Informational masking of negative masking^{a)}

Christopher Conroy,^{b)} Christine R. Mason, and Gerald Kidd, Jr.

Department of Speech, Language & Hearing Sciences and Hearing Research Center, Boston University, 635 Commonwealth Avenue, Boston, Massachusetts 02215, USA

ABSTRACT:

Negative masking (NM) is a ubiquitous finding in near-“threshold” psychophysics in which the detectability of a near-threshold signal improves when added to a copy of itself, i.e., a pedestal or masker. One interpretation of NM suggests that the pedestal acts as an informative cue, thereby reducing uncertainty and improving performance relative to detection in its absence. The purpose of this study was to test this hypothesis. Intensity discrimination thresholds were measured for 100-ms, 1000-Hz near-threshold tones. In the reference condition, thresholds were measured in quiet (no masker other than the pedestal). In comparison conditions, thresholds were measured in the presence of one of two additional maskers: a notched-noise masker or a random-frequency multitone masker. The additional maskers were intended to cause different amounts of uncertainty and, in turn, to differentially influence NM. The results were generally consistent with an uncertainty-based interpretation of NM: NM was found both in quiet and in notched-noise, yet it was eliminated by the multitone masker. A competing interpretation of NM based on nonlinear transduction does not account for all of the results. Profile analysis may have been a factor in performance and this suggests that NM may be attributable to, or influenced by, multiple mechanisms.

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I. INTRODUCTION

Numerous authors have noted a conceptual equivalence between masked detection and intensity discrimination tasks (e.g., Miller, 1947; Tanner, 1958, 1961; Green, 1960; Green and Swets, 1966; Bos and de Boer, 1966; Durlach, 2006). For example, one way to conceptualize a standard, pure-tone intensity discrimination¹ task is as a special case of the masked detection task in which the signal to be detected, ΔA , is a sinusoid and the masker, A (hereafter *pedestal*), is also a sinusoid matched to the signal in frequency, phase, starting time, and duration. Note that, when viewed in this way, ΔA refers to the quantity that is added to the pedestal, i.e., “the signal” as classically defined in a signal detection task, *not* to an increment in a quantity that is caused by this addition (cf. Green, 1988). Under this conceptualization, a peculiar finding arises when “masked” detection thresholds are measured using pedestals in the region near *absolute detection threshold*, A_0 , where A_0 refers to the threshold for the detection of the signal in the absence of a pedestal and thus dB re. A_0 refers to dB sensation level (SL). Namely, under certain conditions, the detectability of the signal can improve in the presence of a pedestal and the level of the just detectable masked signal at threshold, ΔA_{JND} , can “dip” (cf. Solomon, 2009) below A_0 (Hanna *et al.*, 1986; Viemeister and Bacon, 1988; Shepherd and Hautus, 2009; Shepherd *et al.*, 2013). This finding has been termed

negative masking (NM) (Raab *et al.*, 1963a) due to the fact that it represents a situation in which, contrary to Weber’s law, sensitivity *improves* under masking.

NM is a ubiquitous finding in near-“threshold” psychophysics, evident in multiple sensory modalities (see Laming, 1986 and Solomon, 2009 for reviews). As such, it can be defined more broadly as the improvement in the detectability of a near-threshold signal that occurs when that signal is added to a copy of itself, i.e., a pedestal. In audition, NM occurs in the context of intensity discrimination, when both the signal and the pedestal are near 0 dB SL. It has been found using both broadband noise (Raab *et al.*, 1963a,b) and pure-tones (Hanna *et al.*, 1986; Viemeister and Bacon, 1988; Shepherd and Hautus, 2009; Shepherd *et al.*, 2013). In this study, we focus on pure-tone signals and tonal pedestals and so, for simplicity, all subsequent discussions of NM are in terms of such stimuli.

While the existing data on auditory NM suggest that it occurs only under a restricted set of conditions (see Shepherd and Hautus, 2009), a complete understanding of the mechanisms that underlie it may have theoretical implications that extend beyond the limited scope of studies of NM *per se*. For example, one interpretation of NM, known as the channel uncertainty hypothesis (CUH), suggests that NM in an intensity discrimination task reflects a release from uncertainty relative to *simple detection*. Hereafter, the terms *simple detection* and *detection* are used interchangeably and refer to the task of detecting the signal in the absence of a pedestal. More specifically, the CUH suggests that, rather than act as a masker, the pedestal acts as an

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^{b)}Electronic mail: cwconroy@bu.edu

informative cue, thereby reducing uncertainty and improving performance relative to detection in its absence (Green, 1960; Tanner, 1961). This interpretation is interesting because it suggests that the fundamental construct of A_0 itself may be limited by uncertainty (e.g., Green, 1961). A more complete understanding of NM, then, may shed light on how uncertainty influences auditory perception in a more general sense.

Currently, however, NM is not well understood, nor is it particularly well studied. In the psychoacoustic literature, four main interpretations dominate: (1) the CUH (Green, 1960; Tanner, 1961), (2) the nonlinear transducer model (Hanna *et al.*, 1986), (3) units selection (Raab *et al.*, 1963a,b; Leshowitz and Raab, 1967; Viemeister and Bacon, 1988; Shepherd and Hautus, 2009; see also Laming, 1986; Green, 1988; McGill and Teich, 1989), and (4) the sensory analytical model proposed by Laming (1985, 1986). The latter two interpretations (units selection and Laming's sensory analytical model) have been addressed previously (for units selection, see references above; for the sensory analytical model, see Laming, 1985, 1986; Hanna *et al.*, 1986; Shepherd and Hautus, 2009) and are not considered in detail here. Suffice it to say that while units selection is not wholly compelling based on the most recent data (e.g., Shepherd and Hautus, 2009; Shepherd *et al.*, 2013) Laming's model remains a viable interpretation of NM under certain conditions. In fact, of the handful of empirical studies of auditory NM that have appeared in the literature since Laming first proposed his model (Hanna *et al.*, 1986; Viemeister and Bacon, 1988; Shepherd and Hautus, 2009; Shepherd *et al.*, 2013) none have presented data that are entirely inconsistent with its basic predictions (although see Moore, 1988 for criticisms of Laming's model outside of the context of NM). That said, in this study, we chose to focus on the CUH. We also consider the nonlinear transducer model in relation to it. We will, however, return briefly to Laming's model in light of our results.

A. Uncertainty and NM

The CUH begins with the following premise: when an observer is tasked with the detection of a near-threshold signal in the absence of a pedestal they are uncertain about the exact parameters that the signal will assume on each trial, and this is true even when all stimulus parameters are fixed and "known" across trials (Green, 1960; Tanner, 1961). In other words, the observer has a large "default state uncertainty" regarding some (or many) aspects of the stimulus (e.g., Green, 1961). According to the CUH, the consequence of this uncertainty is that the observer monitors some large number of independent sensory channels, $M \gg 1$, on each trial and is completely unable to determine which of these channels is relevant to the detection of the signal.² In this study, we were concerned with the effects of uncertainty in the frequency domain and so the M monitored channels are considered to be tuned along this dimension.³

It is further assumed that (1) the response mechanism associated with each of the M channels grows linearly with respect to stimulus strength, (2) only one of the M channels is responsive to the signal frequency, (3) each of the M channels is corrupted by an independent source of equal-variance noise, and (4) the decision statistic is calculated on the basis of all M monitored channels. For the purposes of this study, the exact form of the decision statistic is not particularly important as there are different choices that make roughly similar predictions (see Nolte and Jaarsma, 1967; Cohn, 1978; Pelli, 1985). What is important is the assumption that a single value is calculated in each of the M channels and that this value is combined with or compared to all others before arriving at the final decision statistic. Here, all such decision statistics are encompassed under the general heading of the CUH.

Taken together, these assumptions imply that, when uncertainty is high, $M-1$ non-signal channels contribute noise during the calculation of the decision statistic. The consequence is that on "noise-alone" presentations, the decision statistic distribution will be skewed in the positive direction relative to the distribution based on the output of a single channel (Pelli, 1985). What this means is that, when $M > 1$, the signal strength required to reach some criterion level of performance will be elevated relative to the "ideal" single-channel observer, as will the slope of the d' vs signal strength psychometric function (Peterson *et al.*, 1954; Green, 1960; Tanner, 1961; Green and Swets, 1966; Nolte and Jaarsma, 1967; Pelli, 1985). In other words, the CUH suggests that empirical estimates of A_0 are contaminated by uncertainty and are spuriously high with respect to the "true" sensitivity of the system.

Whereas A_0 may be tainted by uncertainty, the CUH posits that NM exists because ΔA_{IND} is not. That is, NM in an intensity discrimination task is attributable to a release from uncertainty relative to simple detection. Rather than act as a masker, the argument goes, the pedestal acts as an informative cue that enables the observer to more effectively focus their attention on the signal-bearing channel. In turn, M is reduced, fewer channels contribute noise during the calculation of the decision statistic, and the effects of uncertainty are reversed. Namely, (1) detectability improves, (2) the psychometric function flattens, and (3) NM is obtained. All three of these "uncertainty reduction effects" are borne out in the psychoacoustic literature on NM (e.g., Hanna *et al.*, 1986; Viemeister and Bacon, 1988; Shepherd and Hautus, 2009; Shepherd *et al.*, 2013) and this suggests that when NM is quantified via the equation

$$NM = A_0 - \Delta A_{IND}, \quad (1)$$

it can be regarded as the amount by which A_0 is limited by uncertainty.

B. Uncertainty vs the nonlinear transducer model

Yet, despite a long history of speculation, the relationship between uncertainty and NM remains unclear for two

reasons. The first is that uncertainty *per se* has received virtually no empirical attention in the (admittedly sparse) psychoacoustic literature on NM. To date, support has come primarily from the qualitative consistency of empirical data with theoretical models (Green, 1960; Tanner, 1961). The second, more substantial, reason is that the principal competitor to the CUH, the nonlinear transducer model (Hanna *et al.*, 1986), makes similar predictions to the CUH under a variety of stimulus configurations (Tanner, 1961). This makes it difficult, if not impossible, to distinguish between the two interpretations based on existing data. In this study, we used a novel empirical approach that did allow for such a distinction.

A crucial assumption implicit in the nonlinear transducer model is that NM is a single-channel phenomenon. That is, the nonlinear transducer model assumes a nonlinear transformation of the physical stimulus into an internal response within a single sensory channel (e.g., the signal's "critical band") and contends that the decision statistic is calculated by way of a differencing operation on this internal variable (Hanna *et al.*, 1986). NM reflects the accelerating nature of the transducer function at low levels. Taken at face value, this suggests that no matter what the stimulus configuration NM should be unaffected by non-signal energy falling in non-signal channels. The CUH, on the other hand, inherently depends on stimulus events occurring over a wide frequency range and the magnitude of NM is highly dependent on such energy. That is, according to the CUH, NM occurs only when uncertainty is reduced to a minimum via cueing by the pedestal and any non-signal energy falling in non-signal channels is completely ignored. When uncertainty is high, non-signal energy is obligatorily combined with the signal during the calculation of the decision statistic, "swamping" low-level signals and precluding NM.

C. Current approach

The preceding observation leads us to speculate that we could test the viability of the CUH directly by adding non-signal energy (*non-pedestal maskers*) to frequency regions outside of the signal's critical band and observing the influence of this energy on NM. In two experiments, intensity discrimination thresholds were measured using pedestals in the region near 0 dB SL in quiet and in the presence of two different types of non-pedestal maskers with different amounts of spectral variability but equal energy. The differences in spectral variability were hypothesized to cause different amounts of uncertainty with large amounts of spectral variability yielding large amounts of uncertainty and vice versa (Spiegel *et al.*, 1981; Spiegel and Green, 1982; Neff and Green, 1987; Lutfi, 1990; Durlach *et al.*, 2003). Accordingly, these differences in spectral variability were hypothesized to differentially influence NM via M . The CUH predicts differences in NM across such maskers; a strict interpretation of the nonlinear transducer model based on a single-channel mechanism does not. In fact, the

nonlinear transducer model predicts no difference in NM across any of the intensity discrimination conditions we tested.

In the first experiment, the non-pedestal masker was a random-frequency "multitone masker" typical of studies of *informational masking* (e.g., Neff and Green, 1987; see Kidd *et al.*, 2008). Informational masking often has been defined in contrast to *energetic masking*, where energetic masking refers to masking that results from interactions between the signal and the masker in the auditory periphery. Energetic masking reduces the information in the peripheral representation of the target that is available for processing at higher levels of the auditory system. In contrast, informational masking refers to masking that is not attributable to peripheral interactions and, therefore, presumably reflects non-optimal central processing of a peripheral stimulus representation that is sufficient for solving the task (see Durlach *et al.*, 2003; Watson, 2005; Kidd *et al.*, 2008; Lutfi *et al.*, 2013 for reviews and further definitions). Most generally, informational masking is thought to be due to observer uncertainty (e.g., Neff and Green, 1987; Neff and Callaghan, 1988; Lutfi, 1990; Neff, 1995; Oh and Lutfi, 1998; Wright and Saberi, 1999; Lutfi *et al.*, 2003). For example, consider the task of the detection or intensity discrimination of a pure-tone signal embedded in a simultaneous multitone masker, where the multitone masker comprises a small number of sinusoids, none of which are in close spectral proximity to the signal. When uncertainty is created by randomly choosing the frequencies or levels of the sinusoids that constitute the masker on each stimulus presentation, detection or intensity discrimination thresholds can increase dramatically relative to thresholds that are measured in the absence of such uncertainty (e.g., Spiegel *et al.*, 1981; Kidd *et al.*, 1986; Wright and Saberi, 1999; Tang and Richards, 2003; Durlach *et al.*, 2005). This is informational masking. It is worth noting that there are a variety of factors other than uncertainty that could contribute to informational masking under multitone masking conditions (cf. Durlach *et al.*, 2003; Kidd *et al.*, 2008). In this article, however, informational masking refers to non-energetic masking that is attributable to uncertainty.

The CUH postulates that one of the consequences of uncertainty is a situation in which $M > 1$, and that NM, therefore, will not be present. Similarly, various models of informational masking described in the literature suggest that one of the consequences of randomly varying the spectrum of a multitone masker from presentation to presentation is to cause uncertainty, thus creating a situation in which $M > 1$ (e.g., Lutfi, 1993; Oh and Lutfi, 1998; Richards *et al.*, 2002; Durlach *et al.*, 2005; Richards and Tang, 2006). In this study, we sought to exploit this link and to "break" NM via informational masking. In the first experiment, the random-frequency multitone masker was intended to cause uncertainty, this uncertainty was intended to cause informational masking, and, under informational masking, it was assumed that M would be some number > 1 . We hypothesized that this putative increase in M relative to minimal

uncertainty conditions would counteract the proposed cueing benefit of the pedestal and thus would either mitigate or eliminate NM, consistent with the CUH but not with the nonlinear transducer model. As will be seen, our results generally support this interpretation. In the second experiment, the multitone masker was tested again, as was an energy-matched notched-noise masker intended to control for the effects of energetic masking. In contrast to the multitone masker, the notched-noise masker was hypothesized to cause minimal uncertainty or increase in M (e.g., Spiegel and Green, 1982; Neff and Green, 1987; Durlach *et al.*, 2003; although see Lutfi, 1990) and thus was hypothesized to have little or no effect on NM. Again, our results are generally consistent with this interpretation, with some caveats.

II. EXPERIMENT 1

A. Methods

1. Observers

Three observers, including the first author (Obs 2), participated (3 males; ages 19–30; mean age 23). All observers had normal pure-tone air conduction thresholds (<25 dB hearing level) at octave frequencies between 250 and 8000 Hz.

2. Apparatus

Observers were tested individually while seated in a double-walled, sound-treated Industrial Acoustics Company (IAC, North Aurora, IL) booth. Stimuli were generated digitally on a control computer using MATLAB (MathWorks, Inc., Natick, MA) software at a sampling rate of 44 100 Hz and were presented monaurally to the observer's left ear via Sennheiser HD280 Pro earphones (Sennheiser Electronic GmbH and Co. KG, Wedemark, Germany). Digital-to-analog conversion was accomplished using an RME (Haimhausen, Germany) HDSP 9632 (ASIO) 24-bit sound card. The same equipment was used in Experiments 1 and 2.

3. Stimuli and conditions

Experiment 1 consisted of two parts. In the first part, a simple detection task, A_0 was measured for each observer in quiet. Thresholds obtained in this task are denoted $A_{0, Quiet}$. In the second part, an intensity discrimination task, intensity discrimination thresholds were measured for three pedestal levels bracketing and including $A_{0, Quiet}$: −9, 0, and 9 dB re. $A_{0, Quiet}$, i.e., dB SL. Intensity discrimination thresholds were measured in two conditions: a *quiet* condition (no masker other than the pedestal) and a *random* condition. In the random condition, in addition to A or $A + \Delta A$, a non-pedestal multitone masker was present in each observation interval.

All stimuli were 100-ms and were gated with 5-ms cosine² onset-offset ramps. All stimuli were gated synchronously. In the first part of the experiment, ΔA was a 1000-Hz sinusoid. In the second part, ΔA was a 1000-Hz sinusoid added in-phase to A , a second 1000-Hz sinusoid. ΔA and A both started in the cosine phase. The non-pedestal multitone

masker consisted of four sinusoidal components. Each component was drawn at random on each stimulus presentation from the range 80–8000-Hz (log-spaced, equal probability), excluding a 398-Hz *protected region* centered on 1000-Hz (roughly three times the equivalent rectangular bandwidth at 1000-Hz Glasberg and Moore, 1990). The components of the multitone masker all had equal amplitude and had a starting phase drawn at random from a uniform distribution with a range 0– 2π . No two components were allowed to be closer than the inverse of the total stimulus duration. The overall level of the multitone masker was fixed at 30 dB sound pressure level (SPL), regardless of the pedestal level.

4. Procedures

In the first part of the experiment, $A_{0, Quiet}$ was measured using a two-interval, two-alternative forced-choice (2I-2AFC), two-down, one-up adaptive tracking procedure that estimated the 70.7% correct point of the underlying psychometric function (Levitt, 1971). Each trial consisted of the following sequence: a 545-ms warning light, a 545-ms pause, and two 100-ms observation intervals separated by a 545-ms interstimulus interval, only one of which contained ΔA . On each trial, the observer's task was to identify the interval that contained ΔA . The initial step size in each block of trials was 4 dB. After the first four reversals, it was reduced to 2 dB. A block of trials was terminated after 15 total reversals. The threshold for each block was estimated by taking the mean of all but the first four reversals and was discarded if the standard deviation of that block was >6 dB and the track was deemed unreliable (cf. Viemeister and Bacon, 1988). The cutoff standard deviation was exceeded only rarely. The final estimate of $A_{0, Quiet}$ for each observer was determined by taking the mean of approximately ten blocks and is shown in Table I. These values were then used to set the pedestal levels in the second part of the experiment.

In the second part of the experiment, intensity discrimination thresholds were measured using the same 2I-2AFC adaptive tracking procedure described above except that the step size was quantified in terms of $20 \cdot \log(\Delta A/A)$. In both the quiet and random conditions, on each trial, one observation interval contained A alone while the other contained $A + \Delta A$. The observer's task was to identify the interval that contained ΔA . In the random condition, in addition to A or $A + \Delta A$, each observation interval also contained a non-pedestal multitone masker. The value of A was fixed throughout a block of trials, as was the condition (quiet or random), and quiet and random blocks were completed in a random order, randomized over all blocks.⁴ Final estimates

TABLE I. Final estimates (and standard errors of these estimates) of $A_{0, Quiet}$ for each observer in dB SPL. These values were used to define the pedestal levels in the second part of the experiment on a per-observer basis.

	Obs 1	Obs 2	Obs 3
Quiet ($A_{0, Quiet}$)	5.6 (0.7)	−4.7 (0.7)	8.8 (1.1)

of ΔA_{JND} were determined for each value of A by taking the mean of approximately eight blocks.

B. Results and discussion

Considering A as a masker, plotting ΔA_{JND} as a function of the level of A yields a *masking function* (Miller, 1947). Individual and group mean masking functions for both the quiet and random conditions are shown in Fig. 1. Note that all data in Fig. 1 are normalized by $A_{0, Quiet}$ and thus the ordinate and abscissa of each panel are in units of dB SL. Points that fall below the horizontal dashed line indicate NM.

Turning first to the masking functions obtained in quiet. The basic point to be made with respect to these functions is that NM was obtained by all three observers. While the magnitude of NM varied, the range of values obtained and the general shape of these functions is consistent with previous studies of auditory NM using pure-tones (e.g., Hanna *et al.*, 1986; Viemeister and Bacon, 1988; Shepherd and Hautus, 2009; Shepherd *et al.*, 2013). For 0 dB SL pedestals, where the dip in the masking function was at a minimum for all three observers, the magnitude of NM, quantified using Eq. (1), was 5.0 dB for Obs 1, 9.2 dB for Obs 2, and 12.2 dB for Obs 3. Group mean NM at this point was 8.8 dB. Accepting for a moment the basic premise of the CUH, what 8.8 dB of NM suggests is that the information gleaned from the pedestal effected an 8.8 dB release from uncertainty relative to simple detection in quiet.

In the random condition, NM was eliminated. For 0 dB SL pedestals, thresholds increased by 21.9 dB for Obs 1, 26.8 dB for Obs 2, and 17.6 dB for Obs 3. The group mean increase at this point was 21.7 dB. Under the assumptions of the CUH, what this suggests is that while the pedestal may have been an effective cue in quiet, it was not sufficient to overcome the heightened level of uncertainty that was present in the random condition. In this sense, there was “informational masking of NM.” Whereas NM in quiet suggests a release from uncertainty relative to simple detection, informational masking of NM suggests that when uncertainty is “added back in” via a multitone masker, NM is

eliminated due to an increase in M . Thus, the elimination of NM in the random condition is consistent with the CUH yet it is not consistent with a strict interpretation of the nonlinear transducer model based on a single-channel mechanism that makes no provision for uncertainty.

1. Psychometric functions

Further evidence that uncertainty was a factor in performance comes from an analysis of psychometric function slopes. As noted in Sec. I, the CUH predicts a flattening of the d' vs signal strength psychometric function for intensity discrimination relative to simple detection (Green, 1960; Tanner, 1961). This pattern is also predicted by the nonlinear transducer model (Hanna *et al.*, 1986). Empirical psychometric functions obtained in these two conditions do indeed follow this pattern and this has been taken as evidence in support of either the CUH (Green, 1960; Tanner, 1961; Green and Swets, 1966) or the nonlinear transducer model (Hanna *et al.*, 1986) depending on the study. Therefore, a comparison of psychometric function slopes in our quiet detection and *quiet* intensity discrimination conditions sheds scant additional light on the mechanisms underlying NM.

Notably, however, various models of informational masking described in the literature predict the opposite relationship between the slope of the psychometric function in a tone detection task and the amount of uncertainty that is caused by a multitone masker (e.g., Lutfi, 1993; Oh and Lutfi, 1998; Durlach *et al.*, 2005; see discussion of “fixed-weight” models in Lutfi *et al.*, 2003). That is, in contrast to the CUH, these models predict a *shallow* slope under uncertainty. The reason for the difference lies in the assumed form of the decision statistic and the different types of stimuli that are used to model the effects of uncertainty. On the one hand, the CUH posits that the decision statistic is obtained by calculating a unique value (likelihood ratio) in each of the M monitored channels and either summing these values over all M (the optimal detector under uncertainty; Peterson *et al.*, 1954; Green and Swets, 1966; Nolte and Jaarsma, 1967; Cohn

FIG. 1. Masking functions obtained in quiet (open symbols, solid lines) and in the random condition (black symbols, dashed lines) for the three observers and the mean across observers. Error bars are standard errors of the mean.

et al., 1974) or picking the maximum (non-optimal yet qualitatively similar; Nolte and Jaarsma, 1967; Cohn, 1978; Pelli, 1985). The steep slope under uncertainty is, therefore, attributable to the large number, $M-1$, of uninformative channels that contribute noise to this process. Such noise is particularly damaging at low signal levels (Pelli, 1985), hence, a steep psychometric function.

The CUH's prediction of a steep slope under uncertainty is based on the notion that the $M-1$ non-signal channels are all corrupted by independent sources of equal-variance noise and nothing else, which is obviously not the case under multitone masking. The prediction of a shallow slope under multitone masking is based on the notion that the decision statistic is calculated by measuring the energy at the output of a wide "attentional band," which, in addition to the signal channel, is comprised of some number, M , of constituent frequency channels >1 (e.g., Lutfi, 1993; Oh and Lutfi, 1998; Durlach *et al.*, 2005). The important point to emphasize is that, under multitone masking, the masker is highly variable in terms of its spectral content across trials and thus, rather than being corrupted simply by independent sources of equal-variance noise, the $M-1$ non-signal channels capture large amounts of masker energy on some trials, and little on others, resulting in substantial variability in the decision statistic across trials (assuming that the bandwidth of the attentional band is narrower than the full range of possible masker frequencies; cf. Lutfi *et al.*, 2003), hence, a shallow psychometric function.

What is most relevant for our purposes is that both classes of model are based on the notion that, under uncertainty, $M > 1$. In other words, when $M > 1$, uncertainty exists and NM does not. Therefore, these two classes of model can be unified under a single conceptual framework in which uncertainty is defined as the non-optimal processing of stimulus information across all M monitored channels when it is "more optimal" to focus on the output of the single channel centered on the signal.

With this definition of uncertainty in mind, psychometric functions of the form

$$d' = a(\Delta A/A_{0, \text{Quiet}})^b \quad (2)$$

were fit separately for each observer in three conditions: detection in quiet, intensity discrimination in quiet for 0 dB SL pedestals, and intensity discrimination in the random condition for 0 dB SL pedestals. This function has been used previously in psychoacoustic studies of NM (Hanna *et al.*, 1986) and has a long history of use in studies of intensity discrimination more generally (see Green, 1988). When d' is plotted in log units, b is the slope parameter and a is a constant that accounts for differences in sensitivity. In fitting the functions, the 2I-2AFC adaptive tracking data for each condition were pooled across all blocks (excluding those that were discarded during the calculation of the original threshold estimates). To avoid a spurious fit, the data for a given signal level were included in the fit only if they met the retention criteria described by Zhou and Green (1995, p. 831). Namely, at least 20 trials must have occurred at that signal level and the proportion of correct responses at that signal level must have been at least one standard deviation {calculated as $[p(1-p)/n]^{1/2}$ where p is the proportion of correct responses and n is the number of trials at that signal level} away from 0.50 or 1.0. Psychometric functions for detection in quiet were forced to yield the same threshold as in the adaptive tracking procedure (i.e., $d' = 0.78$; see Macmillan and Creelman, 2005) by setting $a = 0.78$. This was done because this threshold value was used to set the physical levels of the pedestals during the experiment and thus is the value represented by $A_{0, \text{Quiet}}$ in all plots. For the intensity discrimination conditions, a and b were free parameters.

Psychometric functions for each observer are plotted in Fig. 2. Estimates of a , b , and threshold (the point at which the fitted function crossed $d' = 0.78$) are shown in Table II.

FIG. 2. Psychometric functions for all three observers based on fits to the adaptive data. Psychometric functions are least-squares fit to the underlying data, representing the function $d' = a(\Delta A/A_{0, \text{Quiet}})^b$. The three lines in each panel represent three conditions: detection in quiet (solid lines), intensity discrimination in quiet for 0 dB SL pedestals (dashed lines), and intensity discrimination in the random condition for 0 dB SL pedestals (dotted lines).

TABLE II. Estimates of a and b for the psychometric functions shown in Fig. 2 [see Eq. (2)]. Also shown are threshold estimates (where $d' = 0.78$) based on the fitted psychometric functions. Note that while these thresholds are slightly different than those shown in Fig. 1 (which were obtained by averaging the adaptive data), they are in close agreement with those values.

	Obs 1			Obs 2			Obs 3		
	a	b	Thresh.	a	b	Thresh.	a	b	Thresh.
Quiet detection	0.78	1.26	0	0.78	1.80	0	0.78	1.52	0
Quiet discrimination, 0 dB SL	1.35	1.02	-4.7	2.55	0.96	-10.7	1.76	0.66	-10.8
Random discrimination, 0 dB SL	0.44	0.36	14.1	0.17	0.80	16.7	0.61	0.44	5.0

Thresholds were in close agreement with those estimated by taking the mean of the adaptive tracking data (cf. Fig. 1). The main point to be made with respect to the psychometric functions shown in Fig. 2 is that the changes in slope across conditions were consistent with the predictions of *both* the CUH and the various models of informational masking listed above, and thus with uncertainty defined as the non-optimal processing of stimulus information across frequency channels when it is more optimal to focus solely on a single channel centered on or near the signal. Consistent with the predictions of the CUH, the steepest function for each observer was for detection in quiet, a condition theoretically high in uncertainty and with $M > 1$. For intensity discrimination in quiet, a condition that theoretically minimized uncertainty, the slope decreased and, for two observers (Obs 1 and 2), b was near 1, consistent with a complete elimination of uncertainty as per the CUH (i.e., with $M = 1$). When uncertainty was “added back in” via the multitone masker, the slope decreased even further such that $b \ll 1$, consistent with models of informational masking and with $M > 1$. The consistency of these functions with the predictions of both classes of model suggests a shift in decision strategy with condition. While such a shift is somewhat difficult to reconcile intuitively, it is nonetheless consistent with the notion that differences in uncertainty were a factor across conditions. That is, the two different types of “masker” (the pedestal and the multitone masker) seemed to modulate uncertainty in different (i.e., opposite) ways.

Critically, this pattern is inconsistent with a strict interpretation of the nonlinear transducer model based on a single-channel mechanism. While the nonlinear transducer model *does* predict a flattening of the psychometric function for intensity discrimination in quiet relative to simple detection, it does not predict a difference between intensity discrimination in quiet and intensity discrimination in the random condition. As such, we take the pattern of slopes across conditions observed here as crude, qualified support for the CUH.

III. EXPERIMENT 2

A. Introduction

The results of Experiment 1 were generally consistent with the CUH. However, an alternative explanation for the elimination of NM in the random condition is that despite the large protected region, the non-pedestal multitone

masker made a non-zero contribution to energetic masking and thus obscured either A and/or $A + \Delta A$ at the auditory periphery, increasing thresholds and eliminating NM. That is, the elimination of NM in the random condition possibly had nothing to do with a reintroduction of uncertainty relative to intensity discrimination in quiet but rather was attributable to masking of peripheral origin. Experiment 2 was designed to address this possibility.

In Experiment 2, the same intensity discrimination conditions (quiet and random) and pedestal levels (-9, 0, and 9 dB re. $A_{0, \text{Quiet}}$) that were tested in Experiment 1 were tested again, as was a new intensity discrimination condition (*notched-noise*) paired with the same three pedestal levels. The notched-noise condition paired with these three pedestal levels was intended to isolate the contribution of energetic masking to the elimination of NM in the random condition of Experiment 1. More specifically, in the notched-noise intensity discrimination condition, intensity discrimination thresholds for near-threshold pedestals were measured in the presence of a non-pedestal notched-noise masker that was constructed so as to cause similar amounts of energetic masking as the multitone masker that was used in the random condition of Experiment 1 yet cause minimal informational masking. The prediction was that if the elimination of NM in the random condition of Experiment 1 was attributable primarily to energetic masking, the notched-noise condition paired with the same three pedestal levels should fail to yield NM as well because the amount of energetic masking should be comparable in both conditions.

In addition to pedestal levels bracketing and including $A_{0, \text{Quiet}}$, three additional pedestal levels were tested in the notched-noise and random intensity discrimination conditions to further control for energetic masking. These new pedestals were scaled so as to bracket and include each observer’s absolute detection threshold in the specific masking context, i.e., in the presence of either the notched-noise or the multitone masker. These thresholds are denoted $A_{0, \text{Masked}}$; the three additional pedestal levels were -9, 0, and 9 dB re. $A_{0, \text{Masked}}$. Because $A_{0, \text{Masked}} > A_{0, \text{Quiet}}$ for all observers, the physical levels of these new pedestals were higher on average than those tested in Experiment 1 and thus were intended to mitigate the effects of energetic masking in the notched-noise and random intensity conditions by increasing the signal-to-noise ratio (S/N) of A and/or $A + \Delta A$ within the signal’s critical band. The prediction was that if the elimination of NM in the random condition of

Experiment 1 was due primarily to energetic masking, NM should be evident for pedestal levels bracketing and including $A_{0,Masked}$ because the effects of energetic masking on these pedestals should be minimized.

B. Methods

1. Observers

Three observers participated (3 males; ages 20–30; mean age 24). Two observers (Obs 2 and 3) also participated in Experiment 1. Where there was overlap between conditions in Experiments 1 and 2, Obs 2 and 3 contributed new data for Experiment 2. All observers had normal pure-tone air conduction thresholds (<25 dB hearing level) at octave frequencies between 250 and 8000 Hz.

2. Stimuli and conditions

Like Experiment 1, Experiment 2 consisted of two parts. In the first part, a simple detection task, A was not present and ΔA was presented in quiet (yielding $A_{0,Quiet}$) or in the presence of one of two types of non-pedestal masker, either a notched-noise masker or a multitone masker (yielding two different values of $A_{0,Masked}$). In the second part of the experiment, an intensity discrimination task, intensity discrimination thresholds were measured in the same three masking conditions (quiet, notched-noise, random) using three values of A in the quiet condition and six values of A in the notched-noise and random conditions. These values were -9 , 0 , and 9 dB re. $A_{0,Quiet}$ in all three conditions and -9 , 0 , and 9 dB re. $A_{0,Masked}$ in the notched-noise and random conditions.

Like Experiment 1, all stimuli were 100-ms, were gated with 5-ms cosine² onset-offset ramps, and were gated synchronously. ΔA , A , and the multitone masker were the same as in Experiment 1; the notched-noise and multitone maskers were the same in both parts of the experiment. The notched-noise masker was generated by summing individual sinusoids with magnitudes drawn at random from a Rayleigh distribution and phases drawn at random from a uniform distribution with a range $0-2\pi$. The individual sinusoids were spaced 10 Hz apart over the range 80–8000-Hz, excluding a 398-Hz protected region centered on 1000-Hz (the same width as the protected region imposed on the multitone masker). To avoid signal processing delays during testing, 1000 unique notched-noise masker waveforms were pre-generated and stored for presentation. The same set of 1000 waveforms was used for all observers in both parts of the experiment. During testing, a waveform was selected at random with replacement from the set on each stimulus presentation. The overall level of the notched-noise masker was fixed at 30 dB SPL, the same overall level as the multitone masker used here and in Experiment 1.

3. Procedures

Simple detection and intensity discrimination thresholds were measured using the same 2I-2AFC adaptive tracking

procedure described in Sec. II A 4 except that a block of trials was terminated after 12, rather than 15, total reversals. The first part of the experiment (simple detection) consisted of 24 total blocks. Eight blocks were completed in each of the three masking conditions. The masking condition was fixed throughout a block of trials and quiet, notched-noise, and random blocks were completed in random order. The final estimate of $A_{0,Quiet}$ and $A_{0,Masked}$ was determined by taking the mean of approximately eight blocks using the same procedure as described in Sec. II A 4. The final estimates of $A_{0,Quiet}$ and $A_{0,Masked}$ for each observer are shown in Table III. These values were used to set the pedestal levels in the second part of the experiment.

In the second part of the experiment (intensity discrimination), the value of A was fixed throughout a block of trials, as was the masking condition, and quiet, notched-noise, and random blocks were completed in random order. The specific value of A tested in a given block was randomized across all blocks for each masking condition. Each observer completed a total of 60 blocks, amounting to four blocks per pedestal level (again, the pedestal levels were -9 , 0 , and 9 dB re. $A_{0, Quiet}$ in the quiet condition and -9 , 0 , and 9 dB re. $A_{0, Quiet}$ and -9 , 0 , and 9 dB re. $A_{0,Masked}$ in the notched-noise and random conditions). Final estimates of ΔA_{IND} were determined for each value of A by taking the mean of approximately four blocks (using the same procedure as described in Sec. II A 4).

C. Results and discussion

1. Pedestal levels bracketing and including $A_{0,Quiet}$

Masking functions obtained using values of A bracketing and including $A_{0,Quiet}$ are shown in Fig. 3. Note that the quiet and random functions shown in Fig. 3 represent the same condition/pedestal level combinations as were tested in Experiment 1 (cf. Fig. 1). Thus, for the two observers who participated in both experiments (Obs 2 and 3), a direct comparison to the data shown in Fig. 1 is appropriate (with the caveat that the physical levels of the pedestals used in each experiment were different owing to different estimates of $A_{0,Quiet}$ in each experiment).

Consider first the masking functions obtained in quiet. As in Experiment 1, NM was obtained by all three observers. For 0 dB SL pedestals, where the dip in the masking function reached a minimum for all three observers, NM was 16.9 dB for Obs 2, 8.4 dB for Obs 3 dB, and 12.1 dB for Obs 4. Group mean NM at this point was 12.5 dB, a 3.7 dB

TABLE III. Final estimates (and standard errors of these estimates) of $A_{0,Quiet}$ and $A_{0,Masked}$ for each observer in dB SPL. These values were used to define the pedestal levels that were used in the second part of the experiment on a per-observer basis.

	Obs 2	Obs 3	Obs 4
Quiet ($A_{0,Quiet}$)	1.3 (0.6)	11.3 (1.1)	-1.8 (0.9)
Notched-noise ($A_{0,Masked}$)	3.1 (0.9)	13.5 (0.6)	1.2 (1.6)
Random ($A_{0,Masked}$)	13.6 (2.7)	16.4 (1.4)	11.7 (2.8)

FIG. 3. Masking functions obtained in quiet (open symbols, solid lines), in the notched-noise condition (gray symbols, dotted lines), and in the random condition (black symbols, dashed lines) for all three observers and the mean across observers. Error bars are standard errors of the mean.

increase in NM relative to Experiment 1. Again, the magnitude of NM at this point, and the general shape of these functions, is generally consistent with past studies of auditory NM (e.g., Hanna *et al.*, 1986; Viemeister and Bacon, 1988; Shepherd and Hautus, 2009; Shepherd *et al.*, 2013). It is worth noting that, for the two observers who participated in both Experiments 1 and 2 (Obs 2 and 3), the interpretation of the patterns of NM found across experiments was not straightforward. For Obs 2, NM increased by 7.7 dB from Experiment 1 to 2 (from 9.2 to 16.9 dB); for Obs 3 it decreased by 3.8 dB (from 12.2 to 8.4 dB). This may be related to slight changes in $A_{0, Quiet}$ —and thus to the physical levels of the pedestals—across experiments or perhaps to training effects, although if the latter were the case an increase in NM would be expected for Obs 3 as well as for Obs 2. Regardless of these differences across experiments, the important point to be made with respect to the functions shown in Fig. 3 is that NM was obtained by all three observers in quiet.

In the notched-noise condition, NM was attenuated, but not eliminated, for two observers (Obs 2 and 3). It was all but eliminated for the third (Obs 4). Obs 4 did, however, show a slight trend towards NM at the highest pedestal level (reaching 1.7 dB of NM) and this is crucial, as is the fact that for both Obs 2 and 3 the masking function reached a minimum not for 0 dB SL pedestals, as it did in quiet, but for 9 dB SL pedestals. For Obs 2, NM at this point was substantial (9.5 dB). For Obs 3, it was 6.4 dB. Group mean NM at this point was 5.9 dB. What this suggests is that, in the notched-noise condition, there likely was some energetic masking of the A and/or $A+\Delta A$ when the pedestal was small. This is important with respect to our interpretation of the results of Experiment 1. The notched-noise masker tested here was matched in overall level to the multitone masker tested in Experiment 1. It also had the same protected region. Thus, the notched-noise masker tested here likely caused similar amounts of energetic masking to the multitone masker tested in Experiment 1 but presumably

caused little or no informational masking (Spiegel and Green, 1982; Neff and Green, 1987; Durlach *et al.*, 2003). [It is worth noting, however, that, given the fact that the overall levels of the notched-noise and the multitone maskers were the same, noise components falling near the inside edges of the notch were lower in level than any components of the multitone masker that may have fallen in the same spectral region. This means that certain exemplars of the multitone masker could have produced greater energetic masking than the notched-noise masker. Preliminary calculations of the leakage of energy from the two maskers into a roex(p, r) filter centered on the signal (with $p=25$ and $r=0.0001$; cf. Patterson *et al.*, 1982) suggest that this was not a significant factor.] Thus, the fact that NM was attenuated in the notched-noise condition when the pedestal was small but that it began to take root as the pedestal level increased, suggests two important points. First, it suggests that energetic masking likely *was* a factor in the elimination of NM in the random condition of Experiment 1 and here. Second, it suggests that when energetic masking is overcome via improvement of the S/N within the signal's critical band, NM can occur.

With these two points in mind and comparing the notched-noise and random functions shown in Fig. 3, it is clear that energetic masking was not the only factor limiting performance in the random condition. If it was, the masking functions obtained in the random condition would be similar to the functions obtained in notched-noise. This was not the case. Relative to the notched-noise condition, intensity discrimination thresholds in the random condition increased for all pedestal levels for all observers without fail, resulting in the complete eradication of NM for all observers. For 9 dB SL pedestals, thresholds in the random condition increased relative to the notched-noise condition by 24.2 dB for Obs 2, 17.1 dB for Obs 3, and 20.5 dB for Obs 4. The group mean increase at this point was 20.6 dB. This increase in thresholds over and above the increase associated with energetic masking can be attributed to informational masking (Lutfi,

1990; Durlach *et al.*, 2003; Durlach, 2006). Thus, these results suggest that energetic masking was not the sole culprit responsible for the elimination of NM in the random condition in Experiment 1 or here. Rather, it was more likely attributable to uncertainty caused by the multitone maskers. Again, a strict interpretation of the nonlinear transducer model that makes no provision for uncertainty predicts no difference in intensity discrimination thresholds between the notched-noise and random conditions and thus cannot explain these results.

2. Pedestal levels bracketing and including $A_{0,Masked}$

Masking functions obtained using values of A bracketing and including $A_{0,Masked}$ are shown in Fig. 4. Note that the quiet data shown in Fig. 4 are simply replotted from Fig. 3 (i.e., $A_{0,Quiet}=A_{0,Masked}$). Note also that all data shown in Fig. 4 are normalized by $A_{0,Masked}$. What this means is that dB SL and NM are both defined relative to the specific masking context. By way of example, for Obs 2, $A_{0,Masked}=3.1$ dB SPL = 0 dB SL in the notched-noise condition, yet $A_{0,Masked}=13.6$ dB SPL = 0 dB SL in the random condition.

Focusing first on the masking functions obtained in notched-noise. Critically, the slight increase in the physical levels of the pedestals used to obtain these functions relative to those that were used to obtain the corresponding set of functions shown in Fig. 3 (an increase that was meant to control for energetic masking) “rescued” NM. That is, once energetic masking was overcome by increasing the S/N of the pedestal within the signal channel, NM was obtained. For 0 dB SL pedestals, the magnitude of NM was similar in notched-noise as it was in quiet; group mean NM for 0 dB SL pedestals was not substantively different between the two conditions (12.5 dB in quiet vs 10.3 dB in notched-noise). For one pedestal level (9 dB SL), performance was actually better, on average, in the notched-noise condition than it was in the quiet condition, by 7 dB (group mean NM for 9 dB SL pedestals was 0.2 dB in the quiet condition

versus 7.2 dB in the notched-noise condition). This is important in that it suggests an alternate account of our results based on profile analysis (Green, 1988; discussed in Sec. IVC below).

Once again, on average, NM was eliminated in the random condition, despite the use of pedestal levels meant to control for energetic masking. Only one observer (Obs 2) showed a hint of NM and only then for a single pedestal level (-9 dB SL). Thus, we again attribute this effect to uncertainty. Taken together with the notched-noise data, these data provide the strongest support yet for an uncertainty-based interpretation of NM.

IV. GENERAL DISCUSSION

The findings reported here generally support the CUH rather than the nonlinear transducer model with some caveats. Before addressing this issue, however, we consider our results with respect to relevant data from the literature. Then, we address one aspect of our results that, in light of the previous literature, bolsters support for the nonlinear transducer model (yet is not inconsistent with the CUH) as well as another factor that complicates, but does not contradict, an interpretation of our results in terms of the CUH. We then briefly consider the Laming (1985, 1986) sensory analytical model before we suggest an alternative interpretation of our results based on profile analysis.

A. Comparison to previous data

The psychoacoustic literature on NM is remarkably limited. Only a handful of studies have explicitly examined the effect, and in the few that have, only a restricted set of conditions have been tested. These include intensity discrimination for pure-tones in quiet (Hanna *et al.*, 1986; Viemeister and Bacon, 1988; Shepherd and Hautus, 2009; Shepherd *et al.*, 2013) and against a background of broadband noise (Hanna *et al.*, 1986; Shepherd and Hautus, 2009; Shepherd *et al.*, 2013), increment detection for pure-tones in quiet (Viemeister and Bacon, 1988), and increment detection for

FIG. 4. As in Fig. 3 except that the notched-noise and random data shown here were obtained with different physical pedestal levels, chosen so as to bracket and include $A_{0,Masked}$. In quiet, $A_{0,Quiet}=A_{0,Masked}$ and thus quiet thresholds are replotted from Fig. 3.

broadband noise bursts (Raab *et al.*, 1963b). Thus, there are scant data with which to compare ours, particularly in the notched-noise and random conditions, which have no precedent, to our knowledge, in the psychoacoustic literature on NM. In general, the magnitude of NM obtained in our quiet condition was similar to previous studies. Of the previous studies that have measured NM in quiet, all have used 1000-Hz pure-tones, as were used here. Averaged across experiments, we found roughly 11 dB of NM for 0 dB SL pedestals in quiet. Hanna *et al.* (1986) also found 11 dB of NM for 0 dB SL pedestals in quiet and Viemeister and Bacon (1988), Shepherd and Hautus (2008), and Shepherd *et al.* (2013) have all reported similar values. Shepherd and Hautus (2009) present the only data we are aware of on NM using pure-tones with a frequency other than 1000-Hz. They measured NM using both 1000 and 6500-Hz pure-tones. They found that NM was slightly greater, by about 2–4 dB, for 6500-Hz pure-tones than for 1000-Hz pure-tones, raising the possibility of a frequency dependence of NM. It is worth pointing out, however, that, in Experiment 2, we found roughly similar amounts of NM using 1000-Hz pure-tones as they found using 6500-Hz pure-tones.

Neff and Jesteadt (1996) obtained data relevant to our random condition. They were concerned with the more general issue of how informational masking influences supra-threshold intensity discrimination. Among other conditions, they measured detection and intensity discrimination thresholds for 200 ms, 1000-Hz pure-tones in the presence of multitone maskers similar to those used here. Their multitone maskers were comprised of two, six, or ten components, and were fixed at an overall level of either 40 or 60 dB SPL. For the intensity discrimination task, they employed pedestal levels spanning the range 40–80 dB SPL. This meant that some of the pedestals they tested were “inaudible” (Neff and Jesteadt, 1996, p. 2293) in the presence of the multitone maskers (i.e., they were below $A_{0,Masked}$), while some were at or near $A_{0,Masked}$. That is, they measured intensity discrimination thresholds under multitone masking using pedestal levels in the region near $A_{0,Masked}$, very similar to our Experiment 2. They did not find NM (while they did not report this directly, it can be inferred from Fig. 5 in Neff and Jesteadt, 1996). While there are important differences between their study and ours, the findings of Neff and Jesteadt fortify ours in the sense that they demonstrate another instance in which NM did not occur under informational masking, i.e., under uncertainty.

B. Uncertainty vs the nonlinear transducer model

In the present study, NM was obtained in quiet (Figs. 1–4) and in notched-noise (Fig. 4), yet it was eliminated under multitone masking (Figs. 1–4). The latter finding was attributed to a putative increase in uncertainty caused by the multitone masker. Whereas the CUH predicts this effect, a strict interpretation of the nonlinear transducer model that makes no provision for uncertainty does not. Therefore, our conclusion is that the data presented here are broadly

consistent with the CUH rather than the nonlinear transducer model. Note, however, that both Green (1960) and Hanna *et al.* (1986) suggest a potential middle ground between these two positions: a nonlinear transducer with added uncertainty.

Support for this conclusion is tempered somewhat by a comparison of our notched-noise results with data from the literature. Previous studies of NM using pure-tones have shown that NM is often greatly attenuated or eliminated in the presence of a broadband noise background relative to what is obtained in quiet (e.g., Hanna *et al.*, 1986; Shepherd and Hautus, 2009; Shepherd *et al.*, 2013). This is not predicted by the CUH. It is, however, predicted by the nonlinear transducer model, which predicts a linearization of the d' vs signal strength psychometric function and, in turn, an elimination of NM, when a large external noise source is added to the signal channel. This prediction is based on what is commonly referred to as “Birdsall’s theorem” (see Lasley and Cohn, 1981; Pelli, 1991; Klein and Levi, 2009) when applied to the case of a single channel nonlinear transducer mechanism. Birdsall’s theorem postulates that when a noise source of a sufficiently high variance is added to the signal channel prior to the nonlinear transducer all other sources of noise that might arise after the transducer can be ignored. Consequently, the d' vs signal strength psychometric function for detection will be linear (see Lasley and Cohn, 1981, p. 277–278, for a mathematical derivation). A linear d' vs signal strength psychometric function for detection is incompatible with NM and thus, by extension, Birdsall’s theorem predicts no NM when a large external noise source is present in the signal channel.

We did not measure performance in a broadband noise condition. As such, we cannot put the validity of Birdsall’s theorem to a direct test here. The notched-noise results, however, are relevant. What our notched-noise results demonstrate is that NM is relatively robust to noise falling in non-signal channels, assuming that such noise does not cause uncertainty (cf. Fig. 4). Implicit in this statement is that when NM is attenuated or eliminated by broadband noise it is likely the result of noise falling *in the signal channel*, consistent with Birdsall’s theorem and with the nonlinear transducer model. We hasten to add, however, that our notched-noise data are not inconsistent with the CUH and thus further work is needed before a strong conclusion can be drawn regarding the mechanisms that underlie the elimination of NM under broadband noise masking. For the purposes of this study, in which the notched-noise was intended primarily as an energetic masking control for the multitone masker, the basic point still stands: when noise in the non-signal channels does not cause uncertainty (or causes only minimal uncertainty), NM persists.

One potential complication of an interpretation of our results in terms of the CUH, rather than the nonlinear transducer model, arises from a comparison of the physical levels of the pedestals that were used in the notched-noise and random intensity discrimination conditions of Experiment 2. In a subset of those conditions, pedestal levels bracketing and

including $A_{0,Masked}$ were tested. For all observers, the physical levels of these pedestals were lower in the notched-noise condition than in the random condition (cf. Table III). NM was found in the notched-noise condition but in the random condition, it was not (cf. Fig. 4). As noted in Sec. I, the nonlinear transducer model predicts NM as the consequence of an accelerating nonlinear transducer function apparent at low stimulus levels, which gives way to a roughly logarithmic function at higher levels, yielding Weber's law or the near-miss to Weber's law (Hanna *et al.*, 1986). The fact that the physical levels of the pedestals were higher in the random condition than in the notched-noise condition raises the possibility that the pedestal levels that were used in the random condition were sufficient to exceed the region of the accelerating nonlinearity and thus to preclude NM. One finding that runs counter to this proposition is that, for the two observers who exhibited NM for 9 dB re. $A_{0,Masked}$ pedestals in the notched-noise condition (Obs 2 and 4; cf. Fig. 4), the physical levels of the pedestals were similar (roughly 1.5 dB lower) to the 0 dB re. $A_{0,Masked}$ pedestals that were tested in the random condition. If it were simply an issue of where the pedestals fell along the transducer function, a lack (or presence) of NM would have been expected in *both* cases.

Laming's (1985, 1986) sensory analytical model bears mention at this point. In this study, we chose to focus on the CUH and the nonlinear transducer model as competing interpretations of NM, yet, as noted in Sec. I, Laming's model remains a viable alternative. In brief, Laming's model is based on the notion that sensory systems act as contrast analyzers. After making certain assumptions regarding the means by which stimuli are processed, Laming argues that NM is the consequence of a square-law nonlinearity in operation in the region near A_0 . To date, no empirical data on auditory NM exist, to our knowledge, that warrant a rejection of Laming's model (Raab *et al.*, 1963b; Hanna *et al.*, 1986; Viemeister and Bacon, 1988; Shepherd and Hautus, 2009; Shepherd *et al.*, 2013) and the quiet and notched-noise data reported in this study are no different in this respect. However, it is unclear how Laming's model would be extended to account for the present multitone masking data and devising suitable empirical tests specifically intended to evaluate Laming's model, while potentially useful, is beyond the scope of this study.

C. NM and profile analysis

In Experiment 2, intensity discrimination thresholds were lower, on average, in notched-noise than they were in quiet for 9 dB SL pedestals (whether SL was defined in terms of $A_{0,Quiet}$ or $A_{0,Masked}$), yielding up to 10 dB of NM for one observer (cf. Figs. 3 and 4). This is a curious finding and suggests that noise in the non-signal channels was actually *useful* for solving the task. Such a finding is not predicted by either the CUH or the nonlinear transducer model and suggests one of two possibilities. The first possibility is that observers switched decision strategies from one

condition to the next such that, in quiet, NM was obtained by performing an interval-to-interval comparison of a quantity computed at the output of the signal's critical band and in notched-noise NM was obtained by performing a within-interval profile analysis (Green, 1988). Indeed, it is possible that for the two observers who showed better performance in notched-noise than in quiet (Obs 2 and 4; cf. Fig. 4) the physical level of the pedestal was at an optimal level for making use of profile cues (cf. Green and Kidd, 1983).

The second possibility is that the observer employed a profile analysis strategy in *all* intensity discrimination conditions. This would explain why performance was poor in the random condition and improved in the notched-noise condition relative to intensity discrimination in quiet (e.g., Spiegel *et al.*, 1981; Kidd *et al.*, 1986). Intriguingly, this raises the possibility that observers used a profile analysis strategy *even in the quiet intensity discrimination conditions* (i.e., performed a profile analysis on the internal noise spectrum), which is intuitively reasonable when one considers the extremely low physical pedestal levels that were tested in this condition. An improvement in the Weber fraction under profile analysis conditions relative to single-tone intensity discrimination is well documented for suprathreshold stimuli (Green and Mason, 1985). Such a strategy might also prove beneficial in single-tone intensity discrimination for near-threshold pedestals in quiet because the relationship between the physical level of the pedestals and the internal noise spectrum might be optimal for exploiting profile cues. Our results are consistent with either possibility. To the extent that a profile analysis strategy yields NM, this account is inconsistent with both the CUH and the nonlinear transducer model and points-up the possibility that NM may be attributable to, or influenced by, multiple mechanisms. Further work is required, however, before any strong conclusions regarding the role of profile analysis in yielding NM can be drawn.

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¹In this study, the term intensity discrimination is meant as a general term meaning *level discrimination* and is not meant to imply anything about the physical units of the stimulus or about the quantity operated upon by the auditory system. In fact, following Green (1988), our stimuli are quantified in terms of amplitude (hence, ΔA , A , etc.). Rather than adopt the term "amplitude discrimination," however, the words of Viemeister (1988) are heeded: "The long history of the use of 'intensity discrimination' and the likely increase in confusion argues against a change in terminology" (p. 267). The concerned reader can simply read "amplitude discrimination" in place of "intensity discrimination" wherever the latter term occurs.

²The use of M to represent the number of alternatives in a signal detection task has a long history, specifically in the context of the "1-of- M " orthogonal signals problem of signal detection theory (e.g., Peterson *et al.*, 1954; Green and Swets, 1966; Green and Dai, 1991). Thus, we use M to represent the number of monitored channels for largely historical reasons. To avoid confusion, it is worth noting explicitly that the meaning of M in this context does not stand for "masking" and thus bears no relation to the "M" in the abbreviation NM.

³The CUH is agnostic as to the particular physical dimension along which uncertainty may manifest. As such, the M monitored channels can just as easily be conceptualized as channels tuned along a different stimulus dimension (e.g., time, level).

⁴A notched-noise condition, not reported here, was interleaved with quiet and random blocks. The results of this condition were very similar to those reported in Experiment 2. However, the specifics of the notched-noise masker were changed slightly between Experiment 1 and 2 to more carefully control for energetic masking and so the data are not reported here for clarity of presentation.

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