Perception of suprathreshold amplitude modulation and intensity increments: Weber's law revisited[a)]

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(Received 17 May 2007; revised 3 January 2008; accepted 11 January 2008)

The perceived strength of intensity fluctuations evoked by suprathreshold sinusoidal amplitude modulation (AM) and the perceived size of intensity increments were compared across levels of a wideband noise and a 1-kHz tone. For the 1-kHz tone, the comparisons were made in quiet and in a high-pass noise. The data indicate that suprathreshold modulation depths and intensity increments, perceived as equivalent across levels, follow a pattern resembling Weber's law for noise and the "near miss" to Weber's law for a tone. The effect of a high-pass noise was largely consistent with that observed for AM and increment detection. The data suggest that Weber's law is not a direct consequence of the dependence of internal noise on stimulus level, as suggested by multiplicative internal noise models. Equal loudness ratios and equal loudness differences (computed using loudness for the stationary portions before and after the increment) accounted for the increment-matching data for noise and for the tone, respectively, but neither measure predicted the results for both types of stimuli. Predictions based on log-transformed excitation patterns and predictions using an equal number of intensity just-noticeable differences were in qualitative, but not quantitative, agreement with the data. © *2008 Acoustical Society of America.*
[DOI: 10.1121/1.2839889]

PACS number(s): 43.66.Fe, 43.66.Lj [RYL] Pages: 2220–2236

I. INTRODUCTION

An important general question in psychophysics is whether the phenomena seen using threshold measurements, those based on detection and discrimination, generalize to suprathreshold situations where the stimuli are highly detectable and discriminable. An example, and the focus of this paper, is whether the lawful relationships seen for detecting intensity changes are also seen for changes that are highly detectable. For example, does something analogous to Weber's law hold for intensity changes that are readily perceptible?

There are several reasons such questions are important. Clearly, most real-world listening involves changes that are readily perceived. The amplitude and frequency changes that occur in speech, for example, are orders of magnitude larger than intensity and frequency just-noticeable differences (JNDs). The question is whether or not the effects seen in JND measurements are also applicable to suprathreshold changes. It is possible that the strategies, cues, and processes used by listeners in a threshold task are of little relevance to everyday auditory perception. This raises the question of what "threshold psychophysics" has told us about real listening.

At the theoretical level, threshold psychophysics has provided a wealth of information about normal and impaired hearing. However, the theoretical notions that have been developed based on threshold psychophysics may not be applicable to suprathreshold situations. In addition to the strategy/cue problem mentioned previously, there is the problem of "internal noise." Internal noise is an ill-defined but necessary construct that is invoked in most contemporary models of detection and discrimination (e.g., Green and Swets, 1988; Colburn *et al.*, 2003). It often refers to stochastic limitations that are characteristic of sensory transmission (e.g., Teich and Khanna, 1985) but also may involve notions such as decision noise, memory noise, and nonoptimal processing. Internal noise is necessary because in many, perhaps most, threshold situations performance is not limited by the stochastic properties of the stimuli (e.g., Raab and Goldberg, 1975; Tanner, 1961). In intensity discrimination of pure tones, for example, human performance is far worse than that predicted from the (negligible) variability present in the stimuli: some sort of internal variability seems necessary to account for human performance.

The problem with invoking internal noise is, essentially, that we know very little about it. Measurements of auditory-nerve responses have consistently demonstrated that the variance of the spike count can be approximated by a Poisson process (Young and Barta, 1986; Winter and Palmer, 1991). Estimates of spike count variance at higher stages of the auditory pathway have been very sparse. Limited data from the cochlear nucleus (Palmer and Evans, 1982) and the inferior colliculus (Nelson and Carney, 2007) show no clear dependence of the variance on the mean spike count. It is difficult to measure internal noise psychophysically, although attempts to estimate it have been made (Spiegel and Green, 1981; Jesteadt *et al.*, 2003). Thus, we have an unwanted uncertainty in our theoretical efforts. To return to the example of pure-tone intensity discrimination, it is clear that one can "explain" the JND data, including the fundamental

[a)]Portions of these data were presented at the 135th Meeting of the Acoustical Society of America, 1998. June 20–26, Seattle, WA.
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relationship between the JND and intensity, by postulating arbitrary characteristics of the internal noise (e.g., Allen and Neely, 1997). More generally, if the properties of internal noise are even partly responsible for threshold phenomena, such as Weber's law, then models based on threshold data may not be applicable to suprathreshold processing where the internal noise that limits threshold performance is unlikely to affect perception. In the context of signal detection theory (Green and Swets, 1988), threshold discrimination is limited by internal noise because of the variability it imposes: the distributions of the decision variable overlap. For suprathreshold intensity, changes, the distributions are sufficiently separated and the intensities before and after the change are highly discriminable. An evaluation of a suprathreshold difference (change) between two perceived intensities is therefore affected by the difference between the means of the corresponding distributions, but not by the variability from the internal noise that limits the ability to discriminate them.

The present study is concerned with the perception of suprathreshold intensity/amplitude changes, specifically, those produced by discrete intensity changes and those produced by sinusoidal amplitude modulation (AM). The reason for this emphasis is that such dynamic aspects are crucially important for auditory communication and perception (Plomp, 1970; Drullman, 2005): we need to know whether our understanding of dynamic processing based on threshold psychophysics extends to suprathreshold changes.

There is a wealth of data and theoretical work on intensity discrimination and AM detection (Tanner, 1961; Treisman, 1964; Viemeister, 1983; Viemeister, 1988; Viemeister and Bacon, 1988, Durlach *et al.*, 1986; for a review of studies on AM see Joris *et al.*, 2003). In brief, for broadband sounds of all but short durations, the intensity JND (ΔI) increases proportionally with the intensity (I) of the standard or pedestal: the Weber fraction ($\Delta I/I$) is constant and thus Weber's law describes intensity discrimination thresholds. For band-limited sounds such as pure tones, there are relatively small, but significant, deviations from Weber's law: The Weber fraction decreases as I increases, a phenomenon known as the "near-miss" to Weber's law (McGill and Goldberg, 1968). There is a close counterpart to these results for detection of AM. For broadband carriers, the modulation index at detection threshold (m) is independent of a carrier level for levels above approximately 20 dB SL (Bacon and Viemeister, 1985). As m is a relative measure, like the Weber fraction, this result is analogous to Weber's law. Similarly, for band-limited carriers, m decreases as the carrier level increases and thus this result is analogous to the near-miss. There is a close empirical relationship, but uncertain theoretical relationship, between intensity-increment detection and detection of sinusoidal AM for both broadband and pure-tone continuous pedestals/carriers (Wojtczak and Viemeister, 1999).

In contrast to the extensive data on intensity discrimination and AM detection, there are relatively few data on the perception of suprathreshold intensity/amplitude changes. Fastl (1983) and Terhardt (1968), using magnitude estimation, studied the effects of modulation rate, modulation depth, and carrier level on the "roughness" and "fluctuation strength" of AM. Fluctuation strength appears to reach a maximum at a modulation frequency of 4 Hz and roughness at 70 Hz. Both increase with increasing m, and for a fixed m and modulation frequency, both increase with increasing carrier level. The latter result was observed for pure-tone and for noise carriers. For pure-tone carriers this is qualitatively consistent with the near-miss effects seen for AM detection, i.e., the results suggest that the effective envelope fluctuations are "magnified" at higher carrier levels. For noise carriers, however, the results contradict those based on AM detection: Constant m at detection threshold suggests that fluctuation strength should also be constant, independent of the carrier level. The data to be presented are consistent with the detection results; this issue will be revisited in the discussion in Sec. IV.

In a study related to the aspects of the present study, Moore *et al.* (1996) used a modulation-matching procedure to investigate whether the effective amplitude changes produced by AM are magnified by loudness recruitment. The results, obtained from listeners with a unilateral hearing loss, indicate that for equal perceived fluctuation strength, the modulation depth in the recruiting ear was considerably less than that in the normal ear when the carriers were equally loud. This suggests, in contrast to the results from modulation detection (Bacon and Viemeister, 1985; Zwislocki and Jordan, 1986) and intensity discrimination (Hellman and Hellman, 1990; Schlauch, 1994; Schroder *et al.*, 1994), that suprathreshold perceived fluctuation depths are related to the slope of the loudness function and thus are magnified in the case of recruitment.

Existing loudness models are generally successful at predicting the loudness functions for stationary stimuli (Moore *et al.*, 1997) and for temporally varying stimuli (Zwicker and Fastl, 1999; Glasberg and Moore, 2002). However, none of the existing models have been used to quantify the perceived size of an intensity increment in terms of a change in loudness. There is little doubt that suprathreshold increments in intensity are perceived in terms of an increment in loudness but it is not clear how exactly the perceived loudness increment is "computed." Attempts to relate threshold intensity discrimination to a change in loudness have provided ambiguous results, suggesting that either intensity JNDs do not necessarily correspond to a constant change in loudness or that the method of "computation" of the loudness change (e.g., a loudness ratio versus loudness difference) is stimulus dependent. Hellman and Hellman (2001) demonstrated that Ekman's law (Ekman, 1956, 1959) appears to hold for loudness of 3 sones and above when intensity discrimination thresholds of pulsed tones (Rabinowitz *et al.* 1976) and beat detection thresholds (Riesz, 1928) are considered. The law states that intensity increments and beats are detected when the *ratio* between loudness corresponding to the intensities to be discriminated reaches a constant value (an analog of Weber's law for loudness, a subjective magnitude). For tones presented in quiet and in notched-noise, equal loudness *differences* have been shown to predict intensity discrimination across levels (Parker and Schneider, 1980; Schneider and Parker, 1987). However, the same strategy failed to predict intensity discrimination for tones in broadband noise (Schneider and Parker, 1990), likely due to suppression of the basilar-membrane response to the tone by the noise.

As stated previously, threshold measurements are affected by internal noise (for deterministic stimuli) and/or external noise associated with the stochastic properties of noise stimuli. However, the variability imposed by such noises presumably plays an insignificant role in the perceived magnitude of highly detectable intensity changes: The changes in the stimulus are much larger than those created by the internal noise or those resulting from inherent intensity fluctuations in the noise stimuli. Thus, it is not clear if the findings regarding threshold intensity discrimination hold true for suprathreshold intensity changes.

The present study examines the effects of level on the perception of highly detectable intensity increments and AM. The general approach is to determine the intensity increments and modulation depths that, respectively, produce the same perceived intensity changes and intensity fluctuations when the stimuli are at different levels. The general aim is to describe the perception and processing of suprathreshold intensity changes.

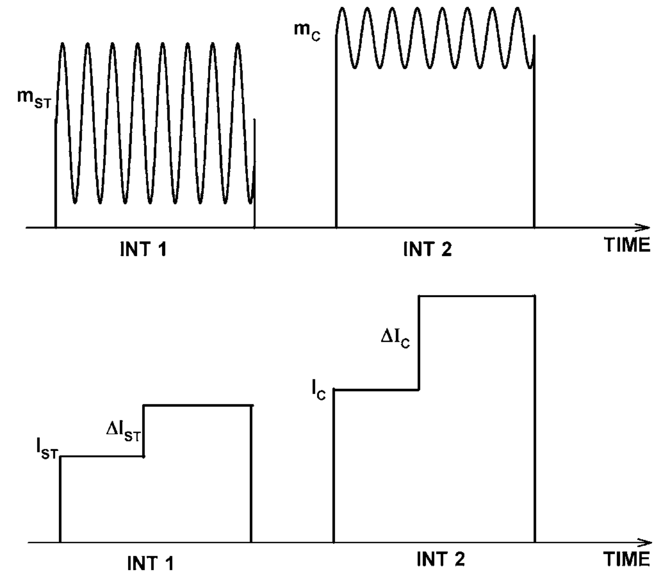

FIG. 1. Examples of envelopes of the stimuli presented in a trial of the modulation-matching (upper panel) and increment-matching tasks. Listeners had to decide which modulation depth, the standard (m_{ST}) or the comparison (m_C), produced stronger perceived fluctuations, or which increment, the standard (ΔI_{ST}) or the comparison (ΔI_C), sounded larger.

II. METHODS

A. Stimuli and procedure

1. Modulation matching

Modulation depths producing perceptually equivalent fluctuations across carrier levels were measured for two types of the carrier: a 1-kHz tone and a Gaussian noise low-pass filtered at 5 kHz. The noise was filtered using an analog filter (Ithaco 4302) with an attenuation rate of 24 dB/oct outside the passband. The carriers were modulated over their entire 500-ms duration by a 16-Hz sinusoid starting at a 0-rad phase. For the tonal carrier, the 500-ms duration included 5-ms raised-cosine ramps. After unsuccessful attempts at using adaptive matching procedures (see Appendix A), a rather complicated roving procedure combined with the two-interval forced-choice (2IFC) technique was used to encourage the listeners to make comparisons between the standard and the comparison intervals within each trial. Examples of the envelopes of the stimuli presented in a trial, consisting of two observation intervals, are shown in the upper panel of Fig. 1. In each trial, a standard and a comparison were presented in a random order. The listeners were instructed to choose the interval, which, according to their subjective judgment, contained stronger intensity fluctuations (terms such as "fluctuations" or "loudness fluctuations" were also used interchangeably to describe the task). The listeners confirmed that they understood the task and they were consistent in their responses, thus no evidence was observed that the instructions were ambiguous. No feedback was provided in this or any subsequent tasks within this study.

Table I lists five conditions (each distinguished by the level of the comparison) in the modulation-matching task, for a 1-kHz carrier. The two numbers used in the name of each condition represent the carrier level of the standard and comparison, respectively. For example, T_60_30 describes a condition where the carrier level of the standard tone (T) was 60 dB SPL and the carrier level of the comparison was 30 dB SPL in every trial within a block. The remaining conditions were: T_60_45, T_60_60, T_60_75, and T_60_90. Thus, for different conditions the carrier level of the comparison was selected from a set of five levels: 30, 45, 60, 75, and 90 dB SPL. In each trial, the modulation depth of the standard was drawn at random from a set of three modulation depths, −6, −8, and −10 dB (in units of $20 \log m$). As shown by Yost and Sheft (1997), the threshold modulation depth for a 1-kHz carrier gated for 500 ms, presented at a level of 70 dB SPL and modulated by a 16-Hz sinusoid is approximately equal to −28 dB. The three standard modulation depths used in the present study were, therefore, highly detectable (AM detection of the three standard modulation depths would yield an immeasurably large d'). The comparison had a modulation depth drawn at random from a set of eight modulation depths. The exact modulation depths for the comparison were selected for each listener individually, based on pilot sessions. The goal was to use a set of comparison modulation depths for which the proportion of "fluctuations stronger in the comparison" responses would span the range from 0 to 1, approximately. Examples of sets of eight modulation depths for each condition are shown in the fifth column of Table I.

Each standard-comparison pair was presented twice within a block consisting of 48 trials (3 modulation depths of the standard ×8 modulation depths of the comparison ×2) and 25 blocks were run for each condition (i.e., each carrier level of the comparison). The order of conditions was randomized.

For the 1-kHz carrier, the experiment was run with the standard and the comparison presented in quiet in one case and in a background of high-pass noise used to mask the

TABLE I. Conditions in AM matching for a 1-kHz carrier: The standard had a carrier level of 60 dB SPL in each condition and the comparison level changed across conditions from 30 to 90 dB SPL in 15-dB steps. In each trial, the modulation depth of the standard was drawn from the set of the three modulation depths listed in the third column and the modulation depth of the comparison was drawn from the set of the eight depths listed in the fifth column. The sets of comparison depths were different for different listeners and they should be viewed as examples rather than the exact values used for all the listeners (AM depth marked by the asterisk in the fifth column).

	Standard		Comparison*	
Condition	Level	AM depth	Level	AM depth
T_60_30				0
	60	−6	30	−2
		−8		−4
		−10		−6
				−8
				−10
				−12
				−14
T_60_45				−2
	60	−6	45	−4
		−8		−6
		−10		−8
				−10
				−12
				−14
				−16
T_60_60				−3
	60	−6	60	−5
		−8		−7
		−10		−9
				−11
				−13
				−15
				−17
T_60_75				−4
	60	−6	75	−6
		−8		−8
		−10		−10
				−12
				−14
				−16
				−18
T_60_90				−5
	60	−6	90	−7
		−8		−9
		−10		−11
				−13
				−15
				−17
				−19

upper side of the excitation pattern in another case. A high-pass noise has been shown to eliminate the near miss to Weber's law for AM detection by raising thresholds measured at high carrier levels, while having a negligible effect on thresholds at lower levels (Zwicker, 1956; Zwicker, 1970; Wojtczak and Viemeister, 2005). As the noise affected AM detection thresholds, the −10-dB modulation depth produced very small perceived fluctuations, the strength of which was hard to evaluate, for some listeners, in the context of the experiment. Thus, the three standard modulation depths used were −4, −6, and −8 dB. The carrier levels of the standard and comparison tested were the same as those listed in Table I, and the sets of comparison modulation depths were chosen individually in pilot runs. The high-pass noise was generated with a random-noise generator (General Radio 1381) and was presented simultaneously with the standard and the comparison at a spectrum level that was 50 dB below the levels of the respective carriers. It was band-pass filtered with cut-off frequencies at 1.5 and 10 kHz (Kemo VBF/25, 135 dB/Oct). The very steep roll-off and the relatively low level were chosen to prevent or maximally reduce excitation of the 1-kHz place on the basilar membrane by the noise. Even though in precise terms the noise was band-pass, for convenience it will be referred to hereafter as high-pass noise because of its wide bandwidth and high-frequency content (above the frequency of the test tone).

For the noise carrier (N), conditions are listed in Table II. Using the same notation as for the tonal carrier, the first number in the name of each condition indicates the spectrum level of the standard and the second number indicates the spectrum level of the comparison. Thus, in conditions N_20_5, N_20_20, N_20_35, and N_20_50, the standard had a spectrum level of 20 dB SPL (measured at 1 kHz) and the comparison had a spectrum level of 5, 20, 35, and 50 dB SPL, respectively. The order of presentation of different conditions was randomized. Within each condition, the standard could have one of three modulation depths (−4, −6, or −8 dB, in units of $20 \log m$) and the comparison could have one of eight modulation depths (from −2 to −16 dB in 2-dB steps) in a trial. The set of comparison modulation depths was the same for every level of the comparison because pilot runs suggested it always covered a range where proportion of "fluctuations stronger in the comparison" responses extended from just above 0 to the vicinity of 1.

The AM-detection threshold for a 500-ms burst of broadband noise modulated by a 16-Hz sinusoid is about −24 dB, as reported by Viemeister (1979). Therefore, all standard modulation depths used in the present study were highly detectable (AM detection would yield an immeasurably large d').

Except for the high-pass noise that was used to mask spread of excitation, all the stimuli were generated digitally on a NeXT computer using a 16-bit digital/analog converter and a sampling rate of 44.1 kHz. The output was routed through an analog attenuator and presented monaurally via Sony MDR-V6 headphones. The listeners were seated in a sound-insulating booth and provided their responses via computer keyboard.

2. Increment matching

A procedure similar to the one previously described was used to find perceptually equivalent intensity increments across levels, for the same two types of stimuli (a 1-kHz tone

TABLE II. Conditions in AM matching for a noise carrier: The standard had a spectrum level of 20 dB SPL in each condition and the comparison level changed across conditions from 5 to 50 dB SPL in 15-dB steps. In each trial, the modulation depth of the standard was drawn from a set of the three modulation depths listed in the third column and the modulation depth of the comparison was drawn from a set of the eight depths listed in the fifth column. The set of comparison depths was the same in all conditions.

	Standard		Comparison	
Condition	Spectrum level	AM depth	Spectrum level	AM depth
N_20_5				−2
	20	−4	5	−4
		−6		−6
		−8		−8
				−10
				−12
				−14
				−16
N_20_20				−2
	20	−4	20	−4
		−6		−6
		−8		−8
				−10
				−12
				−14
				−16
N_20_35				−2
	20	−4	35	−4
		−6		−6
		−8		−8
				−10
				−12
				−14
				−16
N_20_50				−2
	20	−4	50	−4
		−6		−6
		−8		−8
				−10
				−12
				−14
				−16

TABLE III. Conditions in increment matching for a 1-kHz pedestal: In each condition, two levels of the standard (60 or 63 dB SPL) and two levels of the comparison (either 30 and 45 dB SPL or 75 and 90 dB SPL) were mixed within a block. The middle column shows the set of four standards that were selected at random in each trial. The third column shows the set of 16 comparisons that were also selected at random for each trial. In both cases, the first number represents the level of the pedestal and the second number represents the level of the incremented pedestal. The set of comparison increments was selected individually for each subject in pilot runs and thus, levels of the incremented pedestals (second number) given in the third column (marked by the asterisk) should be viewed as examples and not as the exact levels presented to all the listeners.

Condition	Standards	Comparisons*
T_60/63_30_45		30_35
		30_38
		30_41
		30_44
		30_47
	60_65	30_50
	60_68	30_53
	63_65	30_56
	63_68	
		45_46
		45_48
		45_50
		45_52
		45_54
		45_56
		45_58
		45_60
T_60/63_75_90		75_75.5
		75_76.0
		75_76.5
		75_77.0
	60_65	75_77.5
	60_68	75_78.0
	63_65	75_78.5
	63_68	75_79.0
		90_90.4
		90_90.8
		90_91.2
		90_91.6
		90_92.0
		90_92.4
		90_92.8
		90 93.2

and a noise low-pass filtered at 5 kHz). Examples of envelopes of the stimuli presented in a trial are schematically illustrated in the lower panel of Fig. 1.

Each interval of the 2IFC procedure consisted of two 500-ms stimuli whose intensity was incremented halfway through their duration, i.e., a 250-ms increment occupied the second half of the pedestal. The stimuli were separated by a 300-ms silent gap. Listeners were instructed to indicate which increment appeared to be "larger" (terms such as "larger change in intensity" and "larger change in loudness during the stimulus" were also used interchangeably to describe the task). The increments were obtained by an inphase addition of the appropriately attenuated version of the final 250-ms of the pedestal to itself. The amount of attenuation was chosen to produce the desired increment size. For the 1-kHz tone, the pedestal and its attenuated 250-ms portion added to produce an intensity increment were gated using 5-ms raised-cosine ramps.

Two levels of the standard and two levels of the comparison were randomly mixed within a block. Table III lists two conditions tested for a 1-kHz pedestal. In condition T_60/63_30/45, the two levels of the comparison mixed within a block were 30 and 45 dB SPL. In condition T_60/63_75/90, the two levels of the comparison mixed within a block were 75 and 90 dB SPL. In both conditions the two levels of the standard were 60 and 63 dB SPL. In each trial, one standard from the middle column and one comparison from the third column were chosen at random.

TABLE IV. Conditions in increment matching for a noise pedestal: Two spectrum levels of the standard (20 or 23 dB SPL) and two spectrum levels of the comparison (5 and 20 dB SPL in one condition and 35 and 50 dB SPL in another condition) were used within a block. The middle column shows the set of the four standards, from which one was selected at random in each trial. The first number represents the level of the pedestal and the second number represents the level of the incremented pedestal. The comparison was drawn from the set of the pedestal-increment combinations listed in the third column, for each condition. The sizes of comparison increments were the same for all conditions $10\log[(\Delta I+I)/I]$ ranged from 1 to 8 dB in 1-dB steps].

Condition	Standards	Comparisons
N_20/23_5_20		5_6
		5_7
		5_8
		5_9
		5_10
	20_24	5_11
	20_25	5_12
	23_24	5_13
	23_25	
		20_21
		20_22
		20_23
		20_24
		20_25
		20_26
		20_27
		20_28
N_20/23_35_50		35_36
		35_37
		35_38
		35_39
	20_24	35_40
	20_25	35_41
	23_24	35_42
	23_25	35_43
		50_51
		50_52
		50_53
		50_54
		50_55
		50_56
		50_57
		50_58

For example, when standard 60_68 and comparison 45_50 were drawn, the standard had a pedestal level of 60 dB SPL and its level was incremented halfway through to the level of 68 dB SPL (an 8-dB increment in units of $10\log[(I+\Delta I)/I]$). The comparison level changed from 45 dB SPL during the pedestal to 50 dB SPL during the increment (a 5-dB increment). The listener decided which stimulus had a larger perceived change in intensity and responded accordingly. After registering the listener's response, the program randomly selected another pair from the sets of the standards and comparisons for the same condition. The eight comparison increments were different for different listeners and were determined based on pilot sessions to produce the proportion of "comparison increment larger" responses that were approximately symmetrically distributed around the 0.5 value (thus, the values in the third column of Table III are only an example). As with the modulation matching, increment matching for the 1-kHz pedestal was performed in quiet and in the presence of a high-pass noise. The high-pass noise had the same bandwidth as in the modulation-matching task, but its spectrum level was −40 dB relative to the level of the pedestal. A higher relative noise level was used because increments in the comparison stimuli were sometimes much larger than the peak-to-carrier decibel difference for the maximum (100%) modulation. The noise needed to be intense enough to make the upper side of the excitation pattern unusable during the increments.

Table IV shows sets of standards and comparisons used for the noise pedestal in two conditions. In condition N_20/23_5/20, two spectrum levels of the comparison used were 5 and 20 dB SPL. In condition N_20/23_35/50, the two spectrum levels of the comparison used were 35 and 50 dB SPL. Two standard levels used in both conditions were 20 and 23 dB SPL. In each trial, the standard was drawn at random from the set shown in the middle column of Table IV and the comparison was drawn from the third column. Each pair of numbers in the middle and the third columns of Table IV indicate the pedestal level and the level after the increment, respectively. The eight comparison increments for the noise pedestals ranged from 1 through 8 dB in 1-dB steps (in units of $10\log[(I+\Delta I)/I]$. This range of increments was chosen because pilot runs showed that it produced the proportion of "comparison increment larger" responses that approximately covered the range from 0 to 1, for at least two of the standard increments.

For both types of pedestals, the 1-kHz tone and the noise, each standard-comparison pair was used once, resulting in 64 trials within one block (4 standards ×16 comparisons). A total of 50 blocks were run for each condition listed in Tables III and IV. The methods for stimulus generation and presentation were the same as in the modulation-matching task.

B. Subjects

A total of six listeners were used in the experiments, one of whom had prior experience in the modulation-matching task. Not every listener provided usable data in all conditions. Data were considered unusable based on the form of the psychometric functions (as will be discussed later). Not all of the listeners were available to complete all the experiments. All listeners had thresholds within 15 dB of the average normal hearing threshold at all audiometric frequencies, as determined by the lab standards obtained by averaging thresholds at these frequencies from a large number of former listeners (mostly undergraduate students) who reported no hearing problems. Listeners were paid an hourly wage for their participation with the exception of listener S1 who is the first author.

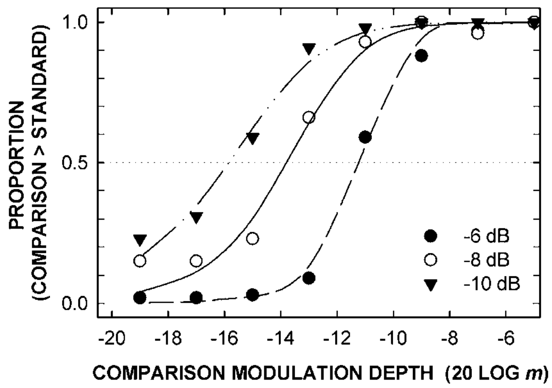

FIG. 2. An example of psychometric functions for a 1-kHz carrier, obtained from modulation matching that used three standard modulation depths, −6, −8, and −10 dB. The carrier level of the standard was 60 dB SPL and the level of the comparison was 90 dB SPL. Data are from listener S1.

III. RESULTS

A. Perceptually equivalent modulation depths (PEMDs)

For each carrier level of the comparison, three psychometric functions were constructed from the modulation-matching data, one for every modulation depth of the standard. Each psychometric function was a plot of the proportion of times the listener evaluated the comparison as having stronger perceived fluctuations than the standard, as a function of the modulation depth of the comparison. Figure 2 shows an example of the three functions obtained from one subject for a 1-kHz tone, where the comparison was presented at 90 dB SPL (condition T_60_90 in Table I).

For a given standard modulation depth, the perceptually equivalent modulation depth (PEMD) of the comparison is defined as the depth yielding the 0.5 proportion of responses that the comparison had stronger fluctuations than the standard. The PEMD was estimated based on a logistic function[1] fitted to the data using a least-squares procedure. As the PEMD is expressed in units of 20 log m, the value of PEMD was constrained to be less than zero while fitting the function.

In the example shown in Fig. 2, the 0.5-point on each psychometric function is shifted toward smaller modulation depths of the comparison relative to the modulation depth of the respective standard. This means that a given modulation depth produces stronger perceived fluctuations in intensity of a 90-dB SPL carrier than in a 60-dB SPL carrier. The psychometric functions are generally distributed over almost the entire range of proportion of "comparison fluctuations stronger" responses between 0 and 1. The functions are ordered along the x-axis according to the magnitude of the standard modulation depth (i.e., the function obtained for the smallest standard modulation depth is to the left of the one for the medium and the largest standard). The fact that the functions do not overlap and that the PEMD increased monotonically with increasing modulation depth of the standard strongly indicates that the listener compared the perceived fluctuation strength between the standard and the comparison intervals rather than making absolute judgments about the fluctuation strength in the comparison.

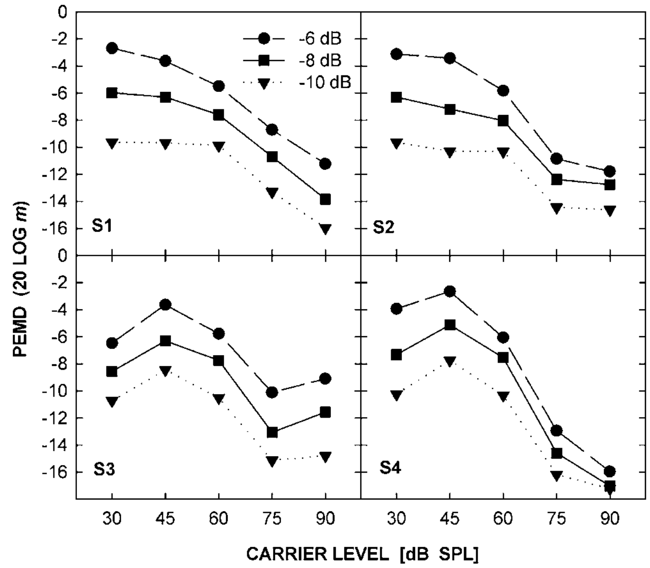

FIG. 3. *PEMDs* for a 1-kHz carrier, plotted as a function of carrier level of the comparison for four listeners. Different symbols and types of connecting lines are for different modulation depths of the standard: −6 dB (circles, dashed line), −8 dB (squares, solid line), and −10 dB (diamonds, dotted line).

In general, the psychometric functions were the steepest when the difference between the carrier levels of the standard and comparison was the smallest (15 dB). The functions became shallower as the difference between the levels increased, but the decrease in slope with increasing difference between carrier levels was greater for comparison levels lower than the standard. In all cases, the range of responses was sufficient to reliably estimate the PEMD.

As subjective tasks that require comparisons of perceived magnitudes sometimes produce results that differ substantially across listeners, individual data will be presented when patterns of results vary across listeners and only mean data will be shown when the patterns of results are consistent across listeners. Figure 3 shows estimated PEMDs plotted as a function of the 1-kHz carrier level, for four listeners. Different symbols (and types of connecting lines) correspond to different standard modulation depths.

Since each function shows the PEMD across levels, the three functions plotted in each panel can be thought of as iso-fluctuation-strength curves. For carrier levels below 60 dB SPL, no consistent changes in PEMD with increasing level are apparent in the data. Two listeners, S1 and S2, show a slight decrease in PEMD with increasing carrier level, whereas for S3 and S4, the function is nonmonotonic over the same range of levels. For levels above 60 dB SPL, all four listeners show a relatively sharp decrease in PEMD between 60 and 75 dB SPL. That decrease is followed by an equally sharp decrease in PEMD (S1), no further change (S2), a slight increase (S3), or a more gradual decrease (S4), for levels between 75 and 90 dB SPL.

Figure 4 shows estimated PEMDs for the noise carrier plotted as a function of its spectrum level. No systematic changes in PEMD are apparent although S2 showed a decrease in PEMD with increasing level over a range of spectrum levels between 35 and 50 dB SPL. A t-test was per-

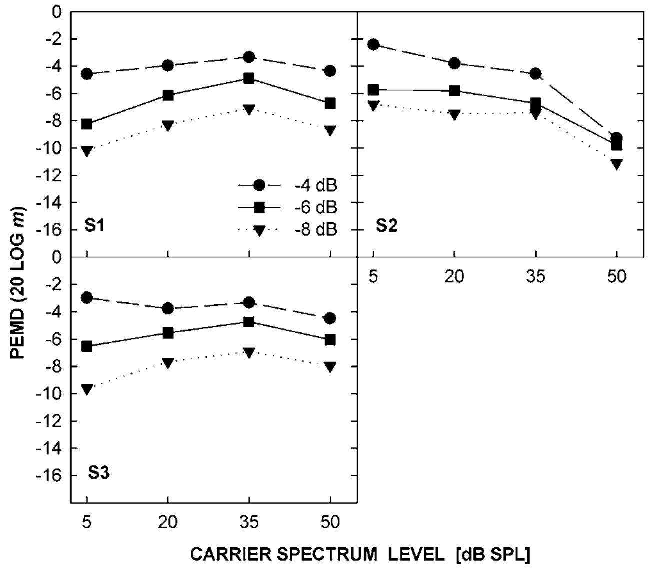

FIG. 4. *PEMDs* for a noise carrier, plotted as a function of carrier level of the comparison for three listeners. Different symbols and types of connecting lines are for different modulation depths of the standard: −4 dB (circles, dashed line), −6 dB (squares, solid line), and −8 dB (diamonds, dotted line).

formed to determine whether or not the slopes of the linear regression functions fitted to each set of data are significantly different from zero, for each listener and each standard modulation depth separately. The test revealed no significant effect of the carrier level on PEMD in all conditions (none of the slopes was significantly different from zero; Howell, 2004).

Thus, the pattern of changes in PEMD depends on the type of carrier, as illustrated by the mean results plotted in Fig. 5, for the 1-kHz tone (left panel) and for noise (right panel). This is not surprising since for tonal carriers, nonlinear spread of excitation is likely to magnify the perceived changes in intensity of the modulated tone at higher levels. For comparison, in the left panel, AM detection thresholds measured for a 1-kHz carrier at different levels are replotted from Wojtczak and Viemeister (1999).

The changes in AM detection threshold across carrier levels for the tone are greater than changes in PEMD over

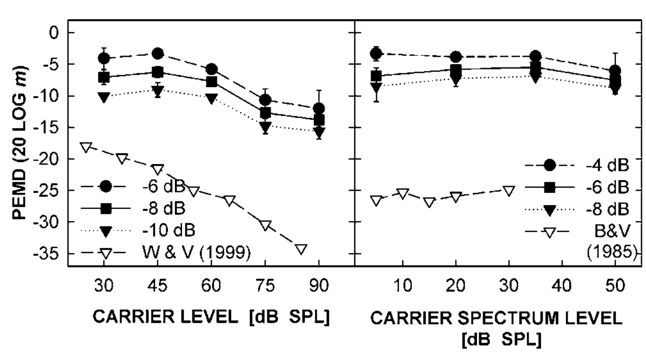

FIG. 5. *PEMDs* averaged across listeners for the 1-kHz carrier (left panel) and the noise carrier (right panel). The error bars represent one standard deviation of the mean. AM detection thresholds are replotted by open triangles from Wojtczak and Viemeister (1999), for a 1-kHz tone (left panel), and from Bacon and Viemeister (1985), for noise (right panel).

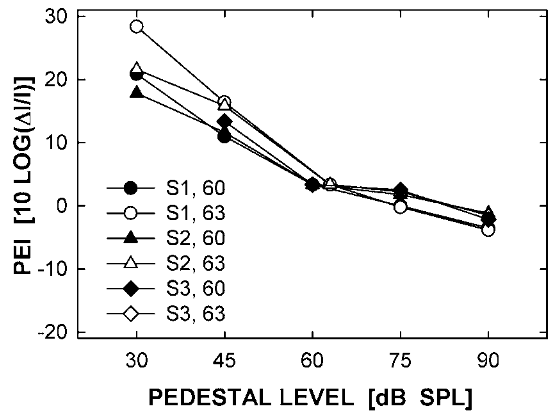

FIG. 6. Individual *PEIs* for a 5-dB increment plotted as a function of the pedestal level of the comparison, for a 1-kHz pedestal. Different types of symbols show data for different listeners. The filled symbols are for the 60-dB SPL pedestal and the open symbols are for the 63-dB SPL pedestal.

the same range of levels (compare the steeper slope of the detection function shown by open triangles with the shallower slopes of the PEMD functions shown by different types of filled symbols, in the left panel). The difference in slopes between the detection function and the PEMD functions in Fig. 5 may in part reflect differences in the stimulus presentation/parameters [a gated carrier modulated at a 16-Hz rate in the present study versus a continuous carrier modulated at a 4-Hz rate, in the study by Wojtczak and Viemeister (1999)]. However, the limited data for pure-tone gated carriers (Zwicker, 1956; Zwicker and Graf, 1987) suggest the level dependence of AM detection is similar to that for continuous carriers and does not differ for the two modulation rates considered. More likely, nonlinear basilar-membrane processing is responsible for the difference between the slopes (as described in detail in the Discussion). The right panel of Fig. 5 shows no change in PEMD across the spectrum level of the noise carrier. This trend is consistent with Weber's law, which holds for AM detection for noise carriers over a comparable range of levels, as shown by the data from Bacon and Viemeister (1985) included for comparison in the right panel (open triangles).[2]

B. Perceptually equivalent increments (PEIs)

Perceptually equivalent increments (PEIs) were estimated from psychometric functions (not presented here) similar to those shown in Fig. 2. For increment matching, the functions showed the proportion of times the listener evaluated the comparison as having a larger intensity increment plotted as a function of the increment in the comparison. As four different standard stimuli were used within each block, four psychometric functions were constructed for every level of the comparison. A logistic function (described in footnote 1) was fitted to the data to estimate the PEI defined as the increment in the comparison yielding the 0.5 proportion of responses that the comparison increment sounded larger than that in the standard. The fitting procedure was performed with a constraint that the PEI expressed in units of $10\log[(\Delta I+I)/I]$ had to be greater than zero.

Figure 6 shows PEIs for a 1-kHz tone plotted as a func-

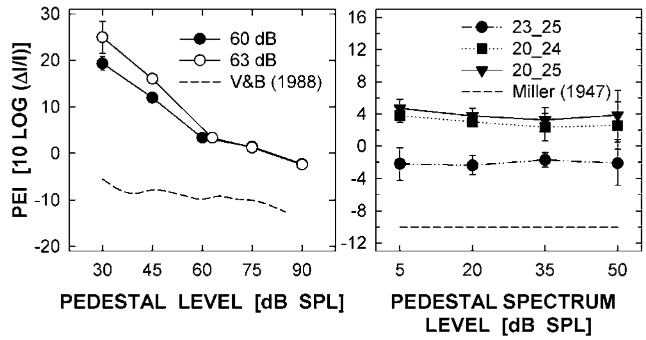

FIG. 7. Mean *PEIs* for a 1-kHz pedestal (left panel) and for a noise pedestal (right panel) averaged across three listeners. The data for the tonal pedestal were obtained for a 5-dB increment in the standard, for two levels of the standard, 60 dB SPL (filled circles) and 63 dB SPL (open circles). The dashed line in the left panel shows increment detection thresholds replotted from Viemeister and Bacon (1988). The data for the noise pedestal (right panel) were obtained for three standards listed in the insert, with the first number representing the spectrum level of the pedestal and the second number representing the spectrum level after the increment. Increment-detection thresholds replotted from Miller (1947) are shown by the dashed line in the right panel. In both panels, error bars represent one standard deviation of the mean.

tion of the pedestal level of the comparison, for three listeners. The PEIs were estimated for only two standard stimuli, the 60-dB pedestal with a 5-dB increment and the 63-dB pedestal with a 5-dB increment (see Appendix B). The functions can be thought of as iso-increment-strength functions.

The PEI (on the *y*-axis) is expressed in units of $10\log(\Delta I/I)$ to emphasize changes in PEI that would be concealed when using the $10\log[(\Delta I+I)/I]$ units that are more compressive for small intensity increments. The general shape of the function is very similar for all the listeners but there are large intersubject differences between the estimated PEIs at low pedestal levels. For the lowest pedestal level of the comparison (30 dB SPL), the psychometric functions obtained from listener S3 were too shallow to estimate the 0.5-point reliably. Consequently, the data for the lowest level are missing for S3. The PEIs corresponding to a 5-dB increment at comparison levels of 60 and 63 dB SPL were not estimated from the matching data. The points were plotted based on the assumption that equal increments in the same pedestal level must sound equal and thus, the PEI converted to units of $10\log[(\Delta I+I)/I]$ was assigned a value of 5 dB in the two conditions. To evaluate the potential effect of the procedure on the matched increments, one listener ran a set of blocks with the comparison levels of 60 and 63 dB SPL (the same as the standards). The PEIs differed by less than 1 dB from the 5-dB standard increments (data not shown) for both pedestal levels of the standard, proving that the assumption about equal increments for equal pedestal levels is justified. For high pedestal levels of the comparison, there is very little variability in PEI across listeners. The left panel of Fig. 7 shows the PEIs for a 1-kHz tone averaged across listeners for the two pedestal levels of the standard used. Both functions show a decrease in PEI with increasing level that is steeper at levels below 60 dB SPL and shallower at higher levels. This result is generally consistent with the increasing role of spread of excitation as the pedestal level increases. Somewhat surprising is the observation that the greatest rate of change in PEI corresponds to the range of levels over which the PEMD remained approximately constant (cf. left panel in Fig. 5). This apparent inconsistency regarding the role of spread of excitation will be discussed below in more detail. The left panel also shows increment detection thresholds as a function of pedestal level (dashed line), replotted from Viemeister and Bacon (1988). Detection thresholds decrease with increasing pedestal level but the rate of that decrease is slower than for suprathreshold intensity changes, for levels below 60 dB SPL. This result can be explained in terms of greater differences across levels between the spread of excitation produced by the pedestal and a suprathreshold increment compared with that between excitations produced by the pedestal and a level that is just discriminable from the pedestal.[3] Although the qualitative changes in PEI with level are predictable, the size of the effect is striking. The mean data (left panel of Fig. 7) show that a change in level from 60 to 65 dB SPL (a 5-dB increment) sounds perceptually equal to a change in level from 30 to 49 dB SPL (a 19-dB increment). A change in level from 63 to 68 dB SPL (a 5-dB increment) sounds perceptually equal to the change in level from 30 to 55 dB SPL (a 25-dB increment). Thus, the near miss to Weber's law observed for detection of intensity increments for tonal pedestals becomes a "severe departure" from Weber's law for suprathreshold intensity changes.

For the noise pedestal, the PEIs were estimated for three out of the four standard stimuli used in the experiment, a 20-dB pedestal with increments of 4 and 5 dB and a 23-dB pedestal with a 2-dB increment. The right panel of Fig. 7 shows PEIs for noise averaged across three listeners.

A t-test performed separately on each set of data revealed that the slopes of the PEI functions were not significantly different from zero ($p > 0.05$). This result is consistent with Weber's law observed for increment-detection threshold, as shown by the dashed line representing the level-independent JND reported by Miller (1947) for broadband noise, expressed in units of $10\log(\Delta I/I)$. Thus, it appears that Weber's law applies to both intensity JNDs and to the perception of suprathreshold intensity increments.

C. Effect of highpass noise on PEMD and PEI functions of level for tones

For tones, AM and increment detection thresholds show level dependence known as the near miss to Weber's law: Thresholds improve with increasing level of the tonal carrier/pedestal due to the nonlinear spread of excitation (Viemeister, 1972; Moore and Raab, 1974; Florentine and Buus, 1981). The level dependence can be eliminated by using a high-pass noise with a cutoff frequency and a level chosen to mask the nonlinear spread of excitation toward regions on the BM that are most sensitive to frequencies above that of the tonal stimulus (e.g., Zwicker, 1956; Plack and Carlyon, 1995). Results presented in the previous sections demonstrate that for a 1-kHz tone, PEMDs and PEIs decrease with increasing stimulus level, although the pattern of the level dependence is different for the two subjective measures. The effect of a high-pass noise on the perception of suprathresh-

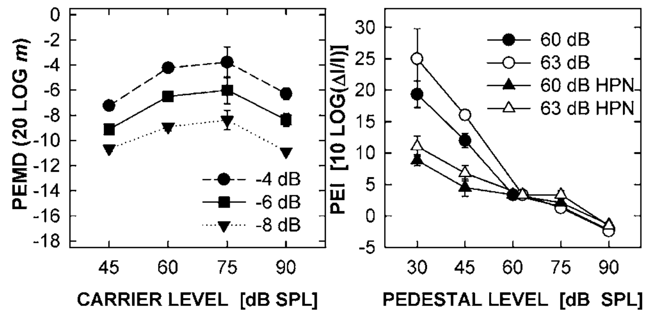

FIG. 8. *PEMDs* (left panel) and *PEIs* (right panel) for a 1-kHz tone in the presence of a high-pass noise. The left panel shows mean data from two listeners, with different symbols representing different standard modulation depths: −4 dB (circles, dashed line), −6 dB (squares, solid line), and −8 dB (triangles, dotted line). The right panel shows mean data for three listeners, with different symbols representing the *PEIs* measured in quiet (circles; replotted from the left panel of Fig. 7) and in high-pass noise (triangles). Filled symbols are for the pedestal level of 60 dB SPL and open symbols are for the level of 63 dB SPL. Error bars represent one standard deviation of the mean.

old fluctuations and intensity increments across levels is illustrated in Fig. 8, which shows the mean PEMDs (left panel) from two listeners (S1 and S2) and the mean PEIs (right panel) from three listeners (S1 and two new listeners who did not participate in the previous experiments).

If the effects of a high-pass noise on the perception of suprathreshold fluctuations and increments were equivalent to those observed for AM and increment detection, the PEMD and PEI should remain constant across levels. The shape of the PEMD function (left panel) differs from that in Fig. 5 (without high-pass noise), but the PEMD remained level dependent. For the 30-dB SPL carrier, the PEMDs (left panel) could not be estimated from the psychometric functions because the functions were very shallow and sometimes nonmonotonic. Consequently, data for only four comparison levels are presented in Fig. 8. Overall, the PEMD varied across carrier levels but the level dependence was nonmonotonic. Multiple t-tests were performed separately on each listener's data. For each carrier level, the estimated *PEMD* was compared to the mean of the PEMDs obtained for the other three carrier levels. These multiple comparisons revealed that for each standard modulation depth, all but one PEMD were significantly different from the mean of the other three at a significance level of 0.05. For S1, the PEMD that was not significantly different from the mean of the other three estimates, for all three standard modulation depths, corresponded to the carrier level of the comparison of 75 dB SPL ($t=2.06$, df=12, $p=0.058$, for the standard modulation depth of −4 dB; $t=2.07$, df=13, $p=0.056$, for the standard of −6 dB; and $t=1.67$, df=11, $p=0.118$, for the standard of −8 dB).[4] All other t-test comparisons yielded $p<0.05$. For S2, the only PEMD that was not significantly different from the mean of the other three corresponded to the carrier level of the comparison of 60 dB SPL ($t=1.72$, df=9, $p=0.124$, for the standard modulation depth of −4 dB, $t=1.31$, df=9, $p=0.226$, for the standard of −6 dB, and $t=0.92$, df=11, $p=0.388$, for the standard of −8 dB). All other t-test comparisons yielded $p<0.05$ indicating significant differences in PEMD across carrier level. Thus, the PEMD function measured in the presence of a high-pass noise differs from that expected based on the effect of a high-pass noise on AM detection (possible reasons for the departure from the expected counterpart to Weber's law in the presence of a high-pass noise will be discussed in Sec. IV.A).

The right panel of Fig. 8 shows average PEIs measured in quiet (circles, replotted from Fig. 5) and the average PEIs measured in three listeners in the presence of a high-pass noise (triangles). The noise substantially reduced the effect of level on the PEI although the slopes of the functions are significantly different from zero (as shown by a t-test of the hypothesis that the slope equals zero, $p<0.05$) for both pedestal levels, likely because the level of the high-pass noise was too low to completely eliminate the use of spread of excitation. The substantial reduction of the slope suggests that subjectively equivalent suprathreshold increments across levels would likely correspond to equal increments in sound level if spread of excitation were made completely unusable.

In summary, the results of matching suprathreshold AM and increments across levels to a large extent reflect the behavior seen in AM and increment detection across levels.

IV. DISCUSSION

The purpose of the study was to examine to what extent lawful relationships observed for detection of amplitude modulation and intensity JNDs generalize to the perception of highly detectable intensity changes and fluctuations. Perceived modulation depths and perceived intensity increments were compared across levels for noise and for a 1-kHz tone. For the tone, additional comparisons were performed in the presence of a high-pass noise that masked upward spread of excitation. Overall, the results appear to mirror threshold data, i.e., for noise, the perceived intensity fluctuation/change does not depend on level, whereas for a pure tone, a given modulation depth and a given change in intensity produces a greater perceived change as the level of the tone increases. Consequently, a counterpart to Weber's law is observed for PEMDs and PEIs for noise, and a counterpart to the near-miss to Weber's law is observed for tones. This is the most important finding of the study as it strongly suggests that the strategies and cues used in AM and increment detection tasks are likely relevant for the perception of suprathreshold intensity changes and that the general laws describing the detection apply to everyday perception of suprathreshold intensity changes.

A. Differences between threshold and suprathreshold perception of intensity fluctuations/changes for tones

Despite the overall qualitative similarities, some differences between the perception of suprathreshold AM and AM detection are worth noting. In the left panel of Fig. 5, the slopes of the PEMD functions (filled symbols) are much shallower than the slope of the threshold function (open triangles). The shallower slope for suprathreshold modulation depths can be explained taking into consideration the presumed shape of the basilar-membrane response function.

Most studies of basilar-membrane compression have found that the growth of response is more linear for levels below 25–30 dB SPL and it becomes compressive above that range of levels (e.g., Nelson *et al.* 2001; Plack *et al.*, 2004). For a 1-kHz tone presented at 30 dB SPL, AM detection threshold is about −20 dB ($20 \log m$), as shown by the data in the left panel of Fig. 5 (open triangles) replotted from Wojtczak and Viemeister (1999). The level in the trough for the threshold modulation depth is 29.1 dB SPL. Assuming that the fluctuations in the instantaneous stimulus level fall into a compressive region of the basilar membrane response, the "internal" depth of fluctuations is smaller than that in the stimulus. At 90 dB SPL, excitation produced by the modulated tone spreads into the regions of the basilar-membrane where the response growth is linear. Listeners likely use the upper side of the excitation pattern to detect AM where (due to the linear response growth) the internal modulation depth (in terms of peak-to-through difference in decibels) is similar to that in the stimulus. Assuming a constant output (internal) modulation depth is needed for threshold, the nonlinear processing would predict that a smaller modulation depth is sufficient to detect AM at high carrier levels, as evidenced by the data. For large (suprathreshold) modulation depths used in the modulation-matching experiment, the trough in the modulated waveform may fall into a more linear region of the basilar-membrane response when the carrier level is 30 dB SPL. In fact, for the input level of −4 dB (a value roughly corresponding to the filled circle at 30 dB SPL in Fig. 5), the instantaneous level in the trough is 21.3 dB. Thus, the internal depth of fluctuations may be compressed less (relative to the input) than that for very small modulation depths. Consequently, the difference between the internal depths of fluctuations at 30 vs 90 dB SPL should be smaller for larger modulation depths, resulting in a shallower slope for the PEMD (compared with AM detection) function. It should be noted that the same reasoning could explain the slope differences at higher carrier levels (e.g., between 75 and 90 dB SPL) if it is assumed that the listeners used fluctuations on the upper side of the excitation pattern to detect AM and to perceive suprathreshold AM. Additionally, it has to be assumed that at 75 dB SPL the response at a place on the basilar membrane where the fluctuations are the strongest is still somewhat compressive relative to the response for the 90-dB SPL carrier and that compression increases progressively with increasing level.

Another discrepancy emerges when comparing differences of slopes between threshold and suprathreshold functions, separately for AM and intensity increments. Wojtczak and Viemeister (1999) have demonstrated a close relationship between the modulation depth at AM detection threshold and the change in intensity needed for increment detection. Because the PEI function is much steeper than the function relating threshold intensity increments to the pedestal level, whereas the PEMD function is much shallower than the function relating modulation depth at threshold to the carrier level, the relationship shown by Wojtczak and Viemeister (1999) cannot generalize to suprathreshold intensity changes. The same factor that yields a shallow slope of the PEMD function might be responsible for the steeper suprathreshold PEI function. For intensity increments, the level does not fall below the pedestal level as the increment increases. A steeper slope of the suprathreshold PEI function can be predicted taking into consideration a possibility that the listeners can use spread of excitation into the regions of the basilar membrane where the response grows in a linear manner at high but not at low pedestal levels (see footnote 3).

In the presence of a high-pass noise, the PEMD function is nonmonotonic (left panel in Fig. 8). This contrasts with AM detection in high-pass noise, which exhibits Weber's law. The listeners required smaller modulation depths in a 45-dB SPL comparison to match those in a 60-dB SPL standard. This result suggests that perceived fluctuations for a 60-dB SPL carrier are attenuated in the presence of a high-pass noise relative to those at lower carrier levels. This would be expected if the high-pass noise eliminated the possibility to process fluctuations on the upper side of the excitation pattern on the basilar membrane, where the response growth is more linear than at the 1-kHz place and the listeners were forced to use changes in excitation level where the response growth is compressive. It is possible that the standard fluctuations (around 60 dB SPL) produced smaller internal fluctuations than those in the comparison (around 45 dB SPL), because of stronger compression around 60 dB SPL. Assuming that the perceived strength of fluctuations is directly related to the rate of response growth, less compressive growth would lead to stronger perceived fluctuations and thus a smaller modulation depth at 45 dB SPL would be sufficient to match the perceived standard modulation depth. As anticipated, the high-frequency noise eliminated the decrease in PEMD with increasing level in the range between 60 and 75 dB SPL. As the amount of compression is likely constant over this range of levels, PEMDs were approximately equal. Above that range, the PEMD decreased indicating that the level of the masking noise may have not been sufficiently high to entirely eliminate the use of spread of excitation at the highest level used.

Although some discrepancies, which can be explained in terms of nonlinear basilar-membrane processing, are observed, the results appear to support the idea that the general laws, which describe detection thresholds can be used to describe the perception of highly detectable intensity changes and intensity fluctuations. This is a very important finding because readily perceived rather than threshold intensity changes are used in real-world auditory perception and identification of sounds. Moreover, the finding suggests that the numerous studies describing intensity coding based on threshold psychophysics might be directly relevant for describing the processing of suprathreshold intensity changes.

Apart from these general considerations, the data from matching suprathreshold intensity changes may help make some inferences about more basic characteristics of the auditory system and perhaps other sensory systems for which similar laws apply. Over decades, studies have attempted to develop robust models of a neural mechanism underlying Weber's law that would explain intensity discrimination under various conditions. A concept of internal noise (discussed below) has proven both physiologically plausible and practically effective in increasing the predictive power of auditory models for detection and discrimination of sound intensity.

B. Internal noise

Almost all contemporary models of detection and discrimination incorporate some form of variability that is intrinsic to the processing. In the language of signal detection theory (Green and Swets, 1988), the decision variable is a random variable, even when the input is deterministic. This variability or internal noise is often ascribed to the characteristics of sensory transmission, for example, to the Poisson-like stochastic properties of auditory nerve discharges (e.g., Siebert, 1968; McGill and Goldberg, 1968; Penner, 1972). In most models of intensity discrimination the internal noise is assumed to increase as the input level increases. This type of internal noise has been dubbed "multiplicative noise" (Eijkman *et al.*, 1966; Green and Swets, 1988). Technically, multiplicative noise refers to the specific situation in which the standard deviation (σ) of the decision variable is proportional to the mean. In the referred studies, the term multiplicative noise is often used to indicate that σ simply increases monotonically with the mean of the decision variable, not necessarily proportionally. This type of internal noise has been used in contrast to additive internal noise, which is independent of the magnitude of the decision variable. The multiplicative-noise models also assume that the neural activity evoked by the stimulus (often integrated over some period of time or/and pooled across a population of neurons) is generally a power function of the stimulus magnitude. Under such assumptions, it can be demonstrated that the multiplicative internal noise would yield Weber's law for intensity discrimination. The sensitivity index for discrimination of two sound intensities, I and $I+\Delta I$ can be expressed as

$$d' = \frac{(I+\Delta I)^n - I^n}{\sigma(I)}, \quad (1)$$

where n is the exponent of the power function that relates stimulus intensity to the internal response and $\sigma(I)$ is the standard deviation characterizing the distribution of the decision variable. Assuming a multiplicative-noise model, $\sigma(I)=kI^n$, where k is a constant. After substituting for $\sigma(I)$, this approach will yield Weber's law, as shown by the following equation, which has been rearranged to solve for the Weber fraction:

$$\frac{\Delta I}{I} = (kd' + 1)^{1/n} - 1. \quad (2)$$

The right side of Eq. (2) has a constant value for a constant d' and thus, it yields an intensity-independent Weber fraction.

Physiological evidence suggests there is a multiplicative component in auditory intensity coding. For example, the variance in spike-counts recorded from auditory nerve fibers increases with discharge rate (Teich and Khanna, 1985; Young and Barta, 1986). The question is whether multiplicative noise plays a determining role in auditory intensity coding and whether it underlies Weber's law, the fundamental law that describes our ability to discriminate intensities at different stimulus levels.

Our results suggest that multiplicative internal noise does not play a major role in intensity discrimination or AM detection. The argument is based on the likely supposition that the internal noise that limits discrimination and detection does not directly affect the perception of the suprathreshold intensity changes used in the present experiments because the variability produced by the noise becomes insignificantly low when compared with changes in the mean internal response produced by the highly detectable AM or intensity increments. Further, the similarity between the PEMD and PEI functions to those for AM detection and intensity discrimination suggests that level-dependent changes in internal noise may not be important in threshold situations. Specifically, the implication is that Weber's law does not result from multiplicative internal noise. An alternative approach that would yield Weber's law for both threshold *and* highly detectable intensity changes is to assume an intensity-independent internal noise combined with a logarithmic transform of the stimulus magnitude (Fechner, 1860; Durlach and Braida, 1969). If the magnitude in question is stimulus intensity, then the sensitivity index characterizing intensity discrimination could be expressed as

$$d' = \frac{\log(I+\Delta I) - \log(I)}{\sigma}, \quad (3)$$

where σ is the standard deviation of the decision variable that does not depend on I. In this case, Eq. (3) can be rearranged to

$$\frac{\Delta I}{I} = 10^{d'\sigma} - 1. \quad (4)$$

For a constant d' that is assumed for threshold, Eq. (4) will yield an intensity-independent Weber fraction. Given the aforementioned physiological evidence, it is possible that the internal noise may have both multiplicative (σ_m) and additive (σ_{add}) components

$$\sigma = \sigma_m + \sigma_{\text{add}}, \quad (5)$$

In that case, Eq. (3) would yield Weber's law if the multiplicative component were negligibly small compared with the additive component. The appeal of this approach is that the log transform would characterize the relationship between the stimulus intensity and the internal response in general and thus would not pose a limiting factor in intensity discrimination. Instead, the predominantly additive internal noise would limit threshold performance but the log transform of stimulus intensity would be responsible for Weber's law observed for threshold intensity discrimination *and* for perception of suprathreshold intensity changes.

C. Loudness

Defining a relationship between the perception of suprathreshold AM and the loudness function is not straightforward, especially for modulation rates that fall into the perceptual category of roughness (Zwicker and Fastl, 1999).

The likely increasing role of forward masking with increasing modulation depth and also with increasing modulation rate makes it impossible to account for the changes in the perceived fluctuation strength or roughness purely in terms of the characteristics of loudness functions for stationary sounds. Because of the possible other factors playing a role in the perception of a 16-Hz AM, the discussion of our results with respect to the loudness function will be limited to intensity increments.

In the increment-matching experiment, listeners were asked to pick the observation interval in which the change in sound intensity appeared larger. As the task was subjective with no "correct" answer, listeners were free to decide what feature of the stimulus they should use as the basis for their judgments about the size of the increment. Based on reports from the listeners, suprathreshold changes in intensity are perceived as changes in loudness. The PEI functions were similar in form across listeners, for a 1-kHz tone and for noise. Thus, the listeners likely used the same strategy to perform the matching task. The shape of the PEI function may provide some cues as to what the strategy and the decision variable were. One possibility is that the listeners used the loudness of the steady-state portions before and after the increment and "computed" the size of the increment using those two end values. Two strategies involving the loudness of the stimulus before the increment (L_1) and the loudness of the incremented portion (L_2) were considered to make predictions about the shape of the PEI functions. The loudness of each steady-state part of the stimulus was computed using a loudness model proposed by Moore *et al.* (1997). One strategy assumes that the listeners perceived intensity increments as equal when the loudness ratio (L_2/L_1) reached the same value for different pedestal levels. This approach is analogous to Ekman's law for loudness JNDs (Ekman, 1956, 1959), except in the current analysis, it was extended to suprathreshold intensity increments. Equal loudness ratios predict that the PEI does not depend on the pedestal level, a result equivalent to that described by Weber's law for intensity discrimination. The predictions based on Ekman's law obtained using the loudness model by Moore *et al.* (1997) account for the PEIs for the noise pedestal very well (see level-independent PEIs the right-hand panel of Fig. 7). The predictions consistent with those obtained using the model by Moore *et al.* (1997; not shown) can also be obtained when Steven's law is used (1957). According to Steven's law, loudness is a power function of stimulus intensity ($L=kI^p$, where k and p are constant values). A loudness ratio for a given suprathreshold intensity increment can be described by $L_2/L_1=k(I+\Delta I)^p/kI^p$. Thus, a constant L_2/L_1 implies a constant $\Delta I/I$ across stimulus levels. Although a constant loudness ratio produces the correct PEI function for noise, it fails to predict the data for the tonal pedestal. Interestingly, Ekman's law generally fails to predict intensity discrimination thresholds across loudness for tones, as demonstrated by Hellman and Hellman (2001).

Another strategy assumed that intensity increments are perceptually equivalent when loudness difference (L_2-L_1) reaches a certain constant value across pedestal levels. This is analogous to a "theory of resolution" based on equal loudness differences, suggested by Parker and Schneider (1980). For the tonal pedestal, the PEI function obtained from the matching task and the predictions assuming constant loudness difference (the left panel in Fig. 9) are in very good agreement, although the predictions slightly underestimate the increment size at most levels. For the noise pedestal, the predictions based on equal loudness differences (with loudness computed using the model by Moore *et al.*, 1997) are compared with the PEI function for the pedestal with a spectrum level of 20 dB SPL and a 4-dB increment. It is clear that for noise, the approach based on equal loudness differences fails to predict the behavioral data (the right panel in Fig. 9). It is worth noting that equal loudness difference cannot predict intensity discrimination for tones in broadband noise (Schneider and Parker, 1990) and would not predict constant intensity JNDs for noise.

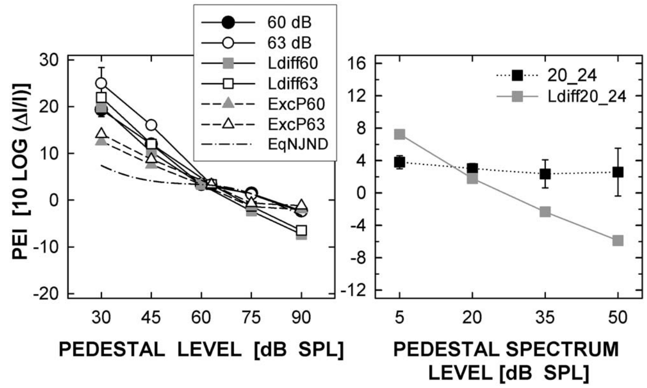

FIG. 9. The left panel shows *PEIs* for a 1-kHz pedestal replotted from the left panel of Fig. 7 (circles) and predictions based on: (i) equal loudness differences (squares); (ii) equal differences between log-transformed excitation patterns integrated over frequency (triangles); and (iii) equal number of JNDs (dashed-dotted line). The filled circles cannot be seen because they overlap with other symbols (they are covered by a gray square at 30 dB SPL, by an open square at 45 dB SPL, and by open circles at 75 and 90 dB SPL). The right panel shows *PEIs* for a noise carrier (replotted from the right panel of Fig. 7 for the 20_24 standard; black squares) and *PEIs* predicted using the assumption of a constant loudness difference (gray squares).

To summarize the previous analyses, equal loudness ratios can account for the data for the noise but not for the tonal pedestal, whereas the opposite is true for equal loudness differences. One implication is that listeners might be using different strategies in the increment-matching task that would depend on the type of the stimulus. More likely, the listeners use the same strategy for both types of stimuli, a strategy that is *not* based on a ratio or difference of loudness of the stationary portions of the stimuli with intensity increments.

Two metrics described below yield predictions that are qualitatively consistent with the PEI function of level for a tone and for noise, but quantitative agreement for the tonal pedestal is quite poor.

D. Constant difference between log-transformed excitation patterns for the pedestal with and without an increment

A metric based on log-transformed excitation patterns was tested for its ability to predict the PEI functions for the tonal and noise pedestals. For each pedestal level of a 1-kHz tone, the excitation patterns were computed from rounded-exponential filters (Patterson and Moore, 1986), for the pedestal, $E_I(f)$, and the incremented pedestal, $E_{I+\Delta I}(f)$. Differences between the log-transformed excitation patterns were integrated over a frequency range for which the excitation exceeded the threshold excitation level (assumed to be equal to 0 dB). Thus, the metric (D) used can be described as

$$10 \cdot \int_{f_{\text{Inc1}}}^{f_{\text{Inc2}}} [\log(E_{I+\Delta I}(f)) - \log(E_I(f))]df = D, \tag{6}$$

where f_{Inc1} and f_{Inc2} denote the frequencies between which the excitation produced by the incremented pedestal was greater than 0 dB. Since for the 1-kHz tone, the range of frequencies stimulated by the pedestal without an increment was smaller than that with the increment, $10\log(E_I(f))$ was set to zero for frequencies between f_{Inc1} and f_{Inc2}, for which its value fell below zero. This is equivalent to assuming, for simplicity, that the excitation level needed for detecting the tone is 0 dB as detection is limited by internal noise at stages above the basilar membrane. Assuming that D needs to be constant for PEIs, first the value of D was computed from Eq. (6) for the 1-kHz standard with a 60-dB SPL pedestal and a 5-dB increment (the same was repeated for a 63-dB SPL pedestal). Subsequently, intensity increments were found for all comparison levels used in the increment-matching task that produced the same value of D. The predicted increments are shown by triangles connected by a dashed line in the left panel of Fig. 9. The increments decrease with increasing pedestal level, consistent with the data, but they underestimate the PEI for the 30-dB pedestal by about 7 dB for the 60-dB SPL pedestal of the standard and by almost 11 dB for the 63-dB SPL pedestal. In addition to the disappointing quantitative agreement, this approach is not physiologically justified as it ignores the band pass filtering due to the outer and middle ear transfer functions. Inclusion of a realistic band pass filter would lead to a value of D that decreases with increasing level for the noise pedestal, because the effective excitation would exhibit spread over a larger area of the basilar-membrane as the noise level increases and more components reach the levels that offset attenuation by the filter.

E. Intensity changes for equal number of JNDs

Lim *et al.* (1977) proposed that different sounds have the same loudness when their levels of presentation correspond to the same proportion of the dynamic ranges for the respective sounds expressed in terms of the number of JNDs. Their approach proved successful in relating intensity discrimination to loudness-matching results (Houtsma *et al.*, 1980). The present study adapted the "proportional JND" hypothesis to increment matching, assuming that for a given stimulus, suprathreshold intensity increments are perceived as equal when their size comprises the same number of intensity JNDs. For noise, the intensity JND does not depend on level over the range of levels tested. This implies that a given suprathreshold intensity increment comprises the same number of intensity JNDs at different pedestal levels. Assuming a constant number of JNDs is perceived as producing the same intensity change at all levels, the predicted PEI will be independent of level leading to a counterpart of Weber's law, which is seen in the data (right panel of Fig. 7). For a tone, the intensity JND decreases with increasing pedestal level. Assuming a constant number of JNDs produces the same perceived intensity change, the PEI should decrease with increasing level, leading to a counterpart of the "near-miss" to Weber's law. The question arises whether or not a constant number of JNDs can account for the sizeable change in PEI across level of the 1-kHz tone in this study. A fourth-order polynomial fit to increment detection thresholds (converted to units of $10\log[(I+\Delta I)/I]$ from the study of Viemeister and Bacon (1988) was first used to determine the number of JNDs in the standard 5-dB increment for the pedestal level of 60 dB SPL. The number of JNDs was computed using the formula provided by Lim *et al.* (1977; footnote 11) using $d'=0.78$ that corresponds to the 70.7% correct responses in a 2IFC task. Next, based on the polynomial fit to the data of Viemeister and Bacon, a size of the intensity increment corresponding to the same number of JNDs was found for every comparison level used in the experiment (through the inverse solution obtained using Mathematica software). The PEIs obtained based on the assumption of an equal number of JNDs are shown by the dashed-dotted line in the left panel of Fig. 9. The results obtained based on an equal number of JNDs predict much lower PEIs for pedestal levels below 60 dB SPL than those measured in the increment-matching task.

In summary, none of the attempted approaches provided a satisfactory account for the data without assuming that the listeners used different decision variables for the noise and tonal stimuli, which seems unrealistic. It is possible that the decisions about the increment size were not based on the loudness of the stationary parts of the stimuli before and after the increment but on some more complicated function describing the transition from the softer to greater loudness during the increment. Additional experiments using pulsed stimuli with differing intensities, for which the listeners cannot hear the transition from softer to louder portion of the stimulus, but have to rely on the stationary loudness, are needed to determine if the dynamic transitional change plays a role in evaluating the size of an increment.

V. CONCLUSIONS

Generally, comparisons of PEMDs and PEIs across level lead to the following observations

(1) For noise carriers, the PEMD does not depend on carrier level. This is consistent with a constant modulation depth needed for AM detection threshold across carrier levels. For tonal carriers, the PEMD decreases slightly (by about 7 dB in units of $20\log m$) with increasing carrier level, with the greatest decrease occurring in the range of levels between 60 and 75 dB SPL. This is consistent with decreasing modulation depth needed for AM detection threshold. The rate of the decrease with in-

creasing level is slower for suprathreshold AM possibly reflecting the role of level-dependent compression on the basilar membrane.

(2) For tonal pedestals, the PEMD varies less across carrier level when a high-pass noise is used to mask the upward spread of excitation.

(3) For noise, the PEI does not depend on the pedestal level revealing a counterpart to Weber's law for suprathreshold intensity increments. For a tone, the PEI decreases with increasing pedestal level. The decrease is much steeper than that observed for threshold intensity increments. Thus, a counterpart to the near-miss to Weber's law is observed for suprathreshold intensity changes, but the level effect is much more sizeable than that seen for intensity-discrimination threshold.

(4) The presence of a high-pass noise greatly reduces the level dependence of the PEI for a tone, implying the involvement of nonlinear spread of excitation when the noise is absent.

(5) The observed counterpart to Weber's law for suprathreshold AM and intensity increments suggests that Weber's law does not reflect changes in the amount of internal noise with stimulus level. Instead, it is consistent with the notion that Weber's law stems from a logarithmic-type transform that relates stimulus intensity to the magnitude of the internal response.

(6) A constant loudness difference and a constant loudness ratio could not account for the functions relating the PEI to the pedestal level, for both the tonal and noise pedestals. This suggests that the listeners might have used different decision variables to determine the size of the increments for the two types of stimuli. Differences between log-transformed excitation patterns integrated across frequency and a model assuming equal JND numbers for PEIs produced predictions that were in qualitative agreement with the data but they severely underestimated the PEIs for levels below 60 dB SPL. It is likely that some transition in loudness that is not related to the stationary loudness before and after the increment in a simple manner was used as a decision variable by the listeners. The nature of that transitional change in loudness remains to be determined.

(7) Overall, the results of the present study indicate that the same strategies and cues are likely used in the perception of suprathreshold intensity changes as those used in increment and AM detection. Thus, findings from threshold psychophysics that use objective procedures to measure just-detectable changes can be, to a large extent, generalized to the perception of more ubiquitous suprathreshold intensity variations.

ACKNOWLEDGMENTS

This study was supported by NIDCD Grant No. DC00683. Two anonymous reviewers provided very helpful comments that improved the earlier version of the manuscript.

APPENDIX A: OBSERVATIONS ON THE USE OF INTERLEAVED ADAPTIVE TRACKING USING ONE STANDARD

Originally, an adaptive matching procedure with two interleaved tracks (Jesteadt, 1980), one upper (3-down, 1-up) and one lower (3-up, 1-down), was first used to estimate the PEMD. This procedure led to some results that failed to fulfill control conditions of symmetry (when comparison B was matched to standard A then comparison A should be matched to standard B, which was not the case) and transitivity (if B was matched to A, and C was matched to B, then A should be matched to C).

Using the Jesteadt procedure, the PEMD was estimated as the mean of two modulation depths, one corresponding to the 79.4% point on the psychometric function and the other corresponding to the 20.6% point. Some listeners showed a large discrepancy between the lower and upper estimates, which suggested very shallow psychometric functions for matching modulation depths at different carrier levels. However, other listeners applied a strategy that led to the lower and upper estimates being very close to one another. That, in turn, suggested very steep psychometric functions, yet the results failed to show symmetry and transitivity. As the standard and the comparison differed in level, it was easy for the listener to identify which stimulus was being manipulated by their responses. Under such circumstances, when comparing fluctuation depths across levels was difficult, it might have been easier for the listeners to "remember" a certain modulation depth of the comparison ("internal PEMD") and perform the matching task without making any comparisons to the "real" standard provided in each trial. In that case the listeners could have made absolute judgments about the modulation depth of the comparison and adjust the modulation depth of the comparison to the internal PEMD. This possibility was informally tested using one listener. To determine how robust matching to an internally stored template is, the standard was unmodulated and the modulation depth of the comparison was adjusted adaptively using the two interleaved tracks, as in the main original experiment. The listener was told to match the comparison modulation depth to the "PEMD" she established on her own during the adaptive tracking. The mean of the six estimates (from six separate runs) had a much smaller standard deviation than the one obtained with the modulated standard, suggesting that it was easier for the listener to provide consistent matches to the memorized modulation depth of the comparison then to compare across the standard and comparison intervals. Moreover, the test was repeated a day later and the subject was instructed to use the same template modulation depth, as she remembered it. Surprisingly, the mean result was within 1 dB ($20 \log m$) of that obtained a day earlier, indicating that listeners may be capable of using a stored internal PEMD over sessions.

The results of matching to the internal template can be very consistent and replicable over days. Moreover, the variability in the data decreases with practice, as training helps establish and fix the template in listener's memory. Therefore, a matching experiment was designed to force the listener to attend to both the standard and the comparison observation intervals. A fixed-level procedure using a few fixed standards, randomly presented in a block of trials, appears to prevent using an internal template for the PEMD. For each standard, a psychometric function relating the proportion of times a given type of response occurred to the level of the comparison can be constructed. Using this method, the strategy based on an internal template could be easily detected. If the listener ignored the actual standard, the psychometric functions like those presented in Fig. 2, would fall on top of one another.

APPENDIX B: INCOMPLETE PSYCHOMETRIC FUNCTIONS

To cover the range of proportion of "comparison increment larger" responses between 0 and 1 with sufficient density for all the 1-kHz standards shown in the middle column of Table III, a larger (than eight) number of comparison increments would have had to be used within a block. This would have substantially increased the duration of each block. To avoid that, eight comparison increments were selected based on pilot runs. They were chosen to allow for estimating PEIs for the 5-dB increment in 60- and 63-dB SPL pedestals from psychometric functions with data distributed over nearly the entire range of proportion of responses between 0 and 1. By choosing only eight increments we compromised the ability to obtain the whole psychometric function for the two remaining increment sizes, 2 and 8 dB in units of $10\log[(I+\Delta I)/I]$. For these increment sizes, the data (proportion of responses comparison increment larger) concentrated in the range between 0.5 and 1, for the 2-dB increment, and in the range between 0 and 0.5 for the 8-dB increment. Thus, the lack of estimated PEIs for these standards should not be considered as resulting from listeners' inability to perform the task reliably. Instead, they were a result of a compromise that was decided upon when designing the experiment. For the same reason, the PEI could not be estimated for a 1-dB increment in the noise standard with a spectrum level of 23 dB SPL.

[1]The form of the logistic function fitted to the data was the same for modulation and increment matching. The function was defined by $P=1/(1+\exp(b(x_0-x_c)))$, where P denotes the proportion of times the comparison was evaluated as having stronger intensity fluctuations (or a larger intensity increment) than the standard, b characterizes the slope of the logistic function, x_0 is the modulation depth (or an intensity increment) in the comparison corresponding to $P=0.5$, and x_c is the modulation depth of the comparison (or the increment in the comparison). Thus, x_0=PEMD for modulation matching, and x_0=PEI, for increment matching.

[2]Data from Bacon and Viemeister (1985) plotted in the right panel of Fig. 5 represent the mean of AM detection thresholds for listeners S1 and S4 in their study, for a 16-Hz rate at a spectrum level of 30 dB SPL adjusted by the relative shift in threshold observed for lower spectrum levels (plotted in their Fig. 4). The adjustment for a 4-Hz modulation rate was used, as data for a 16-Hz rate were not available. However, the similarity of the relative shifts measured by Bacon and Viemeister (1985) for a 4-Hz rate and at a 70-Hz rate suggests that the adjustments for the 4-Hz rate can be applied without much error to detection of a 16-Hz rate for the purpose of comparison with the suprathreshold data for a 16-Hz rate in this study. The carrier was presented continuously in the study of Bacon and Viemeister and it was gated in this study.

[3]Excitation on the basilar membrane in response to a low-level tone spreads over a small region around the characteristic frequency (CF) equal to the frequency of the tone. As the level of the tone increases, excitation spreads over a larger portion of the basilar membrane, mainly toward places with higher CFs. The response growth is compressive at the CF equal to the stimulus frequency and becomes progressively less compressive at places above that CF. For CFs higher than about an octave above the stimulus frequency, the response becomes linear. This is referred to as nonlinear spread of excitation on the basilar membrane. It seems reasonable to assume that our perception of a change in intensity/level of a 1-kHz tone is directly related to the changes in excitation level at a place where the changes are the greatest. Thus, for a 1-kHz tone presented at 30 dB SPL, a given change in level will be determined by a change in excitation level at or close to CF=1 kHz (because the level is not high enough for the excitation to spread to places where the growth of response is more linear). For the same tone presented at 90 dB SPL, a given change in level will be related to changes in excitation level at places far above CF =1 kHz, where the response growth is linear. Assuming that increment detection thresholds measured at different pedestal levels yield perceptually equivalent increments, the PEI function of level should have a shallower slope for threshold increments than for suprathreshold intensity changes due compressive (at 30 dB SPL) versus linear (at 90 dB SPL) growth of excitation.

[4]The number of the degrees of freedom was determined considering the fact that each PEMD was estimated from a logistic fit to eight data points. Thus, eight samples contributed to the standard error of the PEMD estimate. As the t-test compared each PEMD with the mean of the remaining three PEMDs, the variance of the mean was computed as the sum of variances of each individual PEMD included in that mean. The number of samples contributing to the variance (and the standard deviation) of the mean was then $3\times 8=24$. The number of the degrees of freedom (df) was obtained from the following equation (Devore and Peck, 1997):

$$\mathrm{df}=\frac{(V_1+V_2)^2}{\dfrac{V_1^2}{n_1-1}+\dfrac{V_2^2}{n_2-1}},$$

where $V_1=s_1^2/n_1$ and $V_2=s_2^2/n_2$. In the equations, s_1 is the standard deviation of the PEMD that is being compared to the mean of the remaining three PEMDs and s_2 is the standard deviation of that mean. The value of df was truncated to an integer. Correspondingly, $n_1=8$ and $n_2=24$. The differences that based on multiple comparisons were significant remained significant after the Bonferroni correction was applied.

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