a result of these two constraints, the masking functions become shallower with increasing noise level. To estimate the slope of masking, each set of data points was fitted with a linear regression function after excluding points near threshold for the pedestal. Slopes, intercepts, and the range of pedestal levels included in each fit are given in Table III. In the absence of noise, the increment threshold, $10 \log(\Delta I)$, increases 0.87 dB for every decibel increase in the pedestal, $10 \log(I)$. This pattern has been described as a “near miss” to Weber’s law (McGill and Goldberg, 1968a, 1968b). In the presence of noise, the deviation from Weber’s law increases with noise level. This is true regardless of whether the data are plotted in dB SPL or in dB SL.

A model of loudness and partial loudness proposed by Moore *et al.* (1997) that is based on excitation patterns can be used to make predictions for increment detection thresholds in quiet and in noise to determine the extent to which the results in Figs. 1 and 2 can be accounted for on the basis

TABLE III. Parameters for linear functions describing the increase in pedestal level with increment level in Fig. 3. The correlation with the data was greater than 0.995 in all cases.

Noise level	Slope	Y intercept	Min SPL	Max SPL	No. of points excluded
None	0.87	4.0	24	84	4
0 dB N_0	0.60	21.7	24	59	2
10 dB N_0	0.55	27.6	34	74	1
20 dB N_0	0.51	34.1	42	82	1

FIG. 4. A comparison of geometric mean values of ΔL from experiment 1, where the increment duration was 60 ms, with those from experiment 2, where the increment duration was 10 ms, with noise conditions across panels. Error bars represent ± 1 standard deviation. The solid line shows the values of ΔL predicted by the partial loudness model using an 8-phon criterion. In the absence of noise, the two sets of data are in good agreement, showing an expected effect of increment duration, and are well fitted by the model. With noise present, the data for the two studies diverge at low pedestal levels, where the model predicts better than observed performance.

of excitation patterns alone. The model has no information about the temporal properties of stimuli but makes accurate predictions of thresholds for a number of tasks involving detection of tones in noise and intensity discrimination (Jesteadt *et al.*, 2007). The only free parameter in the model is the threshold level of loudness (in phons) associated with detection of the increment. Moore *et al.* (1997) proposed a criterion value of 2 phons for prediction of masked thresholds but used higher levels to approximate results for brief stimuli to compensate for the fact that the model is not sensitive to duration. Data from experiments 1 and 2 are compared with model predictions using an 8-phon criterion in Fig. 4. To compare data and model predictions at each noise level, pedestal levels have been plotted in dB SPL. The pattern within panels would not change if the levels were plotted in dB SL. Data from the two experiments for the no-noise condition are in good agreement, with values of ΔL for experiment 2, where the increment duration was 10 ms, uniformly above those for experiment 1, where the increment duration was 60 ms. The partial loudness model provides a good account of data obtained in the absence of noise. A comparison across experiments for the three noise conditions suggests that there is an effect of increment duration at low pedestal levels in noise but not at high pedestal levels. The model predicts better performance in all noise conditions than is actually observed, with predicted values that parallel those for increment detection in the no-noise conditions, becoming shallower at higher levels. The data, particularly for the longer duration increment in experiment 1, show a curvature that is not predicted by the model. Although the major effect of the

noise is eliminated by expressing pedestals levels in dB SL, as shown in the right panels of Figs. 1 and 2, a comparison of the data with the detailed predictions of a model based on excitation patterns suggests that the effects of noise cannot be accounted for on the basis of excitation patterns alone.

IV. EXPERIMENT 3: EFFECT OF PEDESTAL SL AND INCREMENT DURATION

The goals of experiment 3 were (1) to determine whether the notch in thresholds observed at low pedestal levels in experiment 1 for the 60-ms increment was repeatable in another set of subjects, and if so, at what duration it disappeared; (2) to further explore the increment-duration parameter space over the range of durations used in experiments 1 and 2 to relate the data from these two experiments; and (3) to compare effects of duration with the results from the Glasberg *et al.* and Oxenham studies.

A. Subjects

The same three subjects from experiment 2 participated in experiment 3.

B. Stimuli and procedures

The stimulus parameters, summarized in Table I, were the same as in experiments 1 and 2 wherever possible. The 4-kHz, 370-ms pedestal was presented at 0, 5, 10, 20, and 40 dB SL, with an 80-dB SL condition included when the pedestal was presented without noise. The 8-kHz low-pass noise was presented only at 20 dB N_0 . The increment duration was 20, 40, or 60 ms with 5-ms $\cos^2$ ramps. These subjects had just completed a larger set of conditions with 10-ms increments in experiment 2, and a subset of those data was included in the analyses rather than repeating those conditions. Pedestal SLs for experiment 3 were based on the thresholds in quiet and in noise from experiment 2. Two consecutive 100-trial blocks were obtained in each condition, beginning with the longest increment and ending with the shortest increment, no-noise conditions preceding noise conditions at each increment duration. For each increment duration and noise condition, pedestal levels were tested in increasing order from 0 to 80 dB SL.

C. Results and discussion

Geometric mean values of ΔL obtained with a 60-ms increment in experiment 3 are compared with data for the same increment duration and noise level obtained in experiment 1 in Fig. 5. Given that the two experiments used independent groups of subjects and relatively few trials per data point, the agreement is remarkably good. To quantify the degree of agreement between the two sets of data, predicted values of ΔL in experiment 3 were obtained for each pedestal SPL used in experiment 1 using linear interpolation. The correlation between the 14 predicted and observed values of ΔL was 0.97. There is some indication of a notch in the new data, but it is not as clear as the notch observed at all noise levels in experiment 1.

FIG. 5. A comparison of geometric mean values of ΔL from experiment 1, where the increment duration was 60 ms, with a replication of the 60-ms condition in experiment 3 in the condition without noise and with the 20-dB N_0 noise level used in experiment 3. Error bars represent ± 1 standard deviation. There were no subjects in common between the two groups.

Results for all four increment durations in experiments 2 and 3 are shown in Fig. 6, with data for the 10-ms increment re-plotted from Fig. 2. Although pedestal levels were specified in dB SL, the data have been plotted in dB SPL to avoid total overlap of the data obtained at low pedestal levels with and without noise. The noise shifts the threshold for the pedestal by 42.4 dB. The two sets of functions converge at pedestal levels of 40 dB SL (82.4 dB SPL) in noise and 80 dB SL (79.4 dB SPL) in quiet. Consistent with the pattern observed in Fig. 3, the noise ceases to have an effect on performance at a pedestal level of 40 dB SL.

A within-subjects ANOVA of the log ΔL values for the three subjects for noise and no-noise conditions, increment durations of 10, 20, 40, and 60 ms, and pedestal levels of 5, 10, 20, and 40 dB SL (0-dB SL was not available for the 10-ms increment duration) indicated significant effects of noise [$F(1,2)=18.835$], increment duration [$F(3,6)$

FIG. 6. Geometric mean values of ΔL across subjects for the 20-, 40-, and 60-ms increment durations tested in experiment 3, with data for 10-ms increments for these subjects re-plotted from Fig. 2 (experiment 2). Error bars represent ± 1 standard deviation. The increments were presented 205 ms after the onset of a 370-ms, 4-kHz pedestal. Filled and open symbols show increment detection in quiet and detection in an 8-kHz low-pass, 20-dB N_0 noise equal in duration to the pedestal.

FIG. 7. Geometric mean values of ΔL for all data shown in Fig. 6, as a function of duration. Geometric means were computed across pedestal levels of 5, 10, 20, and 40 dB SL, and then a geometric mean and standard deviation were computed across subjects for each increment duration in quiet and in 20-dB N_0 noise. Increment durations have been corrected to equivalent rectangular durations. Thresholds are lower in noise because the equal-SL conditions correspond to higher dB SPL in noise, but there is an effect of duration with or without noise. The dashed reference indicates increment thresholds in units of $10 \log(\Delta I)$ that decrease by 1.5 dB for every doubling of increment duration.

$=34.870$], and pedestal level [$F(3,6)=209.708$]. There were significant interactions of noise (no noise vs 20 dB N_0) and pedestal level [$F(3,6)=19.695$] and increment duration and pedestal level [$F(9,18)=8.951$]. The significant effect of noise reflected a geometric mean ΔL across subjects and conditions of 4.55 dB in the absence of noise and of 2.91 dB with noise present. This difference is a result of the physical difference in pedestal levels between noise and no-noise conditions and is barely significant. The other two main effects and the two significant interactions are clearly observable in Fig. 6. There is a curvature, if not a clear notch, for data at low pedestal levels in noise for the two longer increment durations but not the shorter durations. The effect is not sufficient to result in a significant interaction of noise, increment duration, and pedestal level.

The effect of increment duration is larger at low pedestal levels, but it is generally the case that values of ΔL decrease as increment duration increases. The lack of a duration-by-noise interaction suggests similar effects of duration in quiet and in noise, as shown in Fig. 7. Geometric mean values of ΔL are lower in the noise conditions only because the pedestals were presented at higher physical levels. To correct for the use of 5-ms onset and offset ramps, durations have been plotted as equivalent rectangular durations. Slopes of the best fitting lines in quiet and in noise would be -0.26 and -0.32 , respectively. These values are comparable to those reported for intensity discrimination with tones by Florentine (1986) and are within the range reported for increment detection with noise stimuli by Heinz and Formby (1999). If values of ΔL are converted to units proportional to increment power, the improvement in increment threshold is 1.53 dB per doubling of duration or 5.1 dB per tenfold increase. Viemeister and Wakefield (1991) noted that detection thresholds would be expected to improve at a rate of 1.5 dB per doubling rather than 3 dB per doubling if the slope of the psychomet-

ric function were steep or if the integration period of an energy detector were matched to the signal duration. Although either condition might be met for conditions in experiment 3, the effect of duration is larger than that observed at 4 kHz by Moore and Peters (1997) or Oxenham (1997). Given the wide variability in duration effects reported in the literature [see Moore *et al.* (1999) and Wojtczak and Viemeister (1999) for summaries], the similarity of the effect in quiet and in noise in Fig. 7 may be more noteworthy than its size.

The results of experiment 3 are consistent with those of experiment 1 in that increment detection improves slowly with increasing pedestal level when the pedestal is near masked threshold in the noise, and the increment is 40 or 60 ms. For increments shorter than 40 ms, the improvement with increasing pedestal level is more uniform at low and high pedestal levels. The results of experiment 3 are also consistent with experiment 2 in showing full recovery from the effects of the noise for conditions where the pedestal is 40 dB above threshold in the noise. The effect of increment duration is similar in quiet and in noise, with an improvement in detection as a function of increment duration in the range observed for detection of tones in noise.

V. EXPERIMENT 4: EFFECT OF PEDESTAL SL AND NOISE BANDWIDTH

The broadband noise conditions in the first three experiments had a detrimental effect on increment detection that could not be entirely explained on the basis of excitation patterns. Values of ΔL were comparable in quiet and in noise when low-level pedestals were equated in dB SL. At high pedestal levels, however, values of ΔL were comparable when pedestals were equated in dB SPL. The purpose of experiment 4 was to explore the effect of high-pass (HP) noise with cutoff frequencies at various points above the pedestal frequency, chosen to restrict spread of excitation while having less effect than broadband noise on threshold for the pedestal. Noise maskers that restrict spread of excitation have been shown to restore Weber's law under conditions in which pedestals and increments are equal in duration (Viemeister, 1972).

A. Subjects

The same three subjects participated as in experiments 2 and 3.

B. Stimuli and procedures

Stimulus parameters are summarized in Table I. The 4-kHz pedestal was the same as in experiments 1–3, except that it was presented at 10, 20, 30, 40, or 50 dB SL re mean threshold across subjects for the pedestal in the presence of each noise. The noise was presented at 20 dB N_0 . Across conditions, the noise bandwidth was 4.8–16 kHz (4.8 HP), 5.6–16 kHz (5.6 HP), 7.2–16 kHz (7.2 HP), or 0–16 kHz (broadband). The 50-dB SL pedestal was used in all but the broadband noise condition, where the pedestal would have exceeded 90 dB SPL. The increment was the same as that in experiment 2, with a duration of 10 ms.

FIG. 8. Geometric mean values of ΔL across subjects for experiment 4 (shown by squares). The 10-ms, 4-kHz increment was presented 205 ms after the onset of a 370-ms, 4-kHz pedestal. Noise conditions are shown across panels. Noise spectrum level for all bandwidths was 20 dB. The solid lines show the values of ΔL predicted by the partial loudness model for each noise condition. Circles in the lower two panels represent data for the 10-ms increment obtained in experiment 2, where the maskers were broadband, but differed in level. Circles in the lower left panel are from the upper right panel in Fig. 4, where the 0-dB N_0 broadband masker produced the same amount of masking as the 4.8 HP masker. The dotted line shows the values of ΔL predicted by the partial loudness model for that broadband masker. Circles in the lower right panel are from the lower right panel in Fig. 4, where the broadband masker was 20 dB, as in experiment 4.

Two consecutive 100-trial blocks were obtained in each condition, first to determine thresholds for the pedestal alone and the increment alone in the presence of a given noise masker and then to determine thresholds for increment detection at each pedestal level in the presence of that masker. Data were obtained for the broadband noise condition first, followed by the 7.2 HP, 5.6 HP, and 4.8 HP noise conditions.

C. Results and discussion

Mean thresholds for the pedestal in each noise condition are given in Table II. Although the ERB of the auditory filter centered on 4 kHz is 0.456 kHz (Glasberg and Moore, 1990), noise bands with low-frequency cutoffs of 4.8 and 5.6 kHz overlap with the high-frequency side of the filter, resulting in some threshold elevation. Note that threshold for the pedestal in the 16-kHz, low-pass noise was comparable, as expected, to the threshold obtained in the 20-dB N_0 , 8-kHz low-pass noise in experiment 2 and that the threshold for the pedestal in the 4.8–16 kHz band-pass noise was comparable to the threshold obtained in the 0-dB N_0 , 8-kHz low-pass noise in experiment 2.

Increment detection results for experiment 4 are shown in Fig. 8, along with predictions from the partial loudness model (Moore *et al.*, 1997) in a format identical to that of Fig. 4. Data from the 0- and 20-dB N_0 conditions from ex-

periment 2 have been re-plotted in the lower two panels in Fig. 8 for conditions with comparable threshold shifts.

A within-subjects ANOVA of the log ΔL values for the three subjects for the four noise conditions and pedestal levels of 10, 20, 30, and 40 dB SL (50-dB SL was not available for the broadband noise condition) indicated significant effects of noise band [$F(3,6)=6.340$], pedestal level [$F(3,6)=112.073$], and a significant noise-band by pedestal-level interaction [$F(9,18)=16.972$]. The significant effect of noise band and the interaction both result from the difference between the broadband noise condition and the narrower bandwidths. Thresholds for increment detection for tones presented in broadband noise decreased more rapidly with increasing pedestal level than for tones presented in high-pass noise.

The data for the broadband noise condition in experiment 4 represent a partial replication of the 20-dB N_0 condition in experiment 2. Although a broader bandwidth was used in experiment 4, the two sets of data are in excellent agreement. Data for the 4.8 HP condition appear to show lower values of ΔL at low pedestal levels and a more gradual shift in ΔL with increasing pedestal level than data obtained in the earlier 0-dB N_0 noise condition, even though the two maskers produced similar shifts in pedestal threshold. Because the same subjects participated in both experiments, it was possible to conduct a within-subjects ANOVA of results obtained in the two noise conditions at four pedestal levels that were equal in dB SL in the two experiments. Results indicated a significant effect of pedestal level [$F(3,6)=167.779$] but no effect of noise band or noise-band by pedestal-level interaction. The dotted line in the lower left panel of Fig. 8 shows the partial-loudness-model predictions for the 0-dB N_0 broadband noise condition. Although the model predicted lower values of ΔL than the data, it showed a similar shift to a shallower function in high-pass noise. Despite the lack of a statistically significant interaction, the general agreement between model and data for the high-pass conditions provides support for the assumption that noise influences increment detection by restricting spread of excitation.

VI. DISCUSSION

Previous studies of increment detection in noise have used a limited number of pedestal-level and noise-level combinations. Either the noise level was constant in all conditions at a given frequency (Glasberg *et al.*, 2001; Moore *et al.*, 1993; Moore *et al.*, 1999; Moore and Peters, 1997), was a constant number of decibels below the pedestal (Moore *et al.*, 1996; Peters *et al.*, 1995), or the pedestal-to-noise ratio was varied for a fixed pedestal level (Oxenham, 1997). One of the primary goals of the present study was to explore the effect of varying pedestal-to-noise ratio at different noise levels. Because recent studies have focused on use of increment detection as a measure of temporal processing, they have typically used a range of pedestal frequencies and increment durations. Several studies included decrement detection as well in an effort to include increment and decrement detection in a single theoretical framework. The current stud-

ies explored the interaction of pedestal level and noise level as two factors limiting the ability to detect the increment, as in Henning (1969). The pedestal frequency, 4 kHz, was chosen to limit the influence of spectral splatter or off-frequency listening (Leshowitz and Wightman, 1971), and multiple increment durations were included only when it appeared that the interaction of pedestal and noise level might vary as a function of increment duration. The pattern of results in the first three experiments indicated that the threshold for increment detection for pedestal levels near the threshold for detection of the increment itself in noise was limited by that noise threshold. For pedestal levels more than 40 dB above the noise threshold, increment detection is determined by the physical level of the pedestal, independent of threshold. This pattern, in which the noise has an effect only for pedestals within 40 dB of the threshold for detection in noise, is similar to that observed for judgments of the loudness of a tone in noise (Humes and Jesteadt, 1991) and for thresholds reported in studies of additivity of masking (Humes and Jesteadt, 1989).

In the studies of increment detection reported by Moore and colleagues, noise spectrum levels in conditions with 4-kHz pedestals were generally 40 or 45 dB below the level of the pedestal. The data in Table II, averaged across all broadband noise conditions, indicate that a pedestal that is 40 dB above the spectrum level of the noise is at 17.1 dB SL. The data are in good agreement with Glasberg *et al.* (2001), who described their condition with a 70-dB SPL pedestal and 30-dB spectrum level noise as a condition where the pedestal was 18 dB above masked threshold. The data in Fig. 2 indicate that this is a condition where threshold for the pedestal is a controlling factor, and increment detection is uniform across noise levels for pedestal levels equated in dB SL. Increment detection would not be expected to be uniform across noise levels for pedestal levels greater than 30 dB SL where the spread of excitation grows nonlinearly. Equal-SL comparisons are useful at low SLs, but at high levels they can lead to the misleading conclusion that increment detection is better in noise than in quiet. This is, of course, never the case when the increments are considered in absolute physical units. Glasberg *et al.* (2001) reported a smaller value of ΔL in noise than in quiet with a pedestal level of 18 dB SL in the 4-kHz condition in their experiment 1. This effect was observed only at higher pedestal SLs in the current data.

Increment detection results from experiments 2 and 4 were compared to predictions from a partial loudness model (Moore *et al.*, 1997). Leibold and Jesteadt (2007) and Buss (2008) reported that this model predicts thresholds for intensity discrimination under some conditions and that it provides an excellent account of increment detection in quiet, as shown in Fig. 4. Two arguments against using the model in this way are that the relation between loudness and intensity resolution is tenuous (Schlauch and Wier, 1987; Zwislocki and Jordan, 1986) and that subjects might find it difficult, if not impossible, to judge the partial loudness of a tone added to another tone of the same frequency. There is, however, a relation between loudness and some measures of intensity resolution (Allen and Neely, 1997), and it is clear that the

model makes accurate predictions under some conditions. This is no doubt because the model is based on excitation patterns, and the improvement in increment detection with level is due to spread of excitation. Loudness per se may have little to do with the specific predictions for these stimuli.

The improvement in intensity discrimination with level, often referred to as the near miss to Weber's law (McGill and Goldberg, 1968a), is generally attributed to spread of excitation to higher frequencies (Florentine and Buus, 1981; Viemeister, 1988; Zwicker, 1956, 1970). Strong effects of level on increment detection were observed in the present data, both in quiet and in noise. Increment detection in quiet for the first three experiments could be described by two straight lines with a breakpoint between 20 and 40 dB SL and a steeper function for pedestal levels below the breakpoint. Results have been presented in units of ΔL on a log axis, but the pattern would be similar if shown in units of $10 \log(\Delta I/I)$. Published functions show a comparable breakpoint for increment detection and a more pronounced breakpoint at a lower SL for intensity discrimination (Viemeister and Bacon, 1988). The partial loudness model has no temporal information and therefore predicts the same function for both increment detection and intensity discrimination. Given the observed differences between the functions for the two tasks, the model may provide a better account of increment detection than of intensity discrimination. The reason for this is unclear.

The results of experiment 4 demonstrate that, given two noises that produce equal threshold shifts for the pedestal, the noise with energy in the same frequency region as the pedestal will have a greater negative impact on increment detection. The effect may be larger than would be predicted on the basis of the excitation patterns incorporated in the partial loudness model. Given that the model is based entirely on spectral information and that increment detection is known to rely on temporal information (e.g., Glasberg *et al.*, 2001; Gallun and Hafter, 2006; Moore *et al.*, 1999; Oxenham, 1997), failure of the model to account for all aspects of the data is not surprising. Noise that falls within the critical band of the pedestal and increment may have a greater effect on temporal processing than noise located above the test frequency. The template models proposed by Moore *et al.* (1999) and Glasberg *et al.* (2001) predict such an effect because they assume that the decision process is based on the temporal properties of a single auditory filter. Glasberg *et al.* noted that noise at the output of the auditory filter centered on the pedestal and increment would have the temporal properties of a narrow-band noise, even if the input were broadband.

Modulation-filter-bank models (e.g., Dau *et al.*, 1996, 1997; Jepsen *et al.*, 2008) assume filters in the modulation frequency domain that receive input from a broad range of carrier frequencies. This assumption has been confirmed in a study of frequency selectivity for amplitude modulation (Ewert and Dau, 2000). Gallun and Hafter (2006) used a modulation filter bank model to account for increment detection as a function of increment duration and showed that modulation of a carrier at 2.013 kHz can interfere with increment detec-

FIG. 9. Data from experiments 2 and 3 fitted by a model where the decision is based on the difference in perceptual intensity created by presentation of the increment. Performance is limited by a temporal integration process and by internal and external noise, where the internal noise includes both an additive and a multiplicative component. The model uses a three-parameter quadratic nonlinearity, a two-parameter temporal integration process, and a two-parameter internal noise. Parameter values were held constant in plotting the functions shown in the left and right panels, except that one of the quadratic-nonlinearity parameters decreased (by as much as 20%) with increasing noise.

tion at 0.477 kHz, a separation of more than two octaves. All of the noise conditions in experiment 4 included noise less than two octaves from the pedestal and increment, but broadband noise was clearly the most effective. More complete data obtained with high-pass or notched-noise maskers are necessary to test the assumptions of modulation-filter-bank and auditory-filter models.

Early multi-stage models of increment detection (Moore *et al.*, 1993, 1996; Oxenham, 1997) assumed a decision based on the maximum difference observed at the output of the temporal window, a measure referred to as ΔO . The emphasis here has been on the later models (Glasberg *et al.*, 2001; Moore *et al.*, 1999) that assumed a decision based on correlation with a temporal template for the increment, a measure more sensitive to the properties of the noise envelope. Neely and Jesteadt (2005) described a model with a decision process based on the overall difference between the two intervals, similar to ΔO . This model assumes a combination of multiplicative and additive internal noise and a quadratic nonlinearity based on loudness-matching data (Neely *et al.*, 2003). Use of a mathematically tractable nonlinearity and a temporal integration time constant rather than a temporal window allowed the authors to develop a single equation for d' that could be solved for signal level at threshold by setting $d' = 1$. Variance in the decision variable due to internal noise is assumed to depend on the pedestal level and to add to the variance due to the noise component of the stimulus. Fits to the data from experiments 2 and 3 using this model are shown in Fig. 9. Note that the model predicts a different shape for the functions that describe the effect of pedestal level in quiet and in noise, whereas the partial loudness model predicts incorrectly that these functions will be similar in shape. Details of the Neely and Jesteadt (2005) model are described in the Appendix.

The lack of a strong effect of noise level at low SLs, the lack of a strong interaction between increment duration and the effect of noise, and the success of the model proposed by Neely and Jesteadt (2005), where decisions are based only on

ΔO rather than on the entire template, all argue that any template-matching or modulation detection cues are proportional to ΔO . Of the models discussed here, only the partial loudness model explicitly assumes use of the information available in higher-frequency channels, but the model described in the Appendix essentially lumps the output of the entire cochlea into a single channel. In experiment 4, the authors attempted to establish the relative contributions of higher-frequency channels to increment detection in noise by varying the frequency cutoff and bandwidth of the noise. The influence of noise bandwidth has not been explored in the model. A useful feature of the model is its potential to predict the influence on d' of any stimulus parameter. This would permit specific predictions concerning the effects of internal and external noises on the form of psychometric functions.

VII. CONCLUSIONS

At low pedestals levels, increment detection is limited by the masking effect of the noise and is similar across noise conditions for pedestals of equal SL. At high pedestal levels, the noise has no effect and increment detection is determined by the pedestal level in dB SPL.

A partial loudness model based on excitation patterns (Moore *et al.*, 1997) provides a good account of the improvement in increment detection with level observed in the absence of a noise masker but underestimates the detrimental effect of noise on increment detection thresholds.

When results are averaged across pedestal levels, the improvement in increment detection as a function of duration is similar in quiet and in noise.

Results suggest that off-frequency listening does not affect increment detection performance and that background noise is not necessary to control such effects.

A model proposed by Neely and Jesteadt (2005) provides a good fit to the data from experiments 2 and 3 by assuming that variance due to external noise adds to the variance due to internal, multiplicative noise.

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APPENDIX: QUADRATIC-COMPRESSION MODEL

Consider the transformation from physical intensity into perceptual intensity in three steps: (1) a logarithmic transformation $L = \mathcal{L}[I]$ from physical intensity I to signal level L (in decibels), (2) a quadratic-compression transformation $E = \mathcal{E}[L]$ from physical signal level L to a perceptual signal level called excitation E , and (3) an anti-logarithmic transformation $N = \mathcal{L}^{-1}[E]$ from excitation E to perceptual intensity N . The first and third steps are easily described as logarithmic expressions,

$$\mathcal{L}[I] = 10 \log_{10} \left(\frac{I}{I_t} \right), \quad (\text{A1})$$

$$\mathcal{L}^{-1}[E] = N_t 10^{E/10}, \quad (\text{A2})$$

where I_t will be defined as the physical intensity of the signal at threshold and the perceptual intensity threshold N_t is arbitrarily set to 1. The fact that the second step is quasi-logarithmic makes the composite three-step transformation have properties similar to a single logarithmic transformation. However, all three steps are needed to allow perceptual intensity to serve as a decision variable for basic psychoacoustics tasks.

The middle step in the physical-to-perceptual intensity transformation represents the compressive response growth of the peripheral auditory system. If compression of the peripheral nonlinearity is modeled as a quadratic function of signal level (Neely and Jesteadt, 2005), then the corresponding excitation is related to signal level by

$$\mathcal{E}(L) = C - \frac{2}{q} \tanh^{-1} \left(\frac{2cL + b}{q} \right), \quad (\text{A3})$$

where $q = \sqrt{b^2 + 4ac}$ and C is an arbitrary integration constant selected to make $\mathcal{E}[0] = 0$. A useful feature of this nonlinear representation is that an explicit expression is available for the inverse of $\mathcal{E}$,

$$\mathcal{E}^{-1}(E) = \left(\frac{q}{2cL + b} \right) \tanh \left[\frac{q}{2} (C - E) \right]. \quad (\text{A4})$$

The complete physical-to-perceptual intensity transformation is represented by the composite function $\mathcal{I}[I] = \mathcal{L}^{-1}[\mathcal{E}(\mathcal{L}[I])]$. The inverse transformation is simply $\mathcal{I}^{-1}[I] = \mathcal{L}^{-1}[\mathcal{E}^{-1}(\mathcal{L}[N])]$. Expressions for these two composite functions are derived by combining Eqs. (A1)–(A4). Besides the signal threshold I_t , this quadratic-compression model (QCM) has only three parameters: a , b , and c .

The QCM provides a foundation for modeling increment detection in noise. Neely and Jesteadt (2005) suggested that performance on an increment detection task may be described by

$$d' = \frac{\mathcal{I}[I_2] - \mathcal{I}[I_1]}{\sigma}, \quad (\text{A5})$$

where I_1 is the intensity of the pedestal, I_2 is the incremented intensity, and σ^2 is the variance associated with the decision variable $\mathcal{I}[I_2] - \mathcal{I}[I_1]$. This variance represents the combined influence of internal noise, external noise, and temporal integration,

$$\sigma^2 = \frac{n_0^2 + n_1^2 \mathcal{I}[I_1] + n_3^2 \mathcal{I}^2[I_3]}{1 - a_i e^{-\tau_i/\tau_i}}. \quad (\text{A6})$$

In this equation, I_3 is the intensity of the external noise and τ_i is the duration of the increment. Equation (A6) introduces six additional model parameters: Two parameters (n_0 and n_1) describe the influence of internal noise on detection, two parameters (a_i and τ_i) represent temporal integration and describe the influence of increment duration on detection, and two parameters (L_{3i} and n_3) specify the external noise thresh-

TABLE IV. Estimated values of parameters for the model proposed by Neely and Jesteadt (2005) used to generate functions in Fig. 9.

Model parameters	
QCM in quiet	$a=0.6, b=0.1, c=-0.00064$
Temporal integration	$a_i=0.99, \tau_i=450 \text{ ms}$
Internal noise	$n_0=2, n_1=0.25$
External noise	$L_{3f}=-42, n_3=0.224$
CGR with external noise	$b=0.090, 0.085, 0.080$

old level (for the purpose of determining its perceptual intensity) and how the external noise combines with internal noise.

If $\Delta L = \mathcal{L}(I_2/I_1)$ is defined and Eq. (A5) is used to derive an expression for I_2 , then

$$\Delta L = \mathcal{L}[\mathcal{T}^{-1}(\mathcal{I}[I_1] + \sigma d')] - \mathcal{L}[I_1]. \quad (\text{A7})$$

The three QCM parameters may be independently determined by requiring consistency with an intensity discrimination task (Jesteadt *et al.*, 1977). The two temporal integration parameters may be independently determined by requiring consistency with a single-tone detection task (Florentine *et al.*, 1988). The pedestal threshold was selected as the reference intensity for all three stimulus intensities. This leaves only two model parameters to describe increment detection in quiet and one additional parameter to describe the strength of the external noise contribution. To provide a better fit to the data for pedestal levels >60 dB SPL, the QCM model that describes compression growth rate (CGR) was decreased (by as much as 20%) in the presence of external noise. Estimated parameter values are summarized in Table IV.

Figure 9 shows ΔL as a function of I_1 (when $d'=1$) for several values of I_3 on the left and several values of τ_s on the right. In the absence of external noise (lowest line in left panel), n_0 determines threshold for pedestal levels below 30 dB SPL, while n_1 determines threshold for pedestal levels above 30 dB SPL. In the presence of external noise (upper lines in left panel), the main effect of decreasing parameter b is to decrease threshold more rapidly for pedestal levels above 60 dB SPL. Increment duration had less effect on model threshold (right panel) than observed in the data. Overall, the QCM model reproduces all of the major trends observed in the data.

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