The effect of narrow-band noise maskers on increment detection^{a)}

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It is often assumed that listeners detect an increment in the intensity of a pure tone by detecting an increase in the energy falling within the critical band centered on the signal frequency. A noise masker can be used to limit the use of signal energy falling outside of the critical band, but facets of the noise may impact increment detection beyond this intended purpose. The current study evaluated the impact of envelope fluctuation in a noise masker on thresholds for detection of an increment. Thresholds were obtained for detection of an increment in the intensity of a 0.25- or 4-kHz pedestal in quiet and in the presence of noise of varying bandwidth. Results indicate that thresholds for detection of an increment in the intensity of a pure tone increase with increasing bandwidth for an on-frequency noise masker, but are unchanged by an off-frequency noise masker. Neither a model that includes a modulation-filter-bank analysis of envelope modulation nor a model based on discrimination of spectral patterns can account for all aspects of the observed data.

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I. INTRODUCTION

The ability to detect a brief increment in the intensity of a longer duration stimulus is often used as a measure of the intensity resolution of the auditory system. Early investigators suggested that the detection of an increment in a tone was based on the energy within the critical band centered on the signal frequency (Henning, 1967; Leshowitz and Raab, 1967). Leshowitz and Wightman (1971) demonstrated that energy in other critical bands could serve as a cue in conditions where the onset and offset of the increment was abrupt. A low-level broadband noise was used in many studies of increment (and decrement) detection to eliminate potential use of such “off-frequency” cues (Moore *et al.*, 1996, 1999; Moore and Peters, 1997; Peters *et al.*, 1995; Plack *et al.*, 2006). It is not clear, however, that the effect of the noise was limited to masking off-frequency energy (Glasberg *et al.*, 2001; Jesteadt *et al.*, 2009; Oxenham, 1997). Recent findings indicate that envelope fluctuations in a masker can increase thresholds in increment detection (Gallun and Hafter, 2006; Jesteadt *et al.*, 2009). The goal of this study

was to evaluate the effect of narrow-band noise on increment detection in an effort to understand the decision processes used in increment detection.

In the first study that evaluated the impact of a background noise on thresholds in increment and decrement detection, Oxenham (1997) measured the threshold for an increment/decrement in the intensity of a 0.5- or 4-kHz tone in a series of experiments designed to isolate specific effects of the background noise masker. In the experiment most relevant to the current study, Oxenham (1997) measured increment detection thresholds at 4 kHz in a 10-dB spectrum level noise that was low-pass filtered at 4.4 kHz, high-pass filtered at 3.6 kHz, or band-reject filtered with cutoff frequencies of 3.6 kHz and 4.4 kHz. For the increment detection conditions, thresholds were poorest in the high-pass noise condition, which is consistent with the assumption that the primary role of the noise is to mask the upward spread of excitation. When results in all noise conditions were compared to thresholds in quiet, however, there was a residual effect of the background noise masker beyond masking the spread of excitation.

Glasberg *et al.* (2001) measured thresholds for increments in the intensity of a 0.25- and 4-kHz sinusoidal pedestal in quiet and in broadband noise. The level of the pedestal was set at 18 dB above the threshold for detection of the pedestal. Thresholds for increment detection at 0.25 kHz were poorer in a background noise than in quiet, especially at short increment durations. At 4 kHz, however, thresholds were poorer in quiet than in background noise. Higher thresholds in noise at 0.25 kHz were attributed to inherent fluctuations resulting from the narrow bandwidth of the auditory filters at low center frequencies. Glasberg *et al.* (2001) hypothesized that inherent fluctuations in a noise masker may impact thresholds in an increment detection task. Neff

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(1985, 1986) demonstrated that confusion effects in forward masking were maximum when the signal duration was equal to the average duration of envelope maxima in the noise masker. The Glasberg *et al.* model made a similar prediction for increment detection. The expected number of maxima per second for a noise of a given bandwidth is calculated by $M = .6411(f_b - f_a)$, where f_a is the upper value of the bandwidth and f_b is the lower value of the bandwidth (Rice, 1954). Both Neff (1985, 1986) and Glasberg *et al.* (2001) assumed that the average period in ms from one envelope minimum to the next could be approximated by $1000/M$. Glasberg *et al.* assumed that detection would be governed by the temporal properties of the narrowband noise at the output of the auditory filters rather than the relatively flat envelope of the broadband noise stimulus.

Glasberg *et al.* (2001) examined this theory by measuring thresholds for detection of an increment in a 4-kHz pedestal tone presented in various bandwidths of a narrow-band background noise (NBN). The bandwidths were all less than the bandwidth of the auditory filter at 4 kHz. They found that for a NBN centered at a signal frequency of 4 kHz, slow fluctuations in the noise envelope had a greater detrimental effect on detection of increments than rapid fluctuations. To further support the idea that the higher thresholds were due to fluctuations at the output of the filter centered on the signal, not an effect of the noise in reducing spread of excitation, Glasberg *et al.* measured the increment-detection threshold at a signal frequency of 4 kHz in the presence of a NBN centered at 7 kHz. The 7-kHz noise was intended to limit off-frequency listening on the high-frequency side of the excitation pattern while producing negligible output from the auditory filter centered at 4 kHz. The NBN centered at 7 kHz did not show an effect of bandwidth or fluctuation rate as was found for the NBN centered at 4 kHz.

Glasberg *et al.* (2001) accounted for their results with a template matching model that incorporated peripheral auditory filtering and a decision device using changes in the amplitude of the internal representation of the input stimulus as the basis of the decision criterion. The model accurately reflected improving thresholds with increasing noise bandwidth as was observed in the data. Although this function was slightly steeper for model predictions than for actual data, the accuracy of model predictions does suggest that decisions may be made at least in part as a function of energy differences.

Jesteadt *et al.* (2009) evaluated the effect of noise on increment detection through a series of experiments where noise level and pedestal-to-noise ratio were varied at a signal frequency of 4 kHz. Results indicated that the detection of an increment in a pedestal whose level was expressed in dB SPL was heavily influenced by the level of the noise, but the effect of noise was greatly reduced when pedestal levels were equated in terms of sensation level (SL). Nonetheless, a model sensitive to excitation patterns was unable to accurately predict thresholds at the low pedestal levels, suggesting some residual effect of the noise. The noise had little or no effect for pedestal levels of 40 dB SL or more. The impact of the noise masker may be related to the temporal properties of the noise as well as its ability to mask the excitation pat-

tern. Neely and Jesteadt (2005) proposed a model that can account for these results in terms of a combination of internal and external noise, but that model included information only about the level of the external noise, not its bandwidth or envelope.

Gallun and Hafter (2006) found that thresholds for increment detection were more negatively impacted by slow fluctuations in the masker envelope than by faster fluctuations. By amplitude modulating a tonal masker, they were able to control the rate of the fluctuations in the masker, just as Glasberg *et al.* (2001) were able to do by restricting the bandwidth of the noise. Gallun and Hafter (2006) attributed the effect of envelope fluctuations to the decision process, suggesting that the decision device for increment detection is based on a bank of filters sensitive to modulation frequency.

Although Gallun and Hafter (2006) were the first to apply such a model to increment detection, many researchers have suggested that envelope fluctuations are detected by filters tuned in modulation frequency (Bacon and Grantham, 1989; Dau *et al.*, 1996a, 1996b, 1997a, 1997b; Ewert and Dau, 2000, 2004; Houtgast, 1989; Oxenham, 1998). Gallun and Hafter modeled results from increment detection using a simplified version of the Dau model proposed by Ewert and Dau (2000). The simplified model bases decisions on the output of a bank of modulation filters that are assumed to be relatively broad, with a Q of 1, but does not include the peripheral filtering or adaptation stages from the original Dau model. In order to apply the modulation filter bank model to increment and decrement detection, Gallun and Hafter (2006) modified the model to base its decisions on the output of the filter that differed the most across the two observation intervals over the duration of the increment. They found that for short-duration increments (total duration of 20 ms), a range of AM rates impacted increment detection equally. At longer durations (85 ms), however, only a 4-Hz AM masker hindered increment detection. Another key finding was that AM at a distant carrier frequency interfered with increment detection. This result is in contrast to results from Glasberg *et al.* (2001) showing no interference by an off-frequency masker. The modified modulation filter bank model was able to accurately account for these data.

If envelope fluctuations do interfere with the ability to detect increments, whether as a result of peripheral auditory filtering (Glasberg *et al.*, 2001) or a more central modulation filter bank (Gallun and Hafter, 2006), the mechanism underlying increment detection can be evaluated by varying characteristics of the modulation. A comparison of the fluctuations resulting from band limiting a noise and amplitude modulating a masker can be made by determining the expected number of envelope maxima per second for each masker. Using the Rice equation, the equivalent amplitude modulation rates of the NBN maskers used by Glasberg *et al.* are in the range of 32–256 Hz, while Gallun and Hafter (2006) used modulation rates of 4–96 Hz. It may be possible to maximize the effect of envelope fluctuations by selecting NBN bandwidths that result in envelope-modulation durations similar to the increment durations being tested.

Confusion between the envelope of the signal and that of the masker may not be limited to a within channel cue. Gal-

lun and Hafter (2006) were able to mask an increment in a 477 Hz tone by an amplitude-modulated 2013 Hz tone, showing that modulation-frequency masking, not just spectral-frequency masking, can have an effect on increment detection. Placing envelope fluctuations in an auditory filter distant from the auditory filter centered at the signal frequency provides a strong test of the modulation-filter-bank model. When determining the carrier frequency of this masker, it is important to place it sufficiently distant to the signal frequency as to avoid excitation issues, while remaining within the range where the auditory system is known to be sensitive to modulation.

The studies to be described here were designed to evaluate the effect of narrow-band noise on increment detection and to use this information to assess the decision device used when detecting increments. Results from the two studies were used to evaluate the ability of current models of auditory decision processes to account for the data. A low and a high pedestal frequency were chosen to evaluate the possible involvement of peripheral auditory filtering as described by Glasberg *et al.* (2001). The bandwidths of the narrow-band noise maskers were chosen so that the average modulation duration of each noise bandwidth approximated the duration of one of the increment durations tested.

II. EXPERIMENT 1: INCREMENT DETECTION IN A BROADBAND NOISE MASKER

Glasberg *et al.* (2001) reported that in increment and decrement detection tasks, thresholds at 0.25 kHz were poorer in a background noise than in quiet, particularly for short duration increments. At 4 kHz, however, thresholds were poorer in quiet than in background noise. Glasberg *et al.* attributed the detrimental effect of noise at 0.25 kHz to fluctuations in the envelope of narrowband noise that were slower at low stimulus frequencies than at high stimulus frequencies due to auditory filtering. Results at 0.25 kHz may also be attributed to reduced spread of excitation (Jesteadt *et al.*, 2009; Oxenham, 1997) or reduced off-frequency listening. This experiment evaluated the effect of a wideband noise masker on increment detection by measuring detection thresholds for increments and decrements in the level of longer duration sinusoids, using pedestal and stimulus frequencies of 0.25 and 4 kHz in quiet and in a wideband noise masker. The purpose of the experiment was to provide control data for the 2nd experiment and to attempt to replicate increment and decrement detection results from Glasberg *et al.* (2001).

A. Subjects

The listeners were eight paid volunteers (3 male, 5 female) with a mean age of 23 years, ranging from 20 to 29 years of age. All were students from local universities who had participated in previous psychoacoustics studies. Hearing for all of the listeners was screened at 0.5, 1, 2, and 4 kHz within the past year using the same two-interval, forced-choice (2IFC) adaptive procedure used in the experiment. Thresholds were at or better than 20 dB SPL for all test frequencies, bilaterally, for each listener.

B. Stimuli and apparatus

The pedestal was a 0.25- or 4-kHz tone with 50-ms rise/fall time and an initial phase of 0°. The pedestal level was set to 18 dB above the average threshold in quiet or in noise, the pedestal-to-noise ratio used by Glasberg *et al.* (2001). The increment or decrement had a 0-ms, 40-ms, or 80-ms steady-state duration, with 5-ms rise/fall time in all cases. Increments and decrements were generated by adding a separate digital signal waveform to the pedestal waveform. The waveform was started in-phase with the pedestal to produce an increment, and 180° out of phase to produce a decrement. The pedestal duration varied with the increment or decrement duration to maintain a 150-ms steady-state duration before and after the increment or decrement.

The noises were generated digitally by finite-impulse-response (FIR) low-pass filtering a Gaussian noise at 0.75 kHz, and 8 kHz, for the 0.25- and 4-kHz conditions respectively. Noises had a rise/fall time of 5 ms created with a cosine-squared window, with total duration equal to the pedestal duration. Each noise sample was drawn from a buffer 20 times as long as the pedestal, with a random starting point within the buffer. Fifty noise samples were drawn. The 0.75- and 8-kHz low-pass noises were presented at spectrum levels of 38.9 dB and 30 dB, respectively. Cut-off frequency and level of the noises were selected to maintain a constant overall noise level at the output of the auditory filter centered at the pedestal frequency as was done in earlier studies (Glasberg *et al.*, 2001; Moore and Peters, 1997; Moore *et al.*, 1999).

All stimuli were generated digitally via MATLAB at a sampling rate of 44 100 Hz with 24-bit resolution, attenuated digitally as necessary, added digitally and output on a single channel of a CardDeluxe Analog soundcard. The headphone output of the soundcard was fed to a remote passive attenuator in the sound treated room, and then to a Sennheiser HD 250 Linear II headphone. Stimuli were presented monaurally to the left ear. Parallel systems made it possible to test up to four listeners simultaneously. Listeners were tested in two groups.

C. Procedure

Threshold for the pedestal in quiet was initially obtained using a two-interval forced choice procedure (2IFC) with a decision rule estimating 71 percent correct (two-down, one up) (Levitt, 1971), with an initial step size of 4 dB moving to a final step size of 2 dB after the first 4 reversals. Listeners were presented two intervals per trial, with one of those intervals containing no stimulus and the other the pedestal. The inter-stimulus interval was 300 ms. The listener responded on a keypad located in the sound treated room. Trial-by-trial feedback was provided contingent upon response. Threshold was calculated as the arithmetic mean of the reversal levels after the fourth reversal. Eight 50-trial repetitions were obtained in randomized order; the first was excluded as practice. Mean threshold was calculated across repetitions for each listener. The pedestal level for the increment- and decrement-detection conditions was then set to 18 dB above the mean threshold for each listener. The same procedure

TABLE I. Pedestal level used for each condition for each listener in Experiment 1. Pedestal level is specified in dB SPL.

(Hz)	Quiet						Wide-band noise					
	250			4000			250			4000		
	10	50	90	10	50	90	10	50	90	10	50	90
Frequency												
Signal duration (ms)												
Listener												
249	35	34	33	20	19	19	69	69	68	75	76	76
371	32	33	34	21	22	22	76	77	77	77	77	78
375	39	38	38	20	20	20	75	75	74	79	78	78
378	42	41	40	24	24	24	73	73	73	75	74	74
379	18	18	18	24	24	24	71	71	72	78	77	77
380	18	18	18	21	21	20	72	71	70	76	76	77
384	31	31	31	19	18	18	76	74	73	76	76	76
385	41	41	41	21	19	20	74	76	75	78	75	77

was followed to obtain thresholds for the pedestal in noise. In this case, each observation interval contained a sample of the noise randomly drawn from the set of 50 noise samples. The pedestal level used for each listener for each condition is shown in Table I.

Next, thresholds for increments and decrements in the pedestal in quiet and in the respective noise were obtained by adapting the level of the increment or decrement using the same 2IFC adaptive procedure that was used when measuring threshold for the pedestal. Eight 50-trial repetitions were obtained in each condition. The first repetition was excluded as practice. A total of 350 trials per condition for each listener were available for further analysis. The threshold level of the increment and decrement for each listener, for each repetition, in each condition was converted to ΔL (Buus and Florentine, 1991).

D. Results and discussion

Results for increment detection were analyzed visually by plotting mean thresholds in units of ΔL [$10 \log(1 + \Delta I/I)$]. Values of ΔL were plotted on a logarithmic scale to make variability more uniform (Buus and Florentine, 1991). Data reported are geometric means and standard deviations (SDs) across repetitions and listeners. When calculating ΔL , decrement thresholds higher than the pedestal level were removed and replaced with the highest level that could be presented to the listener in the adaptive procedure that remained below the pedestal level. This level was chosen because it produced the largest decrement possible in the adaptive procedure.

Mean masked thresholds across listeners for increment and decrement detection at 0.25 and 4 kHz in quiet and in a wide-band noise are shown in Fig. 1; thresholds are plotted as a function of signal duration. Thresholds in increment and decrement detection are within 1 SD of each other except at the shortest duration, where thresholds for decrement detection are poorer than thresholds for increment detection. Thresholds for both increments and decrements improve as the signal duration increases. Thresholds for increment detection at 0.25 kHz are higher than thresholds at 4 kHz at the shortest duration although there is no apparent effect of sig-

nal frequency at longer durations. A wide-band noise appears to impact performance in decrement detection more than increment detection at longer signal durations.

A repeated-measure ANOVA was used to test the statistical significance for the main effect of signal type, increment or decrement. Then results for increments and decrements were evaluated in separate repeated-measure ANOVAs evaluating the main effects of noise, duration, and frequency and the corresponding interactions. Appropriate Greenhouse-Geisser corrections were applied when the sphericity assumptions were not met. All ANOVAs were conducted on the logarithms of the ΔL values. Effects of $\alpha < 0.05$ are assumed to be significant.

The main effect for signal type was significant ($F_{1,7} = 81.511$, $p < 0.001$). For increment detection, the main effects for noise ($F_{1,7} = 9.041$, $p < 0.05$), duration ($F_{2,14} = 139.617$, $p < 0.001$), and frequency ($F_{1,7} = 9.016$, $p < 0.05$), were significant. There was a significant interaction of duration and frequency ($F_{2,14} = 8.776$, $p < 0.05$), as thresholds at 0.25 kHz improved more rapidly with increas-

FIG. 1. Increment and decrement detection threshold in units of ΔL plotted as a function of signal duration. The parameter is the signal frequency. Error bars indicate ± 1 SD across listeners.

ing duration than did thresholds at 4 kHz. Post hoc comparisons using the Bonferroni adjustment for multiple comparisons (based on pair-wise comparisons) showed that, for 0.25 kHz in quiet and in noise, mean increment thresholds at 10 ms were significantly greater than at 50 ms and 90 ms, but thresholds at 50 ms were not significantly different than at 90 ms. The pattern was the same for 4 kHz in quiet. For 4 kHz in noise, mean increment thresholds at 10 ms were significantly greater than 50 ms and 90 ms and thresholds at 50 ms were significantly greater than 90 ms.

For decrement detection, the factors noise ($F_{1,7}=22.408$, $p<0.005$), and duration ($F_{2,14}=436.151$, $p<0.001$), were significant, but frequency was not. There was a significant interaction of noise and duration ($F_{2,14}=13.964$, $p<0.001$), as thresholds improved more quickly with increasing duration in quiet than in noise. Post hoc comparisons showed that, for mean decrement thresholds at 10 ms were significantly greater than those at 50 and 90 ms, but thresholds at 50 ms were not significantly greater than those at 90 ms.

To summarize, results in increment detection were significantly different than decrement detection, but similar general trends were observed for both stimuli. For both increments and decrements, thresholds improved with increasing duration. At the shortest duration for increments, thresholds for the 0.25-kHz conditions were higher than those for the 4-kHz conditions, while for decrements there was no effect of frequency. Thresholds were higher in the WBN conditions than in the quiet-conditions at the shortest duration for increment detection, while for decrement detection thresholds were higher in the WBN conditions than in the quiet conditions at the longer durations.

Results from Experiment 1 are in agreement with previous reports showing that thresholds in increment and decrement detection improve with increasing duration, and that decrements are less detectable than increments at the shortest durations (Forrest and Green, 1987; Glasberg *et al.*, 2001; Irwin and Purdy, 1982; Moore *et al.*, 1999; Oxenham, 1997). A notable difference from findings of Glasberg *et al.* (2001) is that thresholds at 4 kHz in noise are not better than thresholds at 4 kHz in quiet. Results from the current study show that for longer duration increments, the effect of WBN is not significant. Previous researchers have suggested that the effect of the noise is to restrict the spread of excitation (Jesteadt *et al.*, 2009; Oxenham, 1997). Results from Experiment 1 showing no difference in thresholds between quiet and noise at longer durations support this because thresholds were obtained at equal SL, thus resulting in similar excitation patterns for the quiet and noise conditions. The difference in threshold between quiet and noise at the shortest duration may stem from the use of off-frequency energy since increments were generated with 5-ms ramps.

An alternate possibility is that listeners detect the increment through detection of amplitude modulation, as was suggested by Gallun and Hafter (2006). If listeners were performing this task through use of modulation, WBN might not be expected to produce any masking. Though a WBN would introduce amplitude modulation in the envelope, this modulation would be relatively fast (i.e., higher in frequency) in

comparison to the modulation produced by the increment. Results did indicate that a WBN impaired performance in decrement detection at longer signal durations. The effect of noise on decrement detection may also be explained by considering decrement detection as an extension of gap detection (Peters *et al.*, 1995) and assuming that the background noise fills in the gap produced by the decrement. The “filling in” or masking of the gap by a noise might originate from mechanisms occurring in a different domain than modulation masking.

E. Modeling

Observed data were modeled using a modified version of the modulation filter bank model (MFBM) used by Gallun and Hafter (2006). The input to the model was a digital waveform, where an amplitude of 1 V corresponded to a maximum sound pressure level of 105 dB SPL and the amplitudes of the stimuli were scaled to the user-specified level prior to the first stage of the model. The gamma-tone filter bank was in the form proposed by Patterson *et al.* (1987) as implemented by Slaney (1993). It encompassed the frequency range of 0.1 to 12 kHz and contained ten channels, each being one equivalent rectangular bandwidth (ERB) wide, where ERB is defined as suggested by Glasberg and Moore (1990). The outputs of the gamma-tone filters were summed across filters before the envelope was extracted via a Hilbert transform in the second stage. The extracted envelope then passed through a modulation filter bank in the third stage. The modulation filter bank was akin to that used by Ewert and Dau (2000) and Gallun and Hafter (2006). Specifically, it consisted of a series of second-order band-pass filters of logarithmic spacing with a constant Q value of 1. The center frequencies (CF) of the filters were equally spaced with a spacing of 1 in units of $\log_2$ of CF in Hz. The lowest filter had a center frequency of 2 Hz. The maximum modulation-filter center frequency was limited to one quarter of the carrier frequency to avoid the possibility of ill-defined envelopes that might impair the sensitivity of the model. A recent publication from the Dau group has adopted the same rule (Jepsen, *et al.*, 2008).

If the decision variable is determined by the MFB output only, the relative change in amplitude modulation would predict Weber’s law, as in Jepsen, *et al.* (2008). The model used by Gallun and Hafter (2006) would also predict Weber’s law. A listener’s ability to perform intensity resolution tasks does not remain constant, however, but rather improves with increasing level (McGill and Goldberg, 1968a). A level-dependent internal noise can be used to account for the level-dependent improvement in intensity resolution, but recent data do not support that approach (Wojtczak and Viemeister, 2008). The level-dependent improvement in intensity resolution suggests a decision variable that depends on at least two stimulus parameters, level or power and envelope-power fluctuations. Martens (1982) was successful in accounting for a large set of data using a decision variable derived from envelope power, envelope-power fluctuations and envelope spectrum. In the fourth stage of the model used in this study, a decision variable was derived by adding the pedestal enve-

lope to the MFB output. This allowed the model to account for the improvement with level without assuming a level-dependent internal noise.

Following this, the MFB output was then normalized with reference to the pedestal envelope. [Stellmack et al. \(2006\)](#) have suggested that listeners discriminate modulation depth by determining the relative depth of modulation within each interval presented. The output was then passed through a static rectangular window of duration equal to signal duration. Following [Gallun and Hafter \(2006\)](#), the temporal center of the window was aligned with the temporal center of the signal. A summation was performed on the output of each modulation filter and the difference between the summed output for the signal and the non-signal interval was calculated for each modulation filter. An internal noise with a Gaussian distribution (mean of zero) and user-defined standard deviation was added to each modulation-filter sum to simulate limitations of resolution and memory. In the fifth stage, the decision device selected the interval thought to contain the signal based upon the modulation filter producing the greatest difference between the signal and the non-signal interval, with internal noise included.

The actual waveforms used during data collection were used in the simulation and the level of the signal waveform was adapted just as it was during data collection. The pedestal level was set to the mean pedestal level across listeners for each condition, and the noise level was set to that used during data collection. Thresholds for increments and decrements in the pedestal in quiet and in the respective noise were estimated using the same 2IFC adaptive procedure that was used in Experiment 1. The waveforms for each interval were added prior to envelope extraction. All experiments were simulated with an internal noise standard deviation of 2, based on preliminary model runs that suggested that this value resulted in threshold estimates that approximated results observed in the absence of noise. Threshold was calculated as the mean of the reversal levels after the fourth reversal. Eight 50-trial repetitions were obtained for each condition in Experiment 1. At the completion of each repetition, threshold was recorded in units of ΔL . Geometric mean thresholds in units of ΔL were calculated across repetitions for each condition.

Observed and predicted thresholds in units of ΔL as a function of signal duration are plotted in Fig. 2. The open symbols represent observed results from Experiment 1, presented previously in Fig. 1, while the various line types are threshold predictions from the simulation. The error bars for observed thresholds represent the standard deviation across four listeners, while the shading surrounding the predicted thresholds represents the standard error across eight repetitions of the model. Because the observed data were averaged across repetitions then across listeners, while only a single stage of averaging was used in obtaining model predictions (average across repetitions), the two measures of variability are comparable.

Overall, the model predicts results from Experiment 1 quite well, given that uniform internal noise was assumed in all conditions and that the computation time required made it impractical to choose a standard deviation for the internal

FIG. 2. Comparison of observed thresholds to predicted thresholds for Experiment 1. The open symbols represent observed results from Experiment 1, presented previously in Fig. 1. The dashed lines represent mean thresholds predicted using the MFB model (—decrement detection, ··· increment detection). The error bars for observed thresholds represent ± 1 SD across four listeners. The shading surrounding the predicted thresholds represents the SE across eight repetitions of the model.

noise that would minimize the deviation between predictions and observed data across conditions. The model was able to capture the effect of duration on threshold, and the different rate of improvement with increasing duration for increments and decrements. In quiet, the model did not accurately reflect observed thresholds for the 10-ms conditions. For the 0.25-kHz, 10-ms increment-detection condition, the model predicts poorer performance than was observed. This error may suggest that listeners used some cue other than modulation energy to detect this short duration increment. Since this occurred at 0.25 kHz, and the increment was generated with 5-ms ramps, it is reasonable to posit that the listeners may have used spectral splatter to detect the increment. This argument is further supported by the increase in threshold in the presence of the WBN masker observed in listener data.

Another noteworthy aspect of model predictions is the lack of a prediction for decrement detection in the 0.25-kHz, 10-ms condition, where the model was unable to detect the largest available decrement. This result is interesting because, three of the eight listeners tested in Experiment 1 (371, 379, 384) were unable to resolve the largest available decrement in this condition. For 4-kHz, 10-ms decrement detection in quiet, the model predicts better thresholds than were observed. The model also predicts very little impact of a noise masker on decrement detection at 4 kHz. Results from Experiment 1 show that a wide band noise impacts thresholds for longer signal durations in decrement detection and shorter signal durations in increment detection. The different effect of noise on increment and decrement detection in the observed data was attributed to the noise “filling in” the dip produced by the decrement. The inability of the model to show a different effect of noise on decrement detection than increment detection may be viewed as support for the suggestion that decrement detection may not be per-

TABLE II. Pedestal levels used for each listener in each NBN condition for Experiment 2.

Noise bandwidth (Hz)	Signal duration (ms)	Listener: 249		Listener: 375		Listener: 379		Listener: 385	
		500	4000	500	4000	500	4000	500	4000
30	10	83	81	83	82	81	82	84	81
	20	83	81	83	81	80	81	84	81
	30	82	82	84	81	79	80	85	81
	50	82	82	85	80	76	79	85	81
50	10	79	80	80	84	79	79	83	81
	20	80	80	81	84	79	79	84	82
	30	80	80	82	85	79	79	85	83
	50	81	80	83	86	79	79	86	83
80	10	80	81	80	87	81	79	84	81
	20	80	80	80	84	81	79	83	81
	30	81	80	81	82	80	80	83	80
	50	81	79	83	80	80	80	82	80
150	10	66	75	81	80	72	78	88	83
	20	70	78	81	80	75	77	88	81
	30	76	80	80	80	77	76	87	80
	50	81	82	80	80	80	75	87	79

formed through the processes implemented in the model. It is difficult to ultimately evaluate the difference between model predictions and observed data in this condition, however, because of the large error bars for the observed data.

III. EXPERIMENT 2: EFFECT OF MASKER BANDWIDTH

The purposes of this experiment were to evaluate the role of low-frequency modulation by restricting noise bandwidth to ranges that result in slow modulation frequencies, to test the hypothesis that NBN has the greatest effect on increment detection when the average duration of NBN envelope maxima equals the duration of the increment, and to evaluate modulation-frequency masking by determining the effect on increment detection of a NBN at a distant center frequency.

A. Subjects

The listeners were six paid volunteers (3 male, 3 female). All were students from local universities. Two listeners did not complete the study due to inconsistent thresholds across repetitions for detection of the pedestal in the narrow-band noise. The four listeners who completed the study also participated in Experiment 1. The mean age of these four listeners was approximately 24 years, ranging from 20 to 30 years of age.

B. Stimuli and apparatus

The pedestal was a 0.5- or 4-kHz tone with 50 ms rise/fall time generated with a cosine squared envelope and an initial phase of 0°. The pedestal level was set to 18 dB SL as it was in Experiment 1. The increment of the same frequency as the pedestal had 0-ms, 10-ms, 20-ms, or 40-ms steady-state duration, with 5-ms rise/fall time in all cases. The increment with an 80-ms steady-state duration used in Experiment 1 was not used here because that duration was longer than the average duration of NBN envelope modulation in any of the noise stimuli. The frequency used in the lower-frequency condition was increased to 0.5 kHz so that 5-ms

ramps could be used with a reduced possibility of introducing spectral splatter. As in experiment 1, the pedestal duration varied with the increment duration to maintain a 150-ms steady-state duration before and after the increment.

The noises were generated digitally by FIR band-pass filtering a Gaussian noise to bandwidths of 30, 50, 80, and 150 Hz centered at 0.5 or 4 kHz. The corresponding average modulation durations for these noise bandwidths are 50 ms, 30 ms, 20 ms, and 10 ms, respectively. Both noise center frequencies were tested in combination with both pedestal frequencies to allow comparisons of results obtained with on-frequency and off-frequency maskers. The band-pass noises were presented at 65 dB SPL. The noise durations corresponded to those of the pedestal.

C. Procedure

Threshold for the pedestal in quiet or in one of the four noise bands centered on the pedestal frequency were initially measured using a 2IFC adaptive procedure tracking 71 PC, as in Experiment 1. Mean threshold was calculated across repetitions for each listener. The pedestal level for the NBN and quiet conditions was then set to 18 dB above the mean threshold for each listener. The same pedestal level was used in each condition for the on- and off-frequency NBN maskers. The pedestal level used for each listener for each condition in the NBN is shown in Table II.

Thresholds were obtained for increment detection in the presence of each bandwidth of the NBN centered at the same frequency as the signal and pedestal (on-frequency) or centered at the alternate frequency to the signal and pedestal (off-frequency) using the same 2IFC adaptive procedure tracking 71PC. In addition, thresholds for increments in the pedestal in quiet at three different pedestal levels were obtained. Three different pedestal levels were used in the quiet conditions so control data were available at pedestal levels of equal SL and equal overall level for the NBN conditions and at a point in between. The low pedestal level corresponded to

TABLE III. Pedestal levels used for each listener in each quiet condition for Experiment 2.

Pedestal level	Signal duration (ms)	Listener: 249		Listener: 375		Listener: 379		Listener: 385	
		500	4000	500	4000	500	4000	500	4000
Low	10	22	20	28	21	23	27	30	20
	20	22	21	28	21	23	26	30	20
	30	21	21	28	21	24	26	29	19
	50	21	22	29	21	24	25	29	19
Mid	10	44	48	55	51	48	53	55	52
	20	46	50	55	51	49	52	54	51
	30	49	51	54	51	51	51	53	50
	50	50	52	55	51	52	50	53	49
High	10	66	75	81	80	73	78	79	83
	20	70	78	81	80	75	77	78	81
	30	76	80	80	80	77	76	77	80
	50	81	82	80	80	80	75	77	79

18 dB above the pedestal threshold in quiet, the high pedestal level corresponded to 18 dB above the pedestal threshold in 150 Hz-wide NBN, and the mid pedestal level was the mid-point between the low and high pedestal level. The pedestal level used for each listener for each condition in quiet is shown in Table III. Each condition was repeated eight times in a randomized order. The first repetition was excluded as practice. A total of 350 trials per condition were available for further analysis. Geometric mean threshold was calculated in units of ΔL across repetitions for the stimuli in quiet and in noise.

D. Results and discussion

Thresholds for the pedestal showed little variation with signal duration for three of the four listeners. Listener 249 showed increasing thresholds for the pedestal with increasing duration that varied across a large range from the shortest duration to the longest duration in the widest bandwidth NBN masker. Since the pedestal is of a long duration, it is unexpected that threshold would vary as a function of pedestal duration; particularly that pedestal threshold would increase with increasing duration.

Geometric mean threshold across listeners in units of ΔL for increment detection at 0.5 and 4 kHz in quiet and in the four noise bandwidths are shown in Fig. 3; thresholds are plotted as a function of noise bandwidth with signal duration

as the parameter. Data points for 'L' on the abscissa represent thresholds for increment detection in quiet for the low level pedestal. Data points for 'H' on the abscissa represent thresholds for increment detection in quiet for the high level pedestal. Data obtained at the intermediate level will be presented below. Since the four listeners who participated in Experiment 2 also participated in Experiment 1, mean threshold across these four listeners for the WBN increment detection condition at 4-kHz from Experiment 1 are plotted as the data points for 'WBN' on the abscissa.

Thresholds increase with increasing noise bandwidth for both 0.5 and 4 kHz. Thresholds do not appear to improve greatly with increasing increment duration, although little improvement would be expected due to the small duration range that was tested. Interestingly, there is a lack of interaction between signal duration and noise bandwidth. It was hypothesized at the onset of this study that noise that resulted in an average envelope-modulation duration equal to the signal duration would be most effective in masking the signal. Specifically, it was expected that the 150-Hz wide noise masker would impact thresholds for the 10-ms signal more than the other three signal durations, that the 80-Hz wide noise masker would impact thresholds for the 20-ms signal, that the 50-Hz wide noise masker would impact thresholds for the 30-ms signal, and that the 30-Hz wide noise masker would impact thresholds for the 50-ms signal. Observed results do not show this predicted interaction between signal duration and noise bandwidth.

A repeated-measure ANOVA was used to test the statistical significance for the main effects of duration, frequency, and noise and the corresponding interactions. The on- and off-frequency maskers were evaluated in separate repeated-measure ANOVAs conducted on the logs of the ΔL values. For an on-frequency noise masker, the main effect of noise bandwidth was significant ($F_{4,12}=52.446$, $p<0.001$). There was a significant interaction between frequency and duration ($F_{3,9}=10.444$, $p<0.005$), and noise bandwidth and duration ($F_{12,36}=2.747$, $p<0.01$), but these interactions accounted for a small amount of the total variance. Post hoc comparisons using the Bonferroni adjustment for multiple comparisons (based on pair-wise comparisons) showed that for the

FIG. 3. Increment detection thresholds in units of ΔL plotted as a function of noise bandwidth centered on the pedestal frequency. The parameter is the signal duration. Error bars indicate ± 1 SD across listeners.

main effect of noise bandwidth, mean thresholds in a 30-Hz wide noise masker were significantly lower than 50 Hz, 80 Hz, and 150 Hz. Thresholds in a 50-Hz wide noise masker were significantly lower than in a 150-Hz wide noise masker. Thresholds in an 80 Hz wide noise masker were significantly higher than thresholds at the high pedestal level in quiet. Thresholds in a 150-Hz wide noise masker were significantly higher than at the high pedestal level in quiet.

In summary, there was no significant difference between the 0.5- and 4-kHz conditions, or among the four signal durations tested. There was a significant increase in threshold with increasing noise bandwidth and increment-detection thresholds in the widest two noise bandwidths (80 Hz and 150 Hz) were significantly greater than thresholds in quiet at an equal overall pedestal level.

The quiet conditions at the low pedestal level reflect equal SL conditions (L); the quiet conditions at the high pedestal level reflect equal overall level conditions (H). When results for an on-frequency NBN masker are compared to results for an equal-SL pedestal in quiet (L), increment-detection thresholds are better in a narrow NBN than in quiet, but are comparable in NBN and in quiet for the widest bandwidth. The addition of the NBN produces an increase in threshold as a function of increasing bandwidth. The improvement in performance with the introduction of 30-Hz wide NBN in the equal-SL conditions is probably due to the change in the overall level of the stimuli. When the overall level of the signal is increased, the excitation pattern widens and performance generally improves. The pedestal levels for the NBN conditions are higher than the pedestal levels for the quiet conditions at equal SL(L) and the noise is not sufficiently wide to mask the spread of excitation. As the bandwidth of the NBN increases, however, more of the excitation pattern is masked and equal-SL pedestals in quiet (L) and in noise produce more comparable results.

Data obtained at three pedestal levels in quiet can be used to examine the role overall level plays in increment detection. When evaluating the improvement in threshold with increasing level, it is common to plot the data in units of $10 \log \Delta I/I$ versus $10 \log I$. Past studies for intensity discrimination indicate that the Weber fraction, $\Delta I/I$, becomes smaller as level, I , increases (McGill and Goldberg, 1968a, 1968b). The rate of growth of improvement is determined through calculation of the slope of a straight line fitted to the data; the slope is represented as the exponent α in $\Delta I/I = \beta(I/I_0)^\alpha$, where β and I_0 are constants. Jesteadt *et al.* (1977) suggested that for intensity discrimination α is independent of signal frequency and estimated that $\alpha = -0.072$. Estimates of α for increment detection are not as readily available in the literature, though Green *et al.* (1979) found that α does not differ for intensity discrimination and increment detection and estimate that $\alpha = -0.120$. Viemeister and Bacon (1988) reported slopes of -0.08 for intensity discrimination and -0.09 for increment detection for 200-ms increments at 1 kHz.

Mean threshold across listeners in units of $10 \log \Delta I/I$ for increment detection at 0.5 and 4 kHz in quiet at three pedestal levels are shown in Fig. 4; thresholds are plotted as a function of pedestal level with signal duration as the pa-

FIG. 4. Increment detection thresholds in units of $10 \log(\Delta I/I)$ plotted as a function of pedestal level. Each line represents the linear regression line fit for the improvement in threshold with increasing pedestal level.

rameter. The rate of growth of improvement for the current data was estimated using slopes of linear regression line fits between mean increment level and mean pedestal level. These lines of best fit are shown in each panel of Fig. 4 and calculated slopes are provided in Table IV. The slopes for the 4-kHz conditions are shallower than for the 0.5-kHz conditions. For both signal frequencies, the slope is steepest at the shortest duration. This steep slope for the 10-ms increments is the result of elevated thresholds at the lowest pedestal level, which is true for both frequencies. The slopes for longer duration increments are consistently shallower than the slopes estimated by Green *et al.* (1979) or Viemeister and Bacon (1988). Due to the effect of pedestal level on increment detection, results in the NBN will be considered with reference to quiet thresholds obtained at equal overall level, rather than equal SL.

Mean thresholds across listeners for increment detection at 0.5 and 4 kHz in quiet and in the four noise bandwidths for off-frequency maskers are shown in Fig. 5; thresholds are plotted in units of ΔL as a function of noise bandwidth with signal duration as the parameter. Data points for 'L' on the abscissa represent thresholds for increment detection in quiet for the low-level pedestal. Data points for 'H' on the abscissa represent thresholds for increment detection in quiet for the high-level pedestal. As a consequence of the spread of excitation issues described in the review of the on-frequency NBN results, only the quiet conditions at the high pedestal level will be considered.

In the off-frequency masker conditions, thresholds for the 4-kHz increments are higher than thresholds for the 0.5-kHz increments. The off-frequency maskers had little or no effect at any bandwidth. Thresholds for the conditions with the NBN masker do not seem to deviate from the threshold for the increment in the high pedestal level in quiet.

The detection threshold in $\log \Delta L$ was analyzed in a

TABLE IV. Slope of linear regression fits for data from Fig. 3.

Frequency (Hz)	Duration (ms)			
	10	20	30	50
500	-0.184	-0.098	-0.070	-0.065
4000	-0.086	-0.045	-0.050	-0.047

FIG. 5. Increment detection thresholds in units of ΔL plotted as a function of noise bandwidth centered off of the pedestal frequency. The parameter is the signal duration. Error bars indicate ± 1 SD across listeners.

repeated-measure ANOVA to test the statistical significance of the main effects of frequency, noise bandwidth, and duration, and the corresponding interactions. Appropriate Greenhouse-Geisser corrections were applied when the sphericity assumptions were not met. There was a significant interaction between frequency and noise bandwidth, ($F_{4,12} = 3.329$, $p < .05$), and frequency and duration, ($F_{3,9} = 6.766$, $p < .05$). Evaluation of the variance accounted for by these interactions suggested that no meaningful interactions were present.

Glasberg *et al.* (2001) predicted that when a broadband noise is presented to the auditory system, the output of the narrower auditory filters at low center frequencies would include slower fluctuations than auditory filters with high center frequencies and that these slow fluctuations would be more confusable with a brief increment in intensity. Glasberg *et al.* interpreted results showing improving thresholds with increasing signal frequency in a noise background, and no effect of frequency in quiet, as support for the idea that auditory filters that differed in bandwidth as a function of frequency would create narrow-band noises with different temporal properties and resulting differences in masking. One difficulty with this argument is that results from Glasberg *et al.* showed better thresholds at 4 kHz in noise than in quiet. Even if broader filters at higher frequencies resulted in less masking due to the temporal properties of the noise at the filter output, thresholds should not be better than those obtained in quiet. This result could be due to a difference in the presentation level between the quiet and noise conditions since Glasberg *et al.* presented pedestals at equal SL rather than equal overall level.

Experiment 2 directly tested the interaction between a listeners' ability to detect an increment in intensity and fluctuations resulting from a noise masker. Current results show an increase in threshold with increasing noise bandwidth independent of increment duration. Since the fluctuations produced by the noise maskers become more rapid as bandwidth increases, results do not support the prediction of greater confusion between an increment in intensity and slower fluctuations in the noise masker.

The effect of noise bandwidth observed in the current data is more consistent with masking of the spread of excitation. The NBN maskers produced elevated thresholds for

the pedestal. The pedestals and increments were thus presented at higher SPL in NBN when pedestal levels were equated in SL. The NBN maskers do not uniformly control spread of excitation. Increment detection thresholds therefore increase with increasing masker bandwidth because more of the excitation pattern is masked. Results from Jesteadt *et al.* (2009) suggested that the effect of a wide-band noise on increment detection could be largely accounted for in terms of pedestal SL for SL values below 40 dB. Results from the current experiment where pedestals were presented at 18 dB SL in the on-frequency NBN masker conditions, suggest that SL alone is not the determining factor. Current results are more uniform when pedestal levels are equated in dB SPL than in dB SL because the NBN conditions did not control spread of excitation.

Although there is no apparent effect of variability in the envelope on performance in increment detection in the current set of data, it is possible that any interaction that may be occurring is being shrouded by excitation issues. Evaluating performance in off-frequency NBN maskers aids in isolating the potential effect of envelope variability on increment detection. Results suggest that the introduction of a NBN masker centered away from the signal frequency does not produce any masking. This result is consistent with previous findings that suggest the effect of the noise is to restrict the spread of excitation (Jesteadt *et al.*, 2009; Oxenham, 1997). The center frequency of the off-frequency maskers used in this experiment fell far enough away from the signal frequency that they would not have masked any portion of the excitation pattern. Thus it appears that the NBN maskers used in this experiment did not produce envelope-modulation masking of increment detection.

The inability of the off-frequency NBN masker to produce modulation masking does not discount previous findings of Gallun and Hafter (2006) showing masking in increment detection by an AM masker. Results from Gallun and Hafter showed modulation masking by a 4 Hz AM masker, the modulation frequencies in the NBN maskers used in this study were much higher than 4 Hz. The degree of frequency separation between the pedestal and the masker may also have played a role in the off-frequency conditions. The 0.5-kHz pedestal frequency was similar to the 0.447-kHz pedestal used by Gallun and Hafter, but the 4-kHz carrier for the modulation masker was an octave higher than their 2.013-kHz carrier.

E. Modeling

The pattern of results observed in Experiment 2 was qualitatively consistent with masking of the spread of excitation. Quantitative threshold estimates were therefore obtained using the partial loudness model (PLM) described by Moore, *et al.* (1997) in addition to the MFBM used in Experiment 1. The loudness model is composed of the following stages: 1) a filter simulating the transfer through the outer ear; 2) a filter representing a middle ear transfer function; 3) calculation of an excitation pattern; 4) transformation of the excitation pattern into a loudness pattern; and 5) determination of the overall loudness by measurement of the area un-

FIG. 6. Observed thresholds and predicted thresholds for both the modulation filter bank model and the partial loudness model for increment detection in a NBN centered on-frequency. Filled squares represent threshold predictions from the modulation filter bank model. Filled triangles represent threshold predictions from the partial loudness model. Open squares represent observed thresholds from normal hearing listeners.

der the loudness pattern (Moore *et al.*, 1997). The PLM assumes that the loudness of one sound can be determined in the presence of another sound; sounds at absolute threshold have a small but finite loudness that is independent of frequency and spectral content, and a sound at masked threshold is of the same loudness as a sound at absolute threshold. Threshold predictions are based solely on spectral information; the model has no knowledge of the temporal properties of stimuli.

The description of stimulus parameters for each condition from Experiment 2 was used as the input to the PLM. The pedestal level was set to the mean pedestal level across listeners for each condition, and noise level was set to that used during data collection. Threshold for the increment in the pedestal in quiet and in the respective NBN was predicted for a partial loudness of eight phons. Simulations with the MFBM follow the procedure described in Experiment 1. Thresholds in each condition for both PLM and MFBM were converted to ΔL . For conditions that measured threshold at three levels of the pedestal, thresholds also were converted to $10 \log(\Delta I/I)$.

Observed thresholds and predicted thresholds for both the MFBM simulation and the PLM for increment detection in a NBN centered on-frequency are shown in Fig. 6. Thresholds in units of ΔL are plotted as a function of noise bandwidth, signal frequency is plotted across panels, and signal duration is plotted down the panels. The open symbols represent observed results from Experiment 2, previously pre-

sented in Fig. 3, while the filled squares are threshold predictions from the MFBM, and the filled triangles are threshold predictions from the PLM. The error bars for observed thresholds represent the standard deviation across listeners, while error bars for the modulation filter bank simulation thresholds represent standard error across repetitions.

The PLM accurately predicts observed data for the 0.5 kHz conditions, but does not predict the effect of noise bandwidth in the observed data at 4 kHz. An increase in the NBN bandwidth from 30 to 150 Hz keeping the overall level constant, changes the spread of excitation when the noise is centered at 0.5 kHz, but not at 4 kHz since 150 Hz is narrower than 1 ERB at 4 kHz. A model based only on the spread of excitation would fail to predict the observed masker bandwidth effect at 4 kHz. The MFBM as implemented here does predict an effect of noise bandwidth, but the overall impact of the NBN on increment detection is much greater than that in the observed data. The MFBM predicts improving threshold with increasing signal duration at both 0.5 and 4 kHz, though the predicted effect is greater at 0.5 kHz. The interaction between signal duration and the duration of envelope maxima predicted but not observed in Experiment 2 was also not apparent in the predicted thresholds from the MFBM.

In quiet, the PLM more closely predicts observed performance than the MFBM. Both observed data and predictions from the PLM show an improvement in threshold with increasing pedestal level. Predictions from the MFBM implemented here do not show this improvement, suggesting a failure of this model to capture the near miss the Weber's law. The near miss has been attributed to the spread of excitation (Florentine and Buus, 1981; Viemeister, 1988; Zwicker, 1970). A model based purely on level and spread of excitation, such as PLM, would therefore be successful in predicting the observed data in noise at lower frequencies, where the noise masks the spread of excitation cues. It would fail to predict data in noise in higher frequencies where spread of excitation is less important. Comparison of observed thresholds to PLM-predicted thresholds shown in Fig. 6 supports this argument.

The over-prediction of the impact of NBN by the MFBM as implemented here is compounded by the model's inability to capture the near miss but does not appear to result solely from that factor. Note that the predicted thresholds in all bandwidths of the NBN are greater than those in the "H" quiet condition, where the pedestal level was similar to the level in the NBN conditions. If the increased threshold predictions in the NBN were solely a function of the inability to capture the near miss, predicted thresholds in NBN would be the same as in the "H" quiet condition. Negative effects of masker envelope fluctuations on signal detection increase with frequency (Kohlrausch *et al.*, 1997). An amplitude-modulation based model designed to capture modulation cues that are sensitive to carrier frequency may be successful in predicting increment detection in noise. Unfortunately the MFBM implemented in this study was not designed to be sensitive to changes in carrier frequency.

Observed and predicted thresholds for both the MFBM simulation and the PLM for increment detection in a NBN

FIG. 7. Observed thresholds and predicted thresholds for both the modulation filter bank model and the partial loudness model for increment detection in a NBN centered off-frequency. Other information same as in Fig. 6.

centered off-frequency are shown in Fig. 7. For the 0.5-kHz conditions, the PLM again accurately reflects observed data, predicting no masking by the off-frequency NBN. Though minimal, a 4-kHz noise masker does appear to result in increased thresholds for the 0.5-kHz conditions. Predictions from the PLM for the 4-kHz conditions fall below the observed thresholds suggesting there is some degree of masking by the off-frequency noise that is not explained by spread of excitation.

The MFBM as implemented here predicts similar masking for the on- and off-frequency NBN at a signal frequency of 0.5 kHz, but no effect of the off-frequency NBN for the 4-kHz conditions. To provide a clearer comparison of MFBM predictions for on- and off-frequency maskers, predictions for both types of maskers are replotted in Fig. 8. Predicted threshold in log ΔL is again plotted as a function of NBN bandwidth, with 0.5-kHz signal conditions displayed in the left panels, 4-kHz signal conditions displayed in the right panels and signal durations plotted in rows.

Predicted thresholds in the 0.5-kHz conditions are very similar for the on- and off-frequency maskers and increase with increasing noise bandwidth. The on-frequency NBN produces more masking in the 4 kHz signal conditions than the off-frequency NBN. The predicted thresholds improve with increasing signal duration for both the on- and off-frequency NBN maskers for the 0.5-kHz conditions and for the on-frequency NBN 4-kHz conditions. Overall, results from simulations with the MFBM suggest an interaction between the modulation masking produced by a NBN and the carrier frequency of the signal and pedestal.

According to modulation based models, increment de-

FIG. 8. Threshold predictions from modulation filter bank model simulations for increment detection in a NBN centered on- or off-frequency.

tection is mediated by low frequency amplitude modulation cues (e.g., Gallun and Hafter, 2006); therefore, low frequency amplitude modulation would produce greater interference in detection than would high frequency amplitude modulation. The envelope of the noise+signal as a result of the addition of a narrow noise band of low or high center frequency to a low frequency tone of relatively higher amplitude would contain mostly low frequency amplitude modulation. The MFBM-predicted thresholds should, therefore, be elevated at 0.5 kHz for both on- and off-frequency NBN as a result of this low frequency amplitude modulation, as is reflected in Fig. 8. In contrast, when a band of noise is added to a high frequency tone, the envelope of the signal +noise stimulus would contain more low frequency amplitude modulation only when the noise band is center at the same frequency as the tone. For 4 kHz signals, the MFBM should predict elevated thresholds for on-frequency noise conditions due to low frequency amplitude modulation but would not predict elevated thresholds for the off-frequency noise conditions. This is again reflected in Fig. 8.

Predictions from both models for increment detection in quiet at three pedestal levels are shown in the form of linear regression lines in Fig. 9. Observed results have been replotted from Fig. 4. Since the PLM does not have knowledge about the temporal properties of the input stimuli, predictions do not vary with signal duration and thus only one regression line is plotted per signal frequency. The MFBM does make different predictions for each signal duration, shown as different line types.

The PLM captures the basic trend of improving performance with increasing pedestal level seen in the observed

FIG. 9. Increment detection thresholds in units of $10 \log(\Delta I/I)$ plotted as a function of signal duration. The rate of growth of improvement was estimated using slopes of linear regression line fits between mean increment level and mean pedestal level. The line of best fit for predictions from the partial loudness model is denoted as a solid line ($\square$). The lines of best fit for predictions from the modulation filter bank model are denoted as dashed lines ($\square$ 10 ms, $\circ$ 20 ms, $\triangle$ 30 ms, $\diamond$ 50 ms).

data, fitting observed data at 0.5 kHz quite well. The PLM predicts a steeper function at 4 kHz than at 0.5 kHz. Listeners' demonstrate the reverse, a shallower function at 4 kHz than at 0.5 kHz. As noted previously, the MFBM does not show an improvement in performance with increasing pedestal level and thus does not capture the near miss to Weber's law. The MFBM does tend to show an increase in slope with decreasing signal duration. Neither the PLM nor the MFBM captured observed data well, but each was able to account for some sub-set of data, suggesting that listeners may use both level and modulation cues for increment detection.

IV. DISCUSSION

The MFBM and PLM models evaluated in this study failed to capture all aspects of the observed data. First, the MFBM failed to capture the near miss to Weber's law. It is not clear how to produce the near miss to Weber's law in this model without assuming a level dependent internal noise. Lutfi and Jesteadt (2006) have presented evidence against models that assume decreases in internal noise with increasing level. Studies of increment detection and modulation detection in the presence of noise above the pedestal or carrier frequency suggest that the near miss is due to spread of excitation. Any modification to the filter bank model that would make it more sensitive to spread of excitation might therefore improve the accuracy of its predictions for stimuli differing in level as well as its predictions of noise bandwidth effects, bringing it more in line with the partial loudness model.

The failure to observe the bandwidth effect predicted by Glasberg *et al.* (2001) in the model output for either Experiment 1 or 2 suggests that: 1) the greater fluctuations associated with narrower bands of noise are not sufficient to interfere with increment detection; 2) that this effect is small with respect to internal noise; or 3) that the decision mechanism(s) is operating on the summed output of peripheral auditory filtering, rather than on the output of a single auditory filter.

The result of equating pedestal levels in dB SL was higher pedestal and increment levels in dB SPL for those

conditions with a noise back ground. Issues related to compressive non-linearity and the near miss to Weber's law might have been introduced by presenting conditions at different overall levels. The near miss to Weber's law has been observed in both intensity discrimination (Green *et al.*, 1979; Jesteadt *et al.*, 1977; Kohlrausch, 1993; McGill and Goldberg, 1968a, 1968b) and modulation detection (Bacon and Viemeister, 1985; Viemeister, 1979) and these measures appear to be closely related (Wojtczak and Viemeister, 1999). Comparisons of intensity discrimination and increment detection as a function of pedestal level show comparable effects (Green *et al.*, 1979; Viemeister and Bacon, 1988), although the effect of pedestal level on increment detection may be larger at low pedestal levels (Jesteadt *et al.*, 1977).

Due to the apparent connection between increment detection and modulation detection, it is possible that results from the current study are complicated by the modulation sensitivity of the auditory system, and by within and across channel interactions. In normal hearing listeners, the sensitivity of the auditory system to modulation varies as a function of carrier level and carrier frequency and can be impaired by the presence of amplitude modulation presented at distant carrier frequencies (Bacon and Grantham, 1989; Kohlrausch, 1993; Moore and Sek, 1992, 1994; Wilson *et al.*, 1990; Wojtczak and Viemeister, 1999; Yost and Sheft, 1989). Envelope based masking is often referred to as modulation detection interference (MDI) (Yost and Sheft, 1989). By assuming that the modulation resulting from an increment in the intensity of a longer duration tone can be masked by the modulation resulting from a NBN, an increment detection task in noise could be considered an extension of MDI.

Finally, neither the PLM nor the MFBM could predict the observed data in all conditions, but each was able to account for some sub-set of data, suggesting that any decision device that utilizes either energy or modulation cues alone is not sufficient. Listeners may rely upon a combination of level and modulation cues for increment detection.

V. CONCLUSIONS

1. When pedestal level is equated at 18 dB SL, there is a significant effect of a wide band noise masker on the detection of an increment in the intensity of a longer duration pure tone at short increment durations but not at longer increment durations. The presence of a noise masker elevates thresholds for detection of a decrement in the intensity of a longer duration pure tone at longer decrement durations but not at short decrement durations.
2. Increment detection thresholds increase with increasing masker bandwidth for a NBN centered on the signal frequency, but increment detection thresholds are not impacted by a NBN centered three octaves away from the signal frequency.
3. The partial loudness model provided a good account of the improvement in increment detection threshold as a function of pedestal level, but the modulation filter bank model as implemented here failed to predict this effect.
4. Neither a partial loudness model nor a modulation filter

bank model accurately reflect the effect of a narrow-band noise masker on increment detection thresholds, but each captures a key aspect of the observed data.

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