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Top-down gain control in the auditory system: Evidence from identification and discrimination experiments

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The influence of intensity range in auditory identification and intensity discrimination experiments is well documented and is usually attributed to nonsensory factors. Recent studies, however, have suggested that the stimulus range effect might be sensory in origin. To test this notion, in one set of experiments, we had listeners identify the individual tones in a set. One baseline condition consisted of identifying four 1-kHz, low-intensity tones; the other consisted of identifying four 1-kHz, high-intensity tones. In the experimental conditions, these baseline tone sets were augmented by adding a fifth tone at either 1 or 5 kHz. Added 5-kHz tones had little effect on identification accuracy for the four baseline tones. When an added 1-kHz tone differed substantially in intensity from the four baseline tones, it adversely affected performance, with the addition of a high-intensity tone to a set of low-intensity tones having a more deleterious effect than the addition of a low-intensity tone to a set of high-intensity tones. These and further results, obtained in an exploration of this asymmetrical range effect in a third identification experiment and in two intensity-discrimination experiments, were consistent with the notion of a nonlinear amplifier under top-down control whose functions include protection against sensory overload from loud sounds. The identification data were well described by a signal-detection model using equal-variance Laplace distributions instead of the usual Gaussian distributions.

A persistent problem in psychophysics has been, and continues to be, the presence of contextual effects that appear to alter discriminability. For example, increasing the number of stimuli in an identification experiment can influence the discriminability of the original stimuli (Pollack, 1952). Moreover, in a roving-intensity discrimination paradigm, in which the intensity of the standard stimulus changes from trial to trial, the discriminability of two stimuli is affected by the range over which the stimuli rove (Berliner & Durlach, 1973). Effects such as these cannot be attributed to either masking or adaptation produced by extraneous stimuli. For example, the introduction of a fourth tone in an identification experiment containing three tones is unlikely to mask the presentation of the other three because tone presentations are usually widely separated in time. It is also unlikely to result in a significant change in the state of adaptation for the same reason. Therefore, the effect of this addition is often explained in nonsensory terms. For example, Durlach and Braida (1969) and Braida and Durlach (1972), in their model of intensity perception, assume that each stimulus produces a normal distribution of responses along an internal sensory dimension (e.g., a loudness dimension). The distribution's mean is assumed to vary with stimulus intensity, but its standard deviation is assumed to be independent of stimulus intensity. The listener, however, does not have immediate access to this sensory axis. It is presumed that sensory responses contribute to a subsequent representation where decisions are made. Responses along this decision axis are also assumed to be normally distributed and to have the same means as along the sensory axis. However, it is assumed that additional variance is added to the responses when they are mapped onto the decision axis. This additional variance is given the name *memory variance* and is assumed to vary with experimental conditions. In particular, memory variance or noise is assumed to be proportional to the square of the total effective range of stimuli presented in the experiment (see also Gravetter & Lockhead, 1973). Thus, changing the stimulus range is presumed to affect the decision axis but not the encoding of intensity information. In other words, the effect of stimulus range exerts itself at a more central, nonsensory level, consistent with the classical view of how stimulus magnitude is processed (see Figure 1).

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Classically, the sensory system is assumed to map physical stimuli into events along a continuum of sensory magnitude. It is implicitly assumed that this mapping is one-to-one—that is, each intensity has its corresponding sensory magnitude. Therefore, three different stimulus intensities in an identification experiment would produce three distributions of sensory effects along the sensory magnitude continuum. If a fourth stimulus were added, a fourth distribution would result, which, presumably, would not affect the sensory representations of the other three. Rather, the fourth stimulus is thought to alter the representations of all stimuli at some more central locus (the decision axis) by increasing the variability, but not by altering the means of the distributions along the decision axis.

According to this viewpoint, context affects sensory judgments but not the sensory representation of the stimuli. If this is indeed true, then it should be possible, given sufficient ingenuity, to determine the relation between stimulus intensity and sensory magnitude, an endeavor that has occupied psychophysicists for over a century and a half. However, this endeavor has also been plagued by contextual effects. It has long been known, for example, that numerical estimates of loudness are affected not only by the context provided by the instructions but also by the number, spacing, and range of sounds being presented (e.g., Marks, 1979, 1988; Marks, Szczesiul, & Ohlott, 1986; Poulton, 1968; Teghtsoonian, 1973). Therefore, numerical assignments or judgments clearly do not have a one-to-one correspondence with stimulus intensities. Nevertheless, one can retain the conviction that there is a one-to-one correspondence if these context effects are considered as reflecting the operation of higher order, nonsensory processes. Thus, S. S. Stevens (1971) argued that it often was difficult to uncover the "true" psychophysical law (the relation between loudness and stimulus intensity) because of the operation of a number of "psychological" factors that bias the listener's report of sensory magnitude.

Thus, contextual effects in direct scaling experiments, such as the stimulus range effect, where the exponent of the psychophysical power function is reduced as stimulus range increases, are usually considered to be consequences of factors operating at a more central or cognitive level. For example, if listeners had a tendency to use the same range of numbers independent of the intensity range of the stimuli, the loudness function would appear to be compressed as stimulus range increases (Teghtsoonian, 1973). However, Parker and Schneider (1994) and Schneider and Parker (1990) have argued that stimulus range, rather than simply affecting, for example, the range of numbers employed in a magnitude estimation experiment, actually has its effect by altering the nature of the sensory encoding.

Schneider and Parker (1990) and Parker and Schneider (1994) presented listeners with two pairs of tones differing in intensity and had them select the pair with the larger loudness difference. The interesting finding in these two studies is that the observer's judgment as to which pair had the larger loudness interval depended on the range of tones from which the pairs were selected. In one condition, the four tones constituting the two pairs were selected from a set of relatively soft tones. In another condition, they were selected from a set that also contained some very loud tones. Since the tones in these two sets overlapped, there were a number of instances in which the same two pairs of tones were judged within an experimental session that contained only relatively soft tones and also within an experimental session that sometimes contained very loud tones. For a number of these tone pairs, a change in context also reversed the participants' judgments of the relative sizes of the loudness intervals; that is, for some tone pairs, participants would judge Tone Pair A to have a larger loudness interval than Tone Pair B when the tones in A and B were selected from a soft set of tones, but participants would reverse the direction of their judgment when the same pairs of tones were sampled from a set of tones that contained some very loud stimuli. Changing stimulus range changed the rank order of loudness intervals.

Presumably, judgments of loudness intervals also reflect events occurring along a decision axis. In such a model, the four tones used in the two pairs would result in four distributions on the decision axis. The presentation of Pair A would result in a sample taken from each of the two distributions associated with the two tones in this pair. If the difference between these two samples is larger than the sample difference obtained when Pair B is presented, then the observer would respond that Pair A had the larger loudness interval. Note that, in this model, a systematic reversal of the direction of judgment means that the spacing between the stimuli on the decision axis must be affected by stimulus range in a nonlinear fashion and/or that the variances associated with each of these distributions must be changed in some nonlinear way. Schneider and Parker (1990) and Parker and Schneider

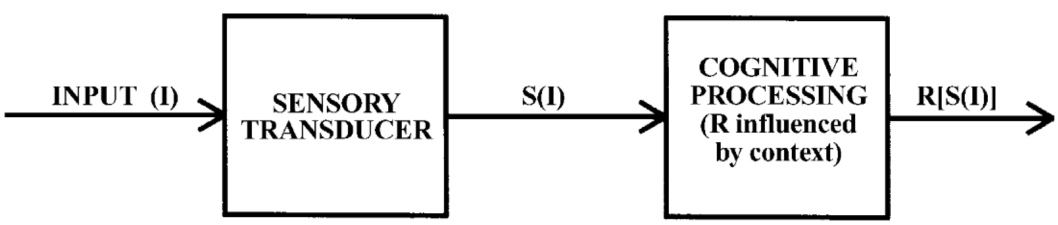

Figure 1. Classical view of how stimulus magnitude is processed.

(1994) argued that the results of their experiments were best explained by assuming that it is the representation along the sensory dimension (the spacing between stimuli) that is altered due to the action of a nonlinear amplifier whose gain is under central control. When only soft sounds are presented and expected, it is assumed that the gain of this amplifier is turned up to boost the amplitude of these sounds to facilitate signal processing. For signals presented at higher amplitudes, the gain, if any, need not be as high. Also, at very high amplitudes, it might be necessary to reduce intensity to avoid saturating the neural network involved in intensity discrimination.

If a nonlinear amplifier is responsible for producing the effects observed in scaling experiments, it should also be functioning in discrimination experiments, as was suggested by Eijkman, Thijssen, and Vendrik (1966). In particular, changing the gain on the nonlinear amplifier should change the relative spacing among stimuli along the decision axis, thereby altering performance in discrimination and identification experiments. Note that, in contrast to Durlach and Braida's (1969) model, we are suggesting that context affects the nature of the sensory representation, not just the memory variance. To be specific, the Durlach and Braida model assumes that there is a mapping of stimulus intensity, I, onto the sensory axis. This mapping is assumed to be variable and normally distributed, with mean, $\alpha(I)$, and variance, β^2, that is independent of I. In their theory, these parameters are not affected by context. However, in their model, the sensory axis is not the decision axis. The representations of the stimuli along the decision axis are still distributed normally with means equal to $\alpha(I)$, but their variances are altered by context. Specifically, the discriminability of stimuli I_i and I_j is given by

$$d'(I_i, I_j) = \frac{\alpha(I_i) - \alpha(I_j)}{\sqrt{\beta^2 + \gamma^2}}, \qquad (1)$$

where $d'(I_i,I_j)$ is the normalized difference between the means, and γ^2 is referred to as *contextual*, or *memory*, variance and is assumed to be independent of both sensory variance and intensity. According to Durlach and Braida, context can affect only memory variance. We are proposing instead that context can change the nature of the sensory representation, $\alpha(I)$, through the operation of a nonlinear gain-control mechanism. In the experiments described below, stimulus range was changed in a variety of ways to induce a change in the gain of the hypothesized nonlinear amplifier. The consequences of these range changes were investigated for both discrimination and identification experiments employing 1-kHz tones in an attempt to show that varying range could also affect the character of the sensory representation.

EXPERIMENT 1
Cross-Channel Effects

The evidence from scaling and direct comparison experiments suggests that separate amplifiers may be associated with distinct critical bands so that the gain can be independently adjusted in different frequency regions (Mapes-Riordan & Yost, 1999; Marks 1992, 1994; Marks & Warner, 1991). If this is true, then the addition of a 5-kHz tone to an identification experiment involving 1-kHz tones should not alter the identifiability of the 1-kHz tones. We had participants identify which of four 1-kHz tones was presented on a trial. In a second session, a 5-kHz tone was added to the original set of four 1-kHz tones to see whether it affected the identification accuracy among the original four 1-kHz tones. To increase the separability between the 1- and 5-kHz tones, the duration of the 5-kHz tone was doubled. Eight different sets of four 1-kHz tones were used: four low-intensity sets (centered at 32.5 dB SPL) and four high-intensity sets (centered at 87.5 dB SPL). The low-intensity sets' interstimulus spacings and, hence, ranges varied, as did the spacings and ranges of the high-intensity sets. The participants encountered the sets in one of 10 counterbalanced sequences. Five participants encountered the low-intensity sets first; the other 5 participants were presented with the high-intensity sets first.

If the amplifier is specific to a particular auditory channel (critical band), then identification accuracy among the four 1-kHz tones should not be affected by the addition of the 5-kHz tone even if its loudness value is similar to those of the 1-kHz tones. On the other hand, an increase in the number of categories in and of itself might possibly lower performance on the original four tones.

Method

Participants. Ten students and staff members at the University of Toronto at Mississauga (6 females, 4 males) served as participants. The participants ranged in age from 22 to 26 years. All reported normal hearing and had normal-looking audiograms. Each participant served in all conditions.

Apparatus and Stimuli. The stimuli for this experiment consisted of 1- and 5-kHz tones varying in intensity and duration. There were two conditions in this experiment: a low-intensity condition in which a set of low-intensity tones was presented in an identification paradigm, and a high-intensity condition in which a set of high-intensity tones was presented in the same identification paradigm. Tone sets were of two types: sets containing four 1-kHz tones, and sets containing four 1-kHz tones plus a single 5-kHz tone.

Eight sets of low-intensity tones were tested. Four of these sets (L1–L4) contained only 1-kHz tones whose four intensities were symmetrically centered around 32.5 dB SPL. The four tone intensities in each set were as follows: L1 = {28, 31, 34, 37 dB SPL}; L2 = {25, 30, 35, 40 dB SPL}; L3 = {22, 29, 36, 43 dB SPL}; and L4 = {19, 28, 37, 46 dB SPL}. Each of these sets was augmented by the addition of a 32.5-dB SPL, 5-kHz tone whose loudness was equal to that of a 32.5-dB SPL 1-kHz tone (Robinson & Dadson, 1956) to produce Sets L5–L8, respectively.

Eight sets of high-intensity tones were also presented. Sets H1–H4 contained four 1-kHz tones centered at 87.5 dB SPL. The intensities of the tones in these sets were as follows: H1 = {86, 87, 88, 89 dB SPL}; H2 = {84.5, 86.5, 88.5, 90.5 dB SPL}; H3 = {83, 86, 89, 92 dB SPL}; and H4 = {81.5, 85.5, 89.5, 93.5 dB SPL}. Each of these sets was augmented by an 83-dB SPL 5-kHz tone whose loudness was equal to that of an 87.5-dB SPL 1-kHz tone (Robinson & Dadson, 1956) to produce Sets H5–H8, respectively.

Tones were digitally generated at a rate of 20 kHz and converted to voltages using a Tucker Davis (T/D) sound system. All tones were

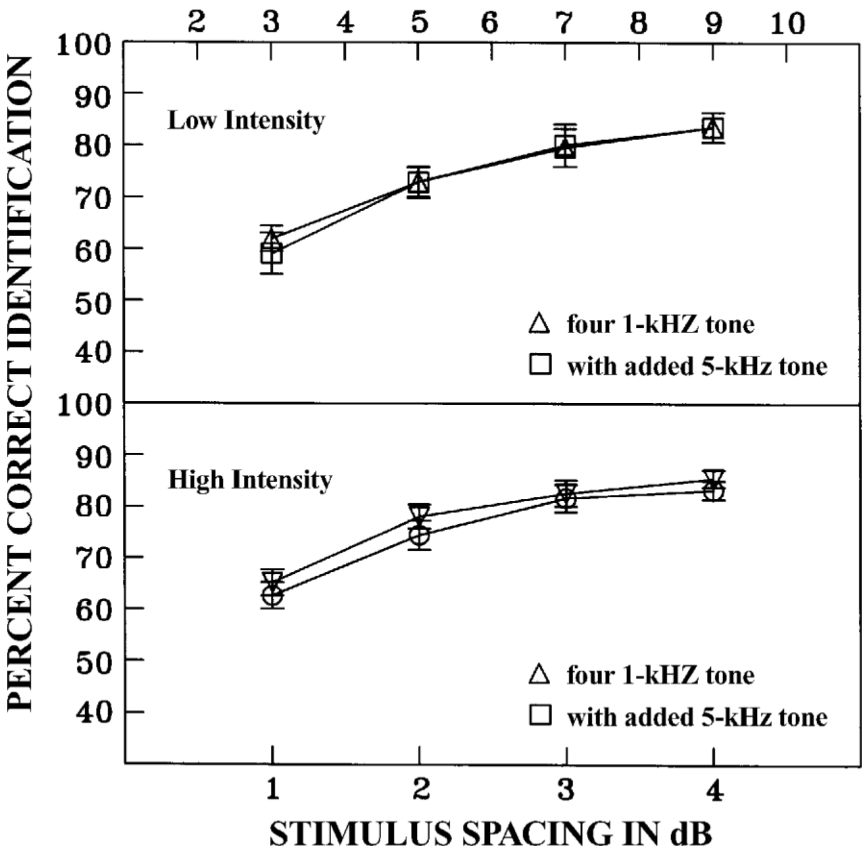

Figure 2. Percent correct identification in Experiment 1 as a function of the spacing of the four 1-kHz tones in a set for the low-intensity base set (upper panel) and the high-intensity base set (lower panel), both with and without the addition of a 5-kHz tone. Standard error bars are shown.

produced with a 10-msec rise/fall time and were attenuated to the proper level by means of a T/D programmable attenuator before being presented diotically via TDH 49 headphones to the participant, who was sitting in a sound-attenuating chamber. Tone durations were 500 msec for the 1-kHz tones and 1,000 msec for the 5-kHz tones.

Procedure. In both low-intensity and high-intensity conditions, the participants were informed that they would be hearing a series of tones and that they were to identify each tone by pressing the button assigned to that tone on the button box that was positioned directly in front of them. The softest 1-kHz tone in a set was always assigned to the leftmost button on the array, and the remaining 1-kHz tones were assigned to the buttons in ascending order of intensity going from left to right. In conditions in which there was a 5-kHz tone present, this tone was always assigned to the rightmost button on the array.

In each portion of the experiment, the participants heard a range of intensities from either the low-intensity condition or the high-intensity condition. In each case, they first identified the four 1-kHz tones alone (from Sets L1–L4 or H1–H4). Then, they identified the same four 1-kHz tones with the 5-kHz tone added into the array (Sets L5–L8 or H5–H8). When responding to only the four 1-kHz tones, the participants were informed that they would be hearing a series of tones and were to identify each tone immediately after it was presented. They were told about the correspondence between tones and buttons and then were given a 40-trial practice session in which each of the tones was randomly presented throughout the practice session a total of 10 times. They then continued to identify the four 1-kHz tones, completing a total of four blocks of 50 trials each.

After the participants completed the session with the four 1-kHz tones alone, the 5-kHz tone was added to the set. The participants first completed a practice session of 50 trials, with each tone being randomly presented 10 times throughout the practice session. Then, they completed five blocks of 50 trials each in the experimental conditions.

Throughout all conditions, following the presentation of each tone, the participants were required to identify it by pressing the button assigned to that tone. The participants were given 2.5 sec in which to respond, and feedback was provided by a light appearing for 200 msec above the correct button. If the participants failed to respond in the time allotted, they were required to start that particular block of 50 trials over again.

Results and Discussion

All participants were virtually perfect in identifying the 5-kHz tone, which is not surprising given that it differed in both frequency and duration. For the high-intensity condition, mean percentage of correct identifications of the 5-kHz tone, averaged over all 10 participants and all four ranges, was 99.7%; for the low-intensity condition, it was 99.6%.

Figure 2 plots the percentage of correct responses as a function of stimulus spacing for the 1-kHz tones when they alone were presented and when they were presented along with a 5-kHz tone. For both high-intensity and low-intensity conditions, performance improved with increases in stimulus spacing. The addition of a 5-kHz tone to a set of four 1-kHz tones appears to have a negligible effect on the accuracy of identification of the 1-kHz tones. For the high-intensity condition, the average reduction in accuracy was 2.35 percentage points; for the low-intensity condition, it was 0.53 percentage points.

The results indicate that accuracy in naming four tones identical in frequency but differing in intensity is hardly affected by the addition to the experiment of a fifth tone whose frequency and duration, but not loudness, differs substantially from that of the original four. Thus, increasing the number of stimuli in an identification experiment does not necessarily affect a listener's ability to identify the original members of the set. This implies that when reductions in performance are observed when a fifth stimulus is added, these reductions are most likely due to the characteristics of the added stimulus, and not to the addition of a stimulus per se.

In Experiment 1, the added stimulus differed in frequency and duration and had little effect on performance. In Experiment 2, the added stimulus differed in intensity, but not in frequency or duration from the original four. Intensity changes should, at least in some circumstances, change the gain on the nonlinear amplifier and produce changes in identification performance.

EXPERIMENT 2
Within-Channel Intensity Effects

Experiment 2 resembled Experiment 1 but for the identity and duration of the fifth tone. Here, the stimulus added to a low-intensity set was a 1-kHz 95-dB SPL tone. Thus, as in Experiment 1, the fifth tone was quite discriminable from the original four. The difference was that, in Experiment 1, the added tone was at a frequency remote from that of the original four but similar to them in loudness; in Experiment 2, the added tone was at the same frequency as the original four, but it differed markedly from them in loudness.

When a loud tone is added to a low-intensity set, we would predict that the amplifier gain would have to be turned down to avoid overloading the discrimination circuits. On the other hand, if a low-intensity tone is added to a high-intensity set, there is no need to alter the amplifier gain to protect against a sensory overload since the gain has already been set to protect against such an event. Thus, if the gain control's only function is to protect against sensory overload, the addition of a low-intensity tone to a high-intensity set should not have much effect on the identification of the high-intensity stimuli.

Method

Participants. Eight students and staff members at the University of Toronto in Mississauga (5 females, 3 males) served as participants. The participants ranged in age from 25 to 33 years. All reported normal hearing and had normal-looking audiograms. Each participant served in all conditions.

Apparatus and Stimuli. The stimuli for this experiment consisted of 1-kHz tones varying only in intensity. As in Experiment 1, there were 16 sets of tones. Four of these sets were identical to the four low-intensity sets in Experiment 1 that contained only 1-kHz tones (Sets L1–L4). Another four of these sets were identical to the four high-intensity sets in Experiment 1 that contained only 1-kHz tones (Sets H1–H4). In this experiment, another four sets were created by adding a 95-dB SPL 1-kHz tone to the four low-intensity sets (L5–L8). An additional four sets were created by adding a 30-dB SPL 1-kHz tone to the four high-intensity sets (H5–H8).

The duration of all tones was 500 msec. In all other respects, the stimuli and apparatus were identical to those of Experiment 1.

Procedure. The procedure was identical to the procedure used in Experiment 1, with the following exception. When the 30-dB SPL tone was added to a high-intensity set, it was assigned the leftmost response button. When the 95-dB SPL tone was added to a low-intensity set, it was assigned the rightmost button. Thus, buttons were assigned in ascending order of intensity proceeding from left to right.

Results

As in Experiment 1, the participants were virtually perfect at identifying the fifth, added tone. For the high-intensity conditions, mean accuracy in identifying the fifth tone, averaged over all 8 participants and all four ranges, was 99.4%; for the low-intensity conditions, mean accuracy was 99.9%.

Figure 3 plots the percentage of correct responses as a function of stimulus spacing for the 1-kHz tones when they were presented alone and when they were presented along with a fifth 1- kHz tone. As in Experiment 1, performance for both low-intensity sets and high-intensity sets improved with increases in stimulus spacing. Unlike in Experiment 1, however, the addition of a fifth tone, even though it was quite discriminable from the other four, reduced identification accuracy, with the reduction in accuracy being larger for the low-intensity condition (average reduction = 14.48 percentage points) than for the high-intensity condition (average reduction = 8.75 percentage points). To test the difference in accuracy reduction for the high- and low- intensity sets, for each of the 8 subjects, at each of the four corresponding stimulus spacings, we recorded whether the accuracy reduction was greater for the loud or the soft stimuli. This provided 32 binary comparisons, of which 1 was tied. Of the 31 determinate comparisons, 26 had the larger accuracy reduction when a high-intensity tone was added to the low-intensity set ($p < .0002$, by sign test). Thus, the addition of a fifth stimulus at the same frequency as that of the original four diminished the identifiability of those original four, even though the fifth was readily discriminated from them. Moreover, the effect was more pronounced when a fifth high-intensity stimulus interfered with the identification of four low-intensity tones than when a fifth low-intensity stimulus interfered with the identification of four high-intensity tones.

Discussion

In Experiment 1, in which the added stimulus differed in frequency and duration and was perfectly discriminable from the original four stimuli, the reduction in identification accuracy was negligible. When, however, the added

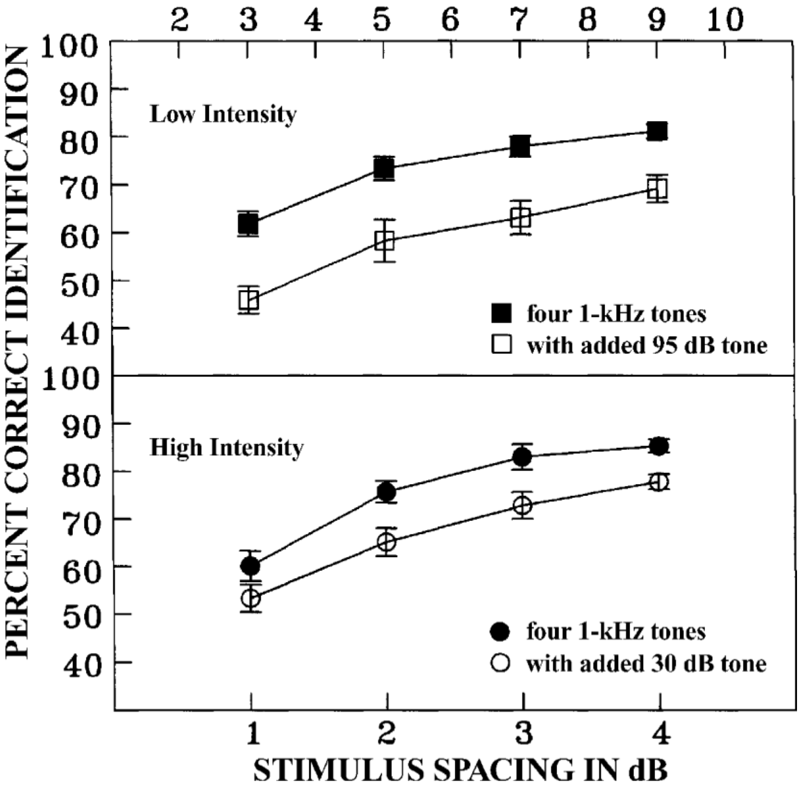

Figure 3. Percent correct identification in Experiment 2 as a function of the spacing of the four 1-kHz tones in a set for the low-intensity base set (upper panel) and the high-intensity base set (lower panel), both with and without the addition of a fifth 1-kHz tone. Standard error bars are shown.

stimulus was in the same frequency channel, but still perfectly discriminable from the other four because of the intensity separation between it and the original four tones, it nevertheless reduced identification accuracy. This suggests that the addition of a perfectly discriminable tone to a stimulus set will only affect intensity identification performance when it is within the same frequency channel as that of the four base stimuli.

The results of Experiment 2 for the sets of low-intensity tones are consistent with the predictions based on a nonlinear amplifier. The addition of a loud tone to a set of low-intensity tones would have forced a reduction in the amplifier's gain in order to protect the sensory system from an overload. This, in turn, would reduce the sensitivity of the sensory system to intensity differences among the low-intensity tones, resulting in a reduction in identification accuracy (see Parker & Schneider, 1994, for an example). The results for the sets of high-intensity tones are somewhat problematical. The reduction in accuracy that occurred when a low-intensity tone was added to the high-intensity tones is not readily predictable by the notion of a nonlinear amplifier. Since a change in gain is not required in this instance to protect the system from an overload, some other factor must be operative. One possibility is that the addition of another stimulus within a channel may produce an increase in variance along the decision axis. This could account for the reduction observed when a softer tone was added to the louder set. In any event, even though the added stimulus increased the stimulus range by approximately the same amount for both low-intensity and high-intensity conditions, this change in range had a much larger effect when the range was extended upward than when it was extended downward.

In the following experiments, we investigated the reasons for this asymmetry in performance. In Experiment 3, we varied the intensity of the 1-kHz tone added to both low- and high-intensity sets to change stimulus range without changing the number of stimuli.

EXPERIMENT 3
Within-Channel Range Effects

Experiment 3 resembled Experiment 2, with the following exceptions. First, only two sets of 1-kHz tones were used: Set L2 (low intensity) and Set H2 (high intensity). Second, the intensity of the fifth 1-kHz tone added to each of these sets was systematically varied to explore the effect of stimulus range on performance.

Method

Participants. Twenty students and staff members at the University of Toronto in Mississauga served as participants in this study. These participants ranged in age from 19 to 25 years and reported normal hearing and had normal-looking audiograms. Ten participants (6 females, 4 males) served in the low-intensity condition. The remaining 10 participants (6 females, 4 males) served in the high-intensity condition.

Apparatus and Stimuli. The apparatus used in this experiment was identical to that used in Experiments 1 and 2. Only two base sets of four tones were tested: a high-intensity set, H2 = {84.5, 86.5, 88.5, 90.5 dB SPL}; and a low-intensity set, L2 = {25, 30, 35, 40 dB SPL}. Seven additional sets of tones were created from the high-intensity set by adding a fifth 1-kHz tone whose intensity was one of the following seven values: 40, 50.5, 60.5, 70.5, 75.5, 80.5, and 82.5 dB SPL. Seven additional sets of tones were also created from the low-intensity set by adding a fifth 1-kHz tone whose intensity was one of the following seven: 45, 50, 55, 60, 70, 80, and 90 dB SPL.

Procedure. The procedure in this experiment closely resembled that used in Experiment 2. The participants were seated in a sound-attenuating chamber and were instructed that they would be hearing a number of tones presented over the headphones. They were told that they were to identify, with a buttonpress, the tones they heard. Each tone was assigned to a button on the basis of its intensity. The softest tone was assigned to the leftmost button, and the loudest tone was assigned to the rightmost button on the array for both of the base sets of tones and for the 14 augmented sets of tones. Feedback was presented on all trials.

In the first testing session, the participants completed the four-base-tones-alone condition. In each of the next seven testing sessions, they were presented with the original four tones augmented by one of the added tone intensities. The sequence of conditions with an added fifth intensity was counterbalanced across participants.

Results

When the fifth tone was added to the high-intensity set, the accuracy with which it was identified varied with its intensity. For the seven levels from 40 to 82.5 dB SPL, mean accuracies in identifying the fifth stimulus were 98.2%, 98%, 97.4%, 96%, 90.4%, 75.8%, and 63.6%. Thus, the participants were more accurate in identifying the fifth tone, the more remote it was from the unchanging four. A similar result was obtained when the fifth tone was added to the set of four low-intensity tones. For the seven levels ranging from 45 to 90 dB SPL, mean accuracies in identifying the fifth stimulus were 72.6%, 87.4%, 95%, 98.8%, 99%, 99.4%, and 99.6%. Again, the participants were more accurate in identifying the fifth tone, the more remote it was from the unchanging four.

Figure 4 plots identification accuracy for the four base tones as a function of stimulus range for the high-intensity and low-intensity base sets. (In computing percent correct for the loudest tone in the low-intensity base set, responses on Buttons 4 and 5 were counted as correct when Stimulus 4 was presented. Similarly, responses on Buttons 1 and 2 were counted as correct when Stimulus 2, the lowest intensity in the base set of high-intensity tones, was presented.) Percent correct for the base set of high-

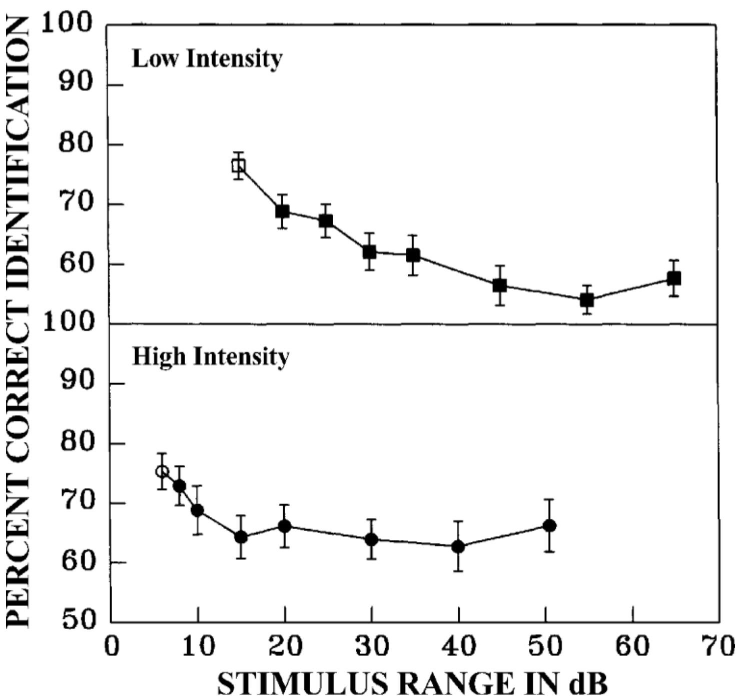

Figure 4. Percent correct identification in Experiment 3 for the four base tones in a set as a function of range in decibels for the low-intensity base set (upper panel) and high-intensity base set (lower panel). Results for the four base tones alone are shown by open symbols. Standard error bars are shown.

intensity tones (range = 6 dB) was 76.5%, approximately equal to the 75.3% accuracy for the base set of low-intensity tones (range = 15 dB). As the stimulus range was increased for the base set of high-intensity tones by adding a lower intensity tone, percent correct decreased up to a range of about 10 dB, before stabilizing at a value of approximately 65%. For the base set of low-intensity tones, however, percent correct continued to decline as range increased to around 50 dB, stabilizing at around 55%.

To confirm this description, we conducted repeated measures analyses of variance (ANOVAs) on percent correct. An ANOVA on the eight ranges of the low-intensity base set showed a main effect of range [$F(7,63) = 27.20$, $MS_e = 0.0020$, $p < .0001$]. When the number of ranges was decreased by eliminating the set with the lowest range (15 dB), the main effect of range was also highly significant [$F(6,54) = 13.99$, $MS_e = 0.0022$, $p < .0001$]. The main effect of range remained significant when the two lowest ranges (15 and 20 dB) [$F(5,45) = 10.29$, $MS_e = 0.0022$, $p < .0001$], three lowest ranges (15, 20, and 25 dB) [$F(4,36) = 5.12$, $MS_e = 0.0023$, $p < .003$], and four lowest ranges (15, 20, 25, and 30 dB) [$F(3,27) = 4.47$, $MS_e = 0.0022$, $p < .012$] were removed, but not when further deletions were made. Thus, percent correct accuracy declined with range until the range reached 45 dB. On the other hand, although there was a significant effect of range for the high-intensity base set when all eight ranges were included [$F(7,63) = 5.90$, $MS_e = 0.0034$, $p < .0001$] and when the number of ranges was decreased by deleting the smallest range (6 dB) [$F(6,54) = 3.83$, $MS_e = 0.0031$, $p < .003$], there were no significant range effects for further deletions, indicating that extending the range beyond 10 dB had no further effect. Thus, changing the range from 10 to 44.5 dB had no significant effect on performance for the high-intensity base set, whereas performance continued to decline for the low-intensity base set when the range was increased from 15 to 45 dB.

Discussion

"Effective" stimulus range. The Braida and Durlach (1972) model states that performance should decrease with "effective" range, where effective range is based on stimulus discriminability. In their preliminary model, effective range is defined as

$$\alpha(I_{\max}) - \alpha(I_{\min}) = \log_{10} I_{\max} - \log_{10} I_{\min}. \qquad (2)$$

Thus, effective range in the preliminary model is the difference in Bels between the highest and lowest intensities in the set. Note that this assumes that the mapping from physical intensity into sensory intensity is logarithmic (Fechner's law). Thus, pairs of stimuli, equally spaced in decibels should be equally discriminable (Weber's law). Because Weber's law does not hold for pure tones (e.g., Jesteadt, Wier, & Green, 1977), Braida and Durlach (1972) argue that a logarithmic mapping should be considered as a first-order approximation to $\alpha(I)$. When they reanalyzed their data after correcting for the near-miss to Weber's law, they concluded that a better approximation to $\alpha(I)$ is

$$\alpha(I) = k \log_{10}^{2}\left(\frac{I}{I_0}\right), \qquad (3)$$

where I_0 is the threshold intensity. In their data, the threshold intensity was 1.2 dB SPL, and the value of k was approximately 0.65. Because the near-miss exponent (0.10) characterizing our data is typical of those found in the literature (Parker & Schneider, 1980), we replotted percent correct accuracy as a function of Braida and Durlach's near-miss correction to the range formula (Equation 3). Note that, when the near-miss correction is used (see Figure 5), the effective ranges of the low-intensity and high-intensity sets are nearly equivalent. For the high-intensity base set, there are no further decreases in accuracy once the effective range exceeds 15. For the low-intensity set, there are declines in performance until the effective range reaches 55. Hence, the asymmetry in the range effect cannot be attributed to the near-miss to Weber's law.

A signal-detection model of range effects. To directly test the predictions of the Braida and Durlach (1972) model and to explore how range affected the discriminabilities of the stimuli within the base sets, we attempted to fit a signal-detection model to the identification experiment. In fitting this model, we combined Responses 1 and 2 when a stimulus was added to the high-intensity set, and we combined Responses 4 and 5 when a stimulus was added to the low-intensity set. We restricted our analysis to the tones in the base sets because their intensities were invariant across conditions. In order to obtain a sufficient number of responses in each cell, the data were aggregated over participants in these analyses. Thus, each of the eight ranges associated with a base set gave rise to a 4 (stimuli) × 4 (responses) matrix, with entries being the frequency with which stimulus i was identified by response j. These matrices were used in the signal-detection analysis.

In a standard signal-detection analysis of an identification experiment with four stimuli, it is assumed that each of the stimuli gives rise to a normal distribution of effects along a decision axis. The observer locates three criteria (c_1, c_2, and c_3) along the decision axis to separate the decision axis into four discrete response regions. In the usual representation of events along this decision axis, it is assumed that stimulus effects are normally distributed and that the standard deviations, σs, of all of the distributions are equal. In addition to fitting an equal variance model, we also fit a model in which the standard deviations were allowed to vary freely. Specifically, we set the mean of Stimulus 2, μ_2, to 0 and its standard deviation, σ_2, to 1, and we used the data to estimate μ_1, μ_3, μ_4, c_1, c_2, c_3, σ_1, σ_3, and σ_4. In the equal-variance model, we assumed $\sigma_1 = \sigma_3 = \sigma_4 = 1$.

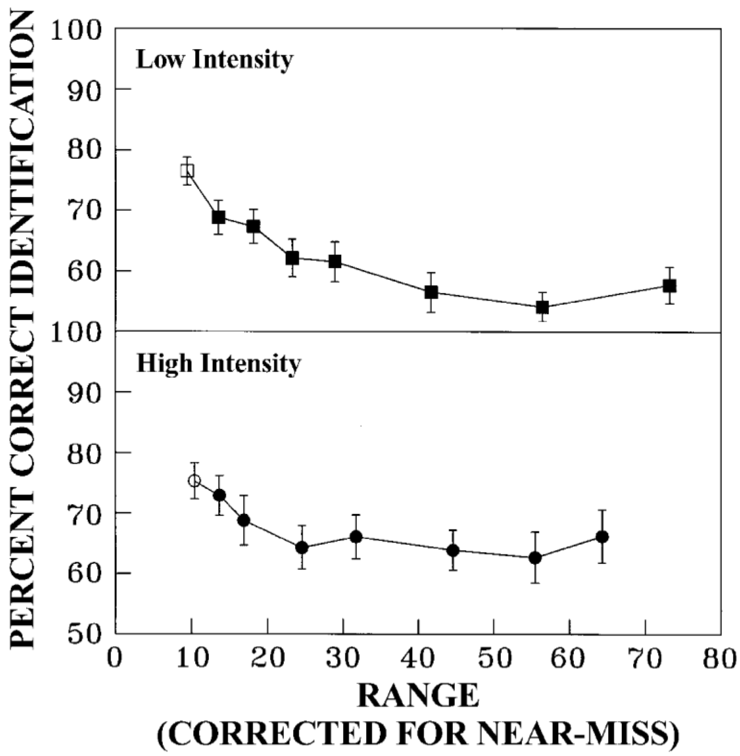

Figure 5. Percent correct identification in Experiment 3 for the four base tones in a set as a function of range in decibels for the low-intensity base set (upper panel) and high-intensity base set (lower panel) when the range has been corrected for the near-miss to Weber's law (see text). Results for the four base tones alone are shown in open symbols. Standard error bars are shown.

In each of these models, we searched for the parameter values that minimized the following quantity:

$$\chi^2 = \sum_{s=1}^{4} \sum_{r=1}^{4} \frac{(R_{s,r} - E_{s,r})^2}{E_{s,r}}, \tag{4}$$

where $R_{s,r}$ is the number of responses in response category r when stimulus s is presented. $E_{s,r}$, on the other hand, is the expected number of responses in category r when stimulus s is presented. If we define $c_0 = -\infty$, and $c_4 = \infty$,

$$E_{s,r} = \frac{N_t}{\sigma_s \sqrt{2\pi}} \int_{c_{r-1}}^{c_r} e^{-\frac{(x-\mu_s)^2}{2\sigma_s^2}} dx, \tag{5}$$

where N_t is the number of trials per stimulus. Note that the quantity, χ^2, in Equation 4 is the Pearson chi-square statistic, a commonly employed measure of goodness-of-fit to categorical data. A more detailed description of the fitting procedure is given in the Appendix.

For each of the low- and high-intensity sets, we found the parameter values for the equal-variance model that minimized Equation 4. These parameter values were then used to predict the probability of response r given stimulus s for all 16 combinations. The left-hand panel of Figure 6 plots the obtained probabilities, $R_{s,r}/N_t$, for the low- and high-intensity conditions against the predicted probabilities. If the fit were perfect, all points would fall on the positive diagonal. Note that the data points depart systematically from the positive diagonal, falling below it for predicted probabilities $<.4$ and above it for predicted probabilities $>.4$.

The relationship between the predicted and obtained probabilities for the unequal-variance model is shown in the right-hand panel of Figure 6. Although the fit to the positive diagonal is much improved, there are still substantial departures in the .5 to .8 range on the abscissa. When we looked at the best-fitting normal distributions for the unequal-variance model, we found in 15 of the 16 cases that the variances of the two outer stimuli were larger than those of the two inner stimuli.

Close inspection of the data suggested that the reason why the outer variances were larger than the inner variances was the large number of remote errors (e.g., identifying Stimulus 1 with Response 4). This suggested that the data could be better fit using a distribution with a higher kurtosis than the normal. Therefore, we replaced the normal distribution with the Laplace distribution (Evans, Hastings, & Peacock, 1993). The Laplace distribution, like

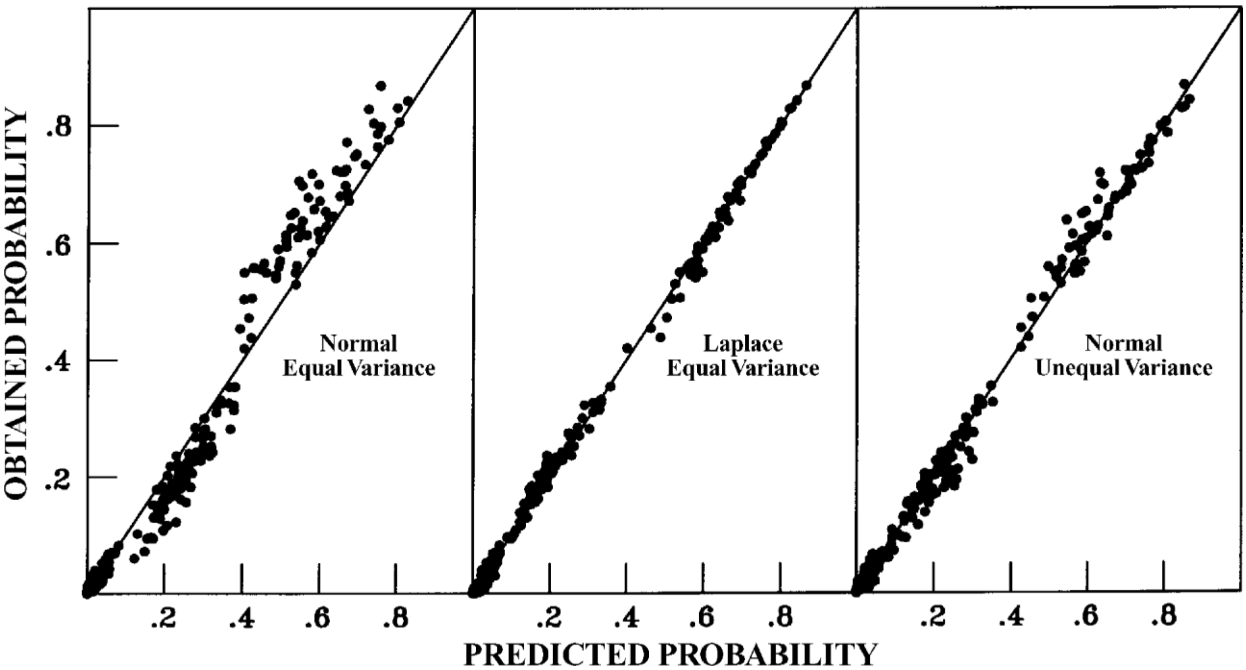

Figure 6. Obtained probability of a response given a stimulus as a function of the predicted probability for the normal equal-variance model (left panel), the Laplace equal-variance model (center panel), and the normal unequal variance model (right panel) for the data from Experiment 3. The lines with unit slopes and zero intercepts represent perfect prediction.

the normal distribution, is symmetrical with independent mean and variance, but has a kurtosis of 6 (twice that of the normal). Its probability density function is

$$D[x] = \frac{1}{\sigma\sqrt{2}} e^{\left(-\frac{\sqrt{2}|x-\mu|}{\sigma}\right)} dx. \tag{6}$$

Substituting this for the normal density function, we reanalyzed the data using Equation 4 and assuming equal variances for all four stimuli. The relation of predicted to obtained probabilities is shown in the middle panel of Figure 6. Figure 6 shows that the equal-variance Laplace model provides an excellent fit to the data. For the three models, we computed the sum of the squared differences between predicted and obtained probabilities. Those sums were .617 for the normal equal-variance model, .119 for the normal unequal-variance model, and .043 for the Laplace equal-variance model. Therefore, the signal-detection analyses that follow are based on the Laplace model.

In signal-detection theory, the discriminability of two stimuli is indexed by d', where d' is the difference between the means of the two stimulus distributions divided by their common standard deviation. Usually, the two distributions are assumed to be normal, but there is no reason why this calculation cannot be applied to two equal-variance Laplace distributions. We shall denote the analog of d' for Laplace distributions by d'_L.

We can use the model parameters to determine the discriminability between Stimuli 1 and 4,

$$d'_{L,(1,4)} = (\mu_4 - \mu_1)/\sigma.$$

Table 1 lists the values of $d'_{L,(1,4)}$ for the eight ranges used for each of the two base sets, along with the degree of sensitivity per Bel, δ_L, which we define as $d'_{L,(1,4)}$ divided by the separation of Stimuli 1 and 4 in Bels. Figure 7 plots $d'_{L,(1,4)}$ as a function of stimulus range for the low- and high-intensity sets. For low-intensity stimuli, $d'_{L,(1,4)}$ tends to shrink as range increases. For high-intensity tones,

Table 1
$d'_{L,(1,4)}$ and δ_L as a Function of Stimulus Range

Low-Intensity Base Set			High-Intensity Base Set		
Range	$d'_{L,(1,4)}$	δ_L	Range	$d'_{L,(1,4)}$	δ_L
15	5.30	3.53	6	5.03	8.38
20	3.96	2.64	8	4.44	7.40
25	3.71	2.47	10	3.98	6.64
30	3.08	2.05	15	3.41	5.69
35	2.95	1.97	20	3.73	6.21
45	2.64	1.76	30	3.48	5.80
55	2.64	1.76	40	3.26	5.44
65	2.71	1.81	50.5	3.71	6.18

Note—For the low-intensity set, $d'_{L,(1,4)}$ is an estimate of the discriminability between the lowest intensity (25-dB SPL) and the highest intensity (40-dB SPL) tones in the base set. For the high-intensity set, $d'_{L,(1,4)}$ is an estimate of the discriminability between the lowest intensity (84-dB SPL) and the highest intensity (90-dB SPL) tones in the base set. δ_L is the sensitivity per Bel. Stimulus range was determined by the intensity of the added tone (when present).

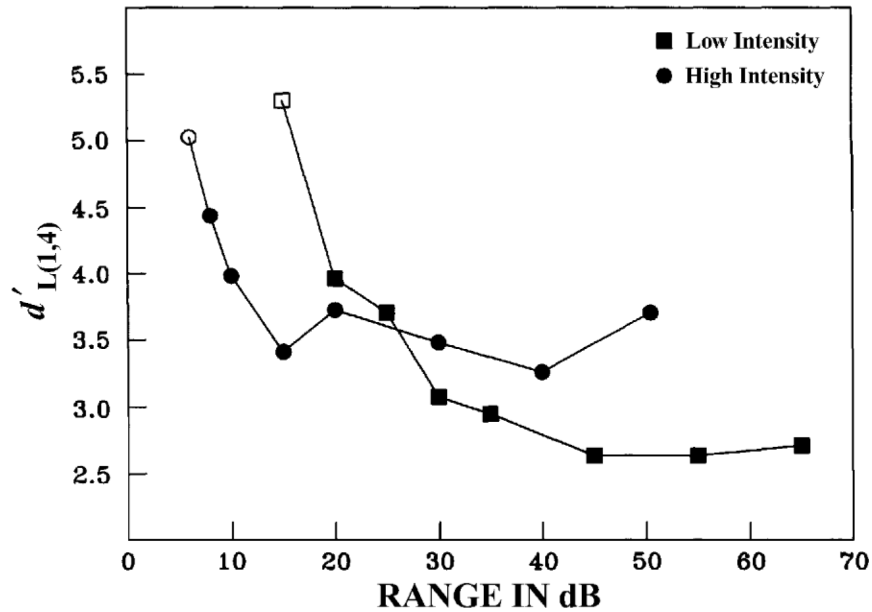

Figure 7. $d'_{L,(1,4)}$, **the distance in the Laplace equal-variance model along the decision axis between the 25- and 40-dB SPL stimuli in the low-intensity base set and between the 84.5- and 90.5-dB SPL stimuli in the high-intensity base set, as a function of stimulus range. Results for the four base tones alone are shown by open symbols.**

$d'_{L,(1,4)}$ decreases with stimulus range up to about 10 dB but remains essentially constant thereafter.

In both the Braida and Durlach (1972) model and the Gravetter and Lockhead (1973) model, the graph of the squared reciprocal of δ_L as a function of the square of the range should be a straight line. Figure 8 plots the squared reciprocal of δ_L as a function of R^2, when R is measured in Bels. The function for the low-intensity set

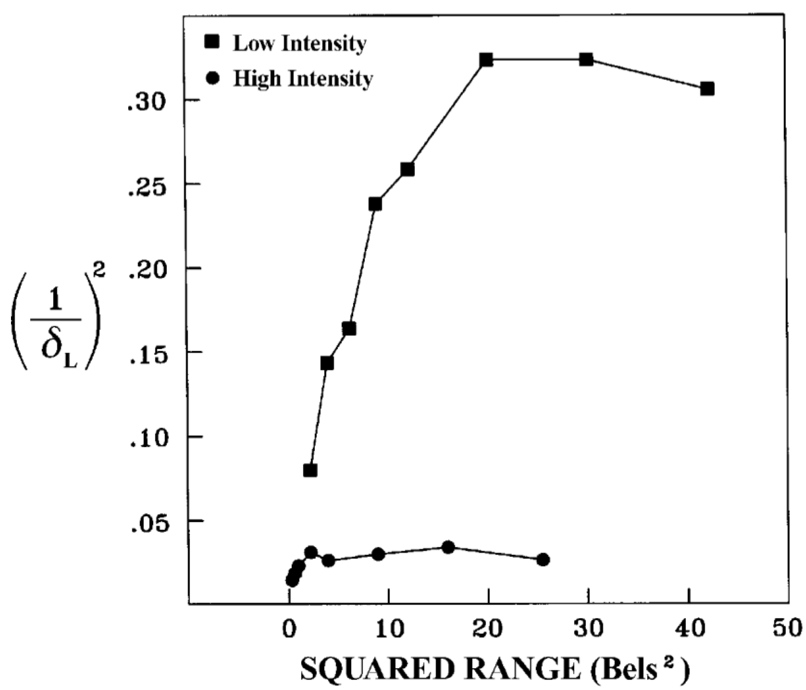

Figure 8. The reciprocal of squared sensitivity in the Laplace equal-variance model, δ_L**, as a function of squared range in Bels for high- and low-intensity base sets.**

is approximately linear over the first six points but flattens thereafter. The function for the high-intensity base set is low and flat over most of the range. Thus, the data for both base sets are inconsistent with both the Braida and Durlach model and the Gravetter and Lockhead model. Moreover, the functions for the two sets are quite dissimilar.

Top-down gain control. A decrease in identification accuracy (or in sensitivity per Bel) for the four original low-intensity tones as the intensity of the added tone is increased would be expected if one of the functions of the nonlinear amplifier was to protect against sensory overload. The amplifier gain would be reduced as the intensity of the added tone is increased. In the Parker and Schneider (1994) version of this amplifier, a reduction in gain lowers the exponent of the power function mapping stimulus intensity into sensory magnitude, thereby compressing the distances along the sensory axis. Thus, the results from the low-intensity conditions are in accordance with the predictions from a nonlinear gain control model.

The results from the high-intensity condition, however, are not predictable from a nonlinear gain control model when stimulus range is less than 8 dB. However, consistent with the model, there is no further change in identification accuracy or in discriminability once the range exceeds 10 dB.

EXPERIMENT 4
Extending Range Without Adding Categories

The addition of a stimulus in the previous experiments always entailed an increase in the number of stimuli to be identified and, as a consequence, the establishment of an additional criterion along the decision axis. The addition of a criterion along the decision axis could conceivably diminish performance. To evaluate the contribution, if any, of this factor, in Experiments 4A and 4B, we explored the effect of an added stimulus under conditions in which the added stimulus did not involve either an additional response category or the addition of another criterion along the decision axis. This entailed moving from an identification paradigm to a discrimination paradigm.

Experiments 4A and 4B differed with respect to stimulus predictability. If the range effect is due to a gain-control mechanism, and if this mechanism is fast acting, then we should not observe a range effect on discrimination performance if the occurrence of the added stimulus is entirely predictable. That is, if the observer knew exactly when an intense stimulus was expected, the gain could be turned down immediately prior to its expected appearance and then turned back up when it was not scheduled to appear. Therefore, the range effect should disappear when the added sound is predictable. In Experiment 4B, we investigated the consequences of predictability on the range effect.

Experiment 4A: Extending Range by Stimulus Substitution

In the baseline condition of Experiment 4A, the listener's task was to identify the interval that contained the louder of two 1-kHz tones in a two-interval forced-choice experiment. Once baseline performance had been established, one of the stimuli was replaced by a third stimulus on one third of the trials. To illustrate this procedure, consider a situation in which the listener is asked to choose the louder of two tones whose intensities are 25 and 28 dB SPL. Suppose that the listener correctly identifies the 28-dB SPL tone as the louder tone 89% of the time. Now suppose we change the paradigm so that on two thirds of the trials we present the 25- and 28-dB SPL stimuli, whereas on the other third we present a 25- and 95-dB SPL stimulus. The listener is made aware of the change but told that the task remains the same: She or he is to identify the interval containing the louder tone. Note that the range of stimuli the listener encounters has been extended but that the task requirements have not. The question then is whether the addition of the 95-dB SPL 1-kHz tone will affect discrimination accuracy on those trials in which the 25- and 28-dB SPL tones are presented.

We also tested intensity discrimination when the baseline pair of 1-kHz tones was high in intensity (e.g., 92 and 93.5 dB SPL). Again, after baseline performance on this task was established, we replaced the 92-dB SPL tone with a 25-dB SPL 1-kHz tone on one third of the trials. The listener was made aware of the change and told to continue to choose the louder tone. Hence, in this instance, the range was extended in a downward direction, but, again, no additional response category was added.

Finally, to check whether the range effects found in this experiment were limited to within-channel stimulus additions, we also conducted sessions in which the substituted stimulus had a frequency of 5 kHz.

Method

Participants. Thirteen students and staff (6 females, 7 males) associated with the University of Toronto Psychology Department participated. All were between 21 and 35 years of age.

Apparatus and Stimuli. The apparatus was the same as that used in the previous experiments. In the baseline condition, a two-interval forced-choice procedure was used to determine baseline performance in an intensity discrimination experiment. The standard stimulus (a 1-kHz tone) could take on one of two values: 25 or 92 dB SPL. A comparison stimulus was selected for each of these two standards (see the Procedure section below) that would result in a discrimination accuracy between 75% and 90%. Both the standard tone and the comparison tone had durations of 500 msec.

Performance on the high-intensity baseline condition was independently determined on each of 2 days. On one of the days, the high-intensity baseline condition was followed by an experimental condition in which the 92-dB SPL standard was replaced by a 30-dB SPL 1-kHz tone on one third of the trials. On the other day, it was followed by an experimental session in which the 92-dB SPL standard was replaced by a 30-dB SPL 5-kHz tone on the same portion of trials. These two experimental sessions are referred to as the *high-intensity 1-kHz substitution* and the *high-intensity 5-kHz substitution*, respectively. Note that each experimental condition had an independently determined baseline.

Performance on the low-intensity baseline condition was also independently determined on each of 2 different days. On one of the days, the baseline session was followed by an experimental condition in which the comparison tone was replaced by a 95-dB SPL 1-kHz tone on one third of the trials. On the other day, the comparison tone was replaced by a 95-dB SPL 5-kHz tone on the same proportion of trials. These two experimental sessions are referred to as the *low-intensity 1-kHz substitution* and the *low-intensity 5-kHz substitution*, respectively.

Procedure. The participants completed the four conditions in blocks. In each block, the participants first completed the baseline conditions in which two tones were presented in a two-interval forced-choice paradigm and the participants were asked to identify the louder of the two tones. The participants recorded their responses by means of a three-button box, which they held in their hands throughout the experiment. The participants began the trial by pressing the middle button on the box, and, 500 msec later, they were presented with two intervals in which the two tones were presented. The first interval, lasting 500 msec, was signified by a light coming on above the left button of the button-box. The second interval (also 500 msec), which began 50 msec following the termination of the first interval, was signified by a light above the right button on the box. The participants were required to press the button representing the interval containing the louder of the two presented tones. Response time was unlimited, and the next trial did not begin until the participant again pressed the middle button.

Thirty practice trials with feedback served to familiarize the participants with the operation of the button box and the two intensities they were to identify. Following the practice session, the participants completed 150 test trials.

In each of the two high-intensity baseline conditions, the participant completed a block of 150 trials in which the standard sound was the 92-dB SPL 1-kHz tone. Starting with a 94-dB SPL comparison tone, the intensity of the comparison tone was varied block by block until a level was found for which the participant's accuracy was above 75% but below 90%. In the experimental block following the high-intensity baseline block, the number of trials was increased to 225, and a third tone was presented in place of the 92-dB SPL standard on one third of these trials. Thus, throughout the experimental blocks of the high-intensity conditions, the loudest tone remained the tone producing accuracy within the 75%–90% range in the baseline block of this condition. Meanwhile, on two thirds (150) of the trials, the softer tone was the same 92-dB SPL tone used in the baseline block; on the remaining one third (75) of the trials, it was a 30-dB SPL tone. In one session, the 30-dB SPL tone had a frequency of 1 kHz; in the other, the frequency of the 30-dB SPL tone was 5 kHz.

In the low-intensity baseline blocks, the standard was a 25-dB SPL 1-kHz tone. Starting with a comparison level of 29 dB SPL, the intensity of the comparison stimulus was varied block by block until a level was found for which the participant's accuracy was above 75% but below 90%. In the experimental block following the low-intensity baseline block, a 95-dB SPL tone was substituted on one third of the trials for the comparison stimulus. The participants were still to identify the louder of the two tones. In one session, the 95-dB SPL tone had a frequency of 1 kHz; in the other session, the frequency of the 95-dB SPL tone was 5 kHz.

The four experimental sessions were conducted on different days. On each day, a stimulus level for the comparison stimulus that resulted in a percent correct score between 75% and 90% was determined in the first blocks. This was immediately followed by an experimental block.

Results and Discussion

Because the four experimental conditions were conducted on separate days, baseline performance for the condition in question was determined on each test day. The average accuracies for the four baseline conditions were 82%, 81%, 83%, and 86% for the low-intensity 1-kHz substitution, low-intensity 5-kHz substitution, high-intensity 1-kHz substitution, and high-intensity 5-kHz substitution, respectively. Thus, with the possible exception of the high-intensity 5-kHz substitution, average baseline performance was comparable across conditions.

On the one third of the trials in which a new tone was substituted for one of the baseline tones, the participants performed with almost perfect accuracy. Average accuracy on substitution trials ranged from 99.4% to 99.8% over the four conditions.

Now we consider performance on the remaining two thirds of the trials, when the standard and comparison tones were identical to those in the baseline conditions, and compare this performance to that in the baseline condition. The reductions in accuracy from the baseline levels are shown in Figure 9 when the substituted tone's frequency was 1 kHz (filled circles) and 5 kHz (unfilled circles). Figure 9 shows that reductions in accuracy were larger for the 1-kHz substitution than for the 5-kHz substitution and when the baseline discrimination was between two low-intensity tones.

Sign tests (two-tailed) showed that accuracy was significantly reduced by the added tone in both of the low-intensity conditions but in neither of the high-intensity conditions. In the low-intensity conditions, accuracy was lower with than without the 1- kHz substitution for all 13 listeners ($p < .001$) and for 12 of the 13 for the 5-kHz substitution ($p < .004$). However, for the high-intensity conditions, accuracy was lower for only 8 of the 13 listeners for the 1-kHz substitution ($p > .58$) and 7 of 13 for the 5-kHz substitution ($p > .99$). Finally, for 11 of the 13 participants ($p < .03$) in the low-intensity condition, there was a greater reduction in accuracy with the 1-kHz substitution than with the 5-kHz substitution.

The results of Experiment 4A show that the substitution of an intense tone for the comparison stimulus in a low-intensity discrimination experiment has an adverse effect on the discrimination even when the introduction of the tone does not require the addition of a criterion along the decision axis. Moreover, the reduction in accuracy is greater for a tone that is in the same channel (the 1-kHz substitution) than for a tone from a different channel (5-kHz substitution). By way of contrast, the addition of a low-intensity tone for the standard stimulus in a high-intensity discrimination experiment had no significant effect on performance for either within-channel (1-kHz) or cross-channel (5-kHz) substitutions.

The results from Experiments 1–4A show that the addition of a high-intensity tone to a set of low-intensity tones reduces the discriminabilities among the low-intensity tones. Note, however, that in all of the cases examined so far, the occurrence of the added or substituted tone was unpredictable. In the identification experiments (Experiments 1–3), the added tone occurred with a probability of .2 on a trial. In Experiment 4A, it occurred on one third of the trials. In Experiment 4B, we examined the effect of the added tone's predictability on performance accuracy.

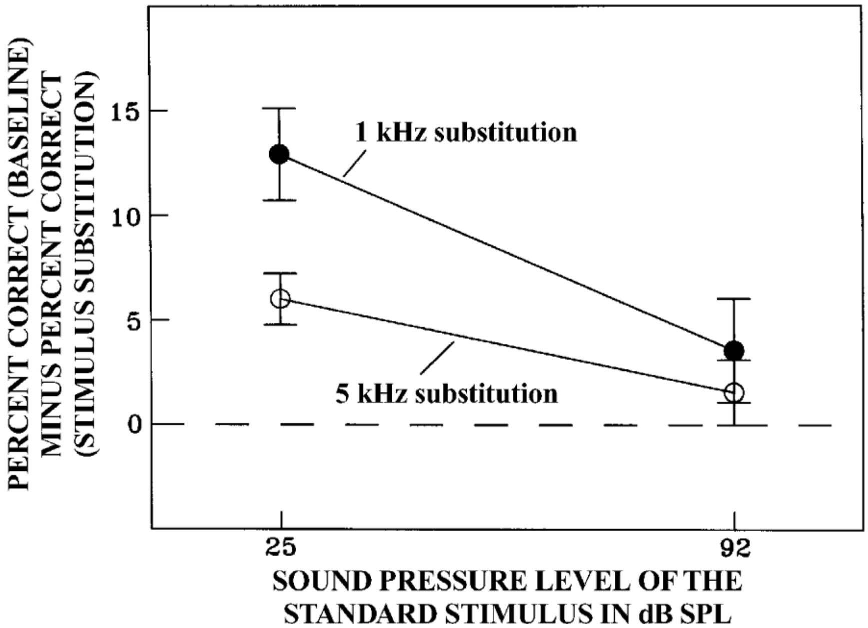

Figure 9. Difference in percent correct between the baseline condition in an intensity-increment experiment (Experiment 4A) and the experimental condition in which a third tone was substituted for one of the two tones. The substituted tones were of two different frequencies, 1 kHz (filled circles) and 5 kHz (unfilled circles), and greatly extended the range in each condition (see text). Standard error bars are shown.

Experiment 4B: Extending the Range With a Warning Tone

In Experiment 4B, listeners participated in an intensity discrimination experiment with and without a warning tone. There were two intensity conditions: a low-intensity discrimination and a high-intensity discrimination. For the low-intensity discrimination, the warning tone was a high-intensity 1-kHz tone in one condition and a high-intensity 5-kHz tone in a second condition. For the high-intensity discrimination, the warning tone was either a low-intensity 1-kHz tone or a low-intensity 5-kHz tone.

Method

Participants. Ten students and staff (5 females, 5 males) associated with the University of Toronto Psychology Department participated. All were between 21 and 35 years of age.

Apparatus and Stimuli. The apparatus was the same as in Experiment 4A. For the high-intensity discrimination, the standard stimulus was a 1-kHz 92-dB SPL tone. For the low-intensity discrimination, the standard intensity was a 1-kHz 25-dB SPL tone. The high-intensity warning tones, when present, were 95-dB SPL 1- and 5-kHz tones. The low-intensity warning tones were 30-dB SPL 1- and 5-kHz tones.

Procedure. The procedure in this experiment was identical to that of the baseline conditions of Experiment 4A, except that, in this experiment, a warning tone was included in the experimental blocks to indicate that the test stimuli were about to be presented. The participants were instructed to pay no attention to the warning tone and to indicate with a buttonpress the interval containing the louder of the two tones presented. A testing session consisted of 30 practice trials and 150 test trials.

In the baseline blocks for the high-intensity discrimination, the standard was a 92-dB SPL 1-kHz tone. Starting with a 94-dB SPL comparison tone, the level of the comparison was varied block by block until a level was found for which the participant's accuracy was above 75% but below 90%. In the experimental block that followed, a 30-dB SPL tone was played as a warning tone before the first interval. The participants were not required to make any response to the warning tone. In one session, the 30-dB SPL warning tone's frequency was 1 kHz; in the other, its frequency was 5 kHz.

In the baseline blocks for the low-intensity discrimination, the standard was a 25-dB SPL 1-kHz tone. Starting with 29 dB SPL, the comparison sound was varied block by block until a level was found for which the participant's accuracy was above 75% but below 90%. In the experimental block that followed, a 95-dB SPL warning tone alerted the participants that the first interval was about to be presented. In one session, the 95-dB SPL warning tone's frequency was 1 kHz; in the other, its frequency was 5 kHz.

The sequence of events on a trial was as follows. Five hundred milliseconds after the participant pressed a button to initiate a trial, a 500-msec warning tone was presented. Fifty milliseconds later, this was followed by two 500-msec trial intervals separated by 50 msec, and the participant indicated which interval contained the louder tone. For baseline sessions, the warning tone was omitted, and the two intervals were presented 500 msec after the trial-initiating buttonpress. The four conditions, which consisted of baseline sessions followed by an experimental session, were presented on separate days.

Results and Discussion

Performance accuracy for the two baseline conditions for the low-intensity discrimination averaged 84% and 83% for the baseline conditions preceding the addition of 1- and 5-kHz warning tones, respectively. For both of the

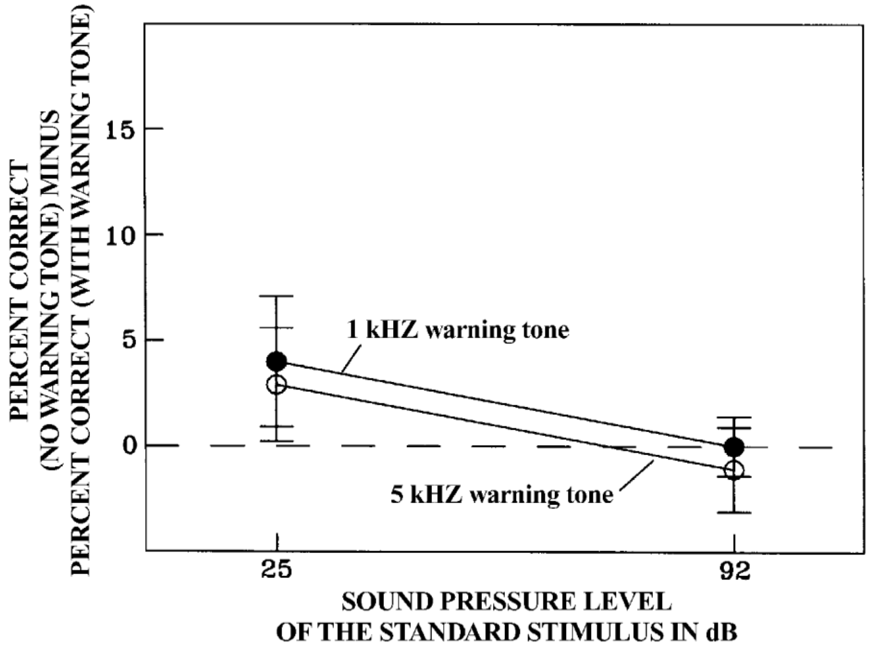

Figure 10. Difference in percent correct in an intensity-increment experiment (Experiment 4B) between the baseline condition (no warning tone) and the experimental condition (warning tone present). Warning tones were of two frequencies: 1 kHz (filled circles) and 5 kHz (unfilled circles). Standard error bars are shown.

high-intensity baseline conditions, performance accuracy averaged 84%.

Figure 10 plots the mean reduction in accuracy due to the introduction of a warning tone. Sign tests indicated that in none of the cases did the presence of a warning tone significantly affect performance ($n = 10$ for each test; $p > .34$ in all instances).

In Experiments 4A and 4B, the participants in the low-intensity discrimination conditions were asked to indicate the louder of two low-intensity stimuli when there was either an occasional substitution of a 1-kHz 95-dB SPL tone for the comparison tone (Experiment 4A) or a consistent presentation of a 1-kHz 95-dB SPL warning tone (Experiment 4B). Thus, in Experiment 4A, the 95-dB SPL tone appeared unpredictably in one of the two intervals of a forced-choice intensity discrimination, whereas in Experiment 4B, it reliably preceded the two intervals. A fast-acting gain control mechanism should be able to turn down the gain for the warning tone and then quickly reset for the two intervals of the forced-choice procedure. Thus, if a rapid adjustment is possible, the presence of a high-intensity warning tone in a low-intensity discrimination experiment should have a negligible effect on performance, as it did in this experiment.

On the other hand, when the 95-dB SPL tone substitutes for one of the tones in the two-interval forced choice, its occurrence is unpredictable. Therefore, if the gain control mechanism is to protect against sensory overload, the gain must be turned down during the interval, which, according to the model, would adversely affect discrimination on those trials in which the 95-dB SPL stimulus did not occur. Thus, the results of Experiments 4A and 4B are consistent with the notion of a rapidly adjustable, nonlinear amplifier whose gain is under top-down control.

GENERAL DISCUSSION

In the experiments reported here, a 1- or 5-kHz stimulus was (1) added to a set of four 1-kHz tones in an identification experiment (Experiments 1–3), (2) substituted for one of two tones in an intensity discrimination experiment (Experiment 4A), and (3) used as a warning tone in an intensity discrimination experiment (Experiment 4B). A consideration of results across these four experiments leads to the following generalizations.

Effects of Stimulus Additions and Substitutions

When a fifth stimulus is added to a set of four at a frequency remote from that of the initial four, it has essentially no effect on identification for the original four. Thus, the addition of a criterion or of a response category does not inevitably degrade identification performance in the base set of four.

When the fifth stimulus is at the same frequency as the original four but remote from them in intensity, it does adversely affect performance. Part of this effect may be due to the addition of a criterion or response category within an auditory channel. However, this cannot be the sole explanation, because reduction in accuracy is much greater when a loud tone is added to four soft ones than when a soft tone is added to four loud ones.

Also, within a single frequency channel, substituting a very high-intensity tone for the louder of two soft tones in a discrimination experiment degrades discrimination performance far more than does substituting a very low-intensity tone for the softer of two loud tones. Hence, the asymmetry observed in the identification experiments holds even without the addition of a response category or criterion.

However, when the substituted tone in a discrimination experiment (either loud or soft) is at a remote frequency, it has little effect on discrimination performance. Hence, as observed in the identification experiments, accuracy is affected primarily when the added (or substituted) stimulus is within the channel.

Finally, using the very loud or soft tone as a warning stimulus in the discrimination experiments does not affect performance. Thus, the mere presence of loud tones in the auditory channel does not suffice to degrade soft tone discrimination.

Range Effects

In these experiments, stimulus range was approximately the same when a high-intensity stimulus was added to a set of soft tones as when a low-intensity stimulus was added to a set of loud tones. Thus, stimulus range per se cannot account for the asymmetry in identification accuracy and in discrimination performance. Rather, in these experiments, it was the presence of unpredictable loud sounds in an auditory channel that mattered.

Top-Down Gain Control

A gain control mechanism, one of whose purposes is to protect the sensory system from overload, is capable of accounting for the effects produced by an upward range extension. We can hypothesize that an upward extension of the range would require that the gain be turned down to keep the system from overloading. Because the amplification is presumed to be nonlinear, such a reduction would reduce the spacing of the low-intensity tones along the decision axis, thereby adversely affecting performance, with the decrement in performance becoming larger as the upper limit of the range is increased. This would occur independent of whether or not the extension of the range required the addition of another response category. However, if the gain control could be adjusted rapidly, a range effect should be observed only when the occurrence of the high-intensity tone is unpredictable. Hence, we would not expect a high-intensity warning tone to adversely affect performance, because the gain could be turned down to accommodate the warning tone but turned up immediately after it. Thus, a nonlinear amplifier whose gain could be rapidly adjusted can account for all of the observed effects when there is an upward extension of the range within a channel. To account for the cross-channel effects, however, it would be necessary to assume that the gain controls on amplifiers serving different frequency regions were not totally independent, so that an intense off-frequency tone might induce a reduction in gain in the 1-kHz channel. This reduction in gain, however, should not be as large as that for a within-frequency upward range extension.

This gain control mechanism, however, cannot account for all of the effects observed when the range was extended in a downward direction in Experiment 3. If the only purpose of the gain control mechanism is to prevent sensory overload, a downward extension of the range should not affect the spacing among the stimuli in the set. Hence, identification performance should be unaffected. But the addition of a softer stimulus in the same channel as a set of four loud stimuli did reduce performance accuracy on the original four stimuli. A uniform decrease that was independent of the softer stimulus' intensity would be consistent with a general increase in variance along the decision axis due to the addition of a fourth response criterion. Indeed, for ranges of 10 dB or greater, the loss of accuracy due to the addition of the fifth softer stimulus was independent of range. However, there was a significant decrease in accuracy when going from an 8-dB range to a 10-dB range.

In addition to protecting the sensory system from overload, the set point of a nonlinear gain control can be adjusted to enhance the discriminability of stimuli presented at a particular intensity level (Parker & Schneider, 1994). So, for example, a listener who knew that the next stimulus would be within ± 5 dB of the previous one could adjust the gain control to maximize discriminability over that range. Nosofsky (1983, Experiment 1) compared participants' performances in two conditions of an absolute identification experiment whose 11 stimuli spanned a 50-dB range. In one condition, the random step condition, each of the stimuli was equally likely to occur on every trial. In a second condition, the small step condition, a stimulus was 5 dB above, 5 dB below, or equal to the previous stimulus (all with probability = 1/3). Thus, in the small step condition, every stimulus after the first was constrained to be within ± 5 dB of the previous one. Nosofsky indexed performance using d' for adjacent stimuli and found that d' values were considerably higher in the small step condition than in the random step condition. He attributed that difference to the participants' ability to focus their attention on a narrow intensity band. Top-down control over a nonlinear amplifier can also account for that result (Parker & Schneider, 1994).

The Laplace Density Function

The Laplace distributions in the analysis of Experiment 3 provided the best fit to the identification data and allowed us to keep the equal-variance assumption that is so useful in signal-detection analyses. To test the generality of the Laplace distribution's utility in analyzing identification experiments, we analyzed the data from Experiments 1 and 2 in which only four stimuli were presented

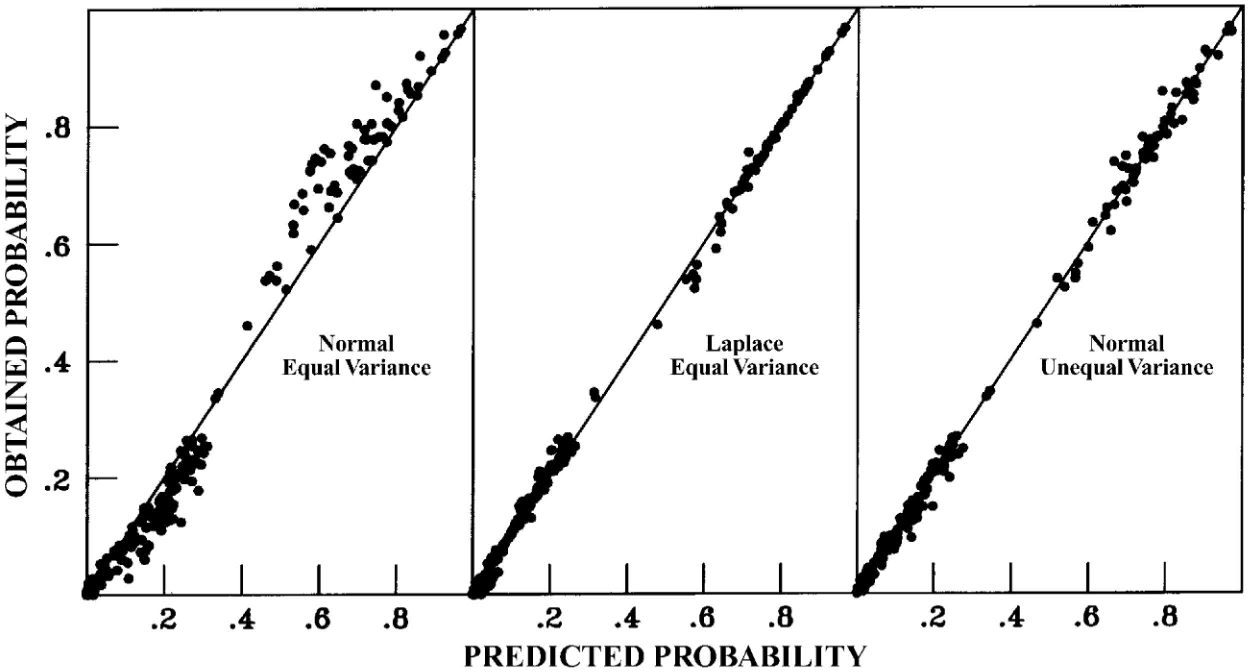

Figure 11. Obtained probability of a response given a stimulus as a function of the predicted probability for the normal equal-variance model (left panel), the Laplace equal-variance model (center panel), and the normal unequal-variance model (right panel) for the data from Experiments 1 and 2. The lines with unit slopes and zero intercepts represent perfect prediction.

but in which stimulus range was varied. Again, the three models (normal equal-variance, Laplace equal-variance, and normal unequal-variance) were fit to the 4 × 4 data matrices in each experiment. Figure 11 shows that the Laplace equal-variance model again provides the best fit, followed by the normal unequal-variance and normal equal-variance models (sum of squared differences = .039, .051, and .546, respectively). (As in Experiment 3, the fit of the normal unequal-variance model produced variances for the outer stimuli that were larger than those of the inner stimuli in 14 of 16 cases.) Thus, the Laplace equal-variance model provides the best fit, irrespective of whether range is extended by adding a fifth stimulus and response to the base set or by extending the range of the base stimuli.

The Locus of the Gain Control Mechanism

It is interesting that the notion of a nonlinear amplifier with top-down control is consistent with some views of middle-ear function and of cochlear mechanics and the role played by the olivocochlear efferents (see Dulon & Schacht, 1992, and Liberman & Guinan, 1998, for reviews). However, Scharf, Magnan, and Chays (1997), in reviewing case studies of patients whose olivocochlear bundles were severed, found little change in hearing, except for reduced ability to focus in on a particular frequency region. Thus, the locus of the amplification stage is still a matter of speculation.

Gain Control in Other Senses

It is also interesting to note that evidence is accumulating that suggests the existence of gain control mechanisms in other senses. In vision, a number of studies, both behavioral and physiological, suggest a gain control mechanism for contrast. For example, Ohzawa, Sclar, and Freeman (1982) showed that the effective operating range (the range of contrasts that produced response rates above the spontaneous rate and less than the saturation rate) of a number of cortical neurons shifted with shifts in mean contrast. Schneider, Parker, and Moraglia (1996) have shown that contrast matches across frequency (derived from magnitude estimates) were affected by the range of grating contrasts employed. Wilson and Humanski (1993) have proposed a negative feedback loop for receptive fields that can reduce the effective input to the receptive frequency. Moreover, they also postulate that the gain control mechanism for a particular receptive field also receives inputs from other units having similar spatial frequencies and orientations. Thus, it is interesting to note that, in both audition and vision, qualitatively similar models of gain control have been proposed to explain how these two sensory systems adjust their gain so as to operate efficiently over a wide range of inputs. It is also interesting to note that Hulshoff Pol, Hijman, Baaré, and van Ree (1998) have reported context effects that are consistent with the existence of a gain control mechanism for olfactory intensity.

A Revised Picture of Sensory Systems

The existence of gain control mechanisms in a number of sensory systems forces us to reevaluate the classical model of sensory processing, which assumes peripheral (i.e., sensory) processing to be more or less automatic and bottom-up. Top-down control of sensory events suggests a much more flexible and intelligent system, wherein the parameters of the sensory system can be adjusted to fit the task requirements. Thus, if the task requires fine discriminations to be made among a set of weak stimuli, sensory gain will be turned up. According to this viewpoint, sensory systems are not passive processors of information but rather should be considered as systems that can be directed, focused, and tuned to accomplish the task at hand.

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APPENDIX

In the fitting procedure, each of the parameters was varied sequentially over a wide range to find the value that minimized the quantity in Equation 4. The first model to be fit was the normal equal-variance model. The model assumed a set of starting values for the criteria and means (with all σs fixed at 1.0) and then varied c_1 over a wide range of values to find the value that minimized the χ^2 statistic. This value was substituted for the original value of c_1 in the starting configuration, and the procedure was repeated for c_2, and then for the rest of the parameters to be fitted, following the sequence c_1, c_2, c_3, μ_1, μ_3, and μ_4, decreasing the step size with each iteration. After proceeding once through this sequence, the sequence was repeated, using a smaller step size, until no further reductions in χ^2 were obtained.

The parameter values obtained in the fit to the normal equal-variance model were used as starting values for the normal unequal-variance model, σ_2 was set at 1.0, and σ_1, σ_3, and σ_4 were added to the parameter list. Finally, the same procedure used for the normal equal-variance model was used for the Laplace equal-variance model.

Note that this procedure guarantees convergence only to a local minimum.

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