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THE EFFECT OF NOISE BANDWIDTH ON AUDITORY INTENSITY DISCRIMINATION

by

Paul N. Schacknow

A dissertation submitted to the Graduate Faculty
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1975

This manuscript has been read and accepted for the Graduate Faculty in Psychology in satisfaction of the dissertation requirement for the degree of Doctor of Philosophy.

March 16, 1976
date

David H. Raab
Chairman of Examining Committee

March 16, 1976
date

Florence L. Denmark
Executive Officer

Prof. David H. Raab

Prof. Eric Heinemann

Prof. Eli Osman

Supervisory Committee

The City University of New York

Abstract

THE EFFECT OF NOISE BANDWIDTH ON AUDITORY INTENSITY DISCRIMINATION

by

Paul N. Schacknow

Advisor: Professor David H. Raab

Raab and Goldberg (1975) have noted that discrimination between the intensities of two bursts of noise was only slightly affected by changes in the bandwidth of the stimuli. Specifically, threshold signal-to-masker ratios improved by only 1 dB when the bandwidth of the bursts was increased from 500 Hz to 5000 Hz. This result differs sharply from what has been reported by Green (1960). In that paper, the reciprocity between signal power density and bandwidth was given by both theory and experiment to be 5 dB per log-unit of bandwidth. Since the signal and masker in the Raab and Goldberg study were gated together and filtered together, whereas the masking noise in Green's experiment was continuous and broad-band, it seemed worthwhile to examine the effects of bandwidth and presentation mode on noise intensity discrimination.

An experiment was performed to study intensity discrimination of band-limited, Gaussian noise signals presented in maskers of various bandwidths. In some conditions, signal and masker bandwidths were identical (homogeneous conditions); in other conditions, masker bandwidth was broader than signal bandwidth (heterogeneous conditions). Signal and masker (half-power) bandwidths ranged from 100 Hz to 10,000 Hz. The noise masker was either presented continuously throughout an experimental session or gated during the observation intervals. A forced-choice psychophysical procedure was employed to obtain thresholds for 100-msec noise signals at three levels of noise masker.

It was found that when signal and masker are filtered together, intensity discrimination of noise bands is relatively independent of both noise bandwidth and presentation mode of the masker. On the other hand, increasing signal bandwidth results in better discrimination performance in heterogeneous conditions with both continuous and gated maskers. Furthermore, the degree of intensity-bandwidth reciprocity depends on the mode of the masker under the heterogeneous conditions.

These results suggest modifications of the theoretical energy-detector model for noise-intensity discrimination (Green, 1960). Specifically, we consider the effects of neural compression ("whitening") of the stimulus by human observers, and optimal adjustment of the auditory filter to maximize the signal-to-masker ratio of the input stimulus.

While we are able to account for many features of the data with respect to bandwidth effects, our understanding of the effect of masker mode is less complete.

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A special note of thanks goes to Mr. Michael Bass for his conscientiousness in serving for many hours as a listener in the experiments.

I dedicate this dissertation to my mother, Evelyn, and father, Max.

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Chapter I

INTRODUCTION

Both pure tones and white noise have long served as the stimuli of choice in studies of intensity discrimination. A continuous, sinusoidal tone is completely specified by its fixed amplitude, frequency and phase, while noise is a stochastic process and thus stands at the other end of a scale of waveform complexity (Miller, 1947). Because there is a great deal of uncertainty about its parameters from moment to moment, noise is an information-rich stimulus (cf., Shannon and Weaver, 1949); its use as a signal can aid in determining which of the available stimulus cues are utilized by observers in intensity-discrimination experiments.

Empirically, the accuracy of subjects is limited when they seek to discover the presence or absence of a signal in an auditory detection task; both misses and false-alarms occur. Contributing to this less-than-perfect performance are constraints imposed by the random nature of the stimuli themselves. While it is undoubtedly true that the nervous system of a real observer adds some sort of "internal noise" to the decision process, "stimulus-oriented" theories of detection hold that the inherent trial-by-trial fluctuations of the stimuli are the cause of faulty performance.

Receivers have been described that are optimal for the detection of various kinds of signals in noise (Peterson, Birdsall, and Fox, 1954). These ideal receivers serve as models for comparison with the performance of real observers. Indeed, these receivers are optimal in the sense that no other receivers -- real or theoretical -- could achieve better performance, given the information provided by the stimuli. For the several types of signals they investigated, Peterson, Birdsall and Fox showed that an optimal receiver is one that bases its decisions on the computed likelihood ratio of inputs, or on some quantity that is monotonic with likelihood ratio. Specifically, for the case where the signal is itself a sample of noise, they demonstrated that the optimal receiver is an energy-detector.

Green has conducted several experiments which provide some support for the energy-detector model for the detection of a noise signal in a noise masker (Green, 1960; Green and Sewall, 1962). In the 1960 paper, he investigated the influence of the bandwidth, duration, and center frequency of a noise signal on intensity discrimination, and compared the results with predictions of the ideal-receiver model. He concluded: "For some constant detectability the equation generated by the model and one constant, an attenuation factor, closely fit the experimental data over the major range of the experimental parameters" (Green, 1960, p. 121).

In particular, the obtained reciprocity between signal power density and signal bandwidth (henceforth referred to as the "bandwidth effect") was approximately -5 dB per log-unit of bandwidth, the value generated by the energy-detector model. Raab and Goldberg (1975) found, however, that threshold signal-to-masker ratio decreased by only about 1 dB when noise bandwidth was increased tenfold. In the Raab and Goldberg study, the signal and masker were gated together and filtered together, whereas in Green's experiment, the masker was presented continuously and was broader in bandwidth than the signal. The receiver of the optimal model does not distinguish among the different experimental procedures employed by Green and by Raab and Goldberg; its performance is identical under either set of conditions. Thus it appeared worthwhile to examine in greater detail the effects of bandwidth conditions and mode of the masker on noise-intensity discrimination.

That Green disagrees with Raab and Goldberg on the magnitude of the bandwidth effect is not a trivial problem. Factors such as "internal noise" make it unlikely that human observers will perform as efficiently as ideal receivers. The usefulness of the mathematical models lies, however, in

(1) their ability to point out important stimulus parameters, and (2) their ability to predict the way in which manipulation of these parameters will affect changes in the detection process. If varying stimulus parameters changes the performance of a real observer in a manner that parallels the detection process for the ideal receiver, then the model has some validity. Green's (1960) results have contributed to the acceptance of the energy-detector as a valid analog of the human auditory system (Green and Sewall, 1962; Pfafflin and Mathews, 1962; de Boer, 1966; Henning, 1967); that the experiment of Raab and Goldberg (1975) neither confirms Green's findings nor supports a fundamental prediction of the model is therefore a matter of some consequence.

A. Energy-Detection Model for Audition

Green (1960) extended the Peterson, Birdsall and Fox (1954) energy-detector model for noise-intensity discrimination to the two-interval, forced-choice (2IFC) experiment. A burst of noise (the "signal") is added to a continuous background of noise (the "masker") in one of two temporal intervals. The receiver's task is to determine which of the intervals contained the added segment of noise. The model assumes that there is precise knowledge of stimulus parameters: signal starting time, duration, bandwidth and center frequency.

The ideal receiver incorporates an input filter with a "rectangular" passband that is adjustable with respect to its bandwidth and center frequency. The receiver matches its passband to that of the noise signal. Stimulus energy outside the signal passband has no influence on the detection process. Hence, the ideal observer performs equally well with noise maskers having either the same bandwidth as the signal (as in Raab and Goldberg, 1975), or a greater bandwidth than the signal (as in Green, 1960). Center frequency *per se* is also unimportant so long as the passbands of the receiver and signal are matched. The random fluctuations in stimulus energy that serve to limit performance are a function of signal bandwidth (W_s) but are independent of the center frequency (f_c) of the passband. Thus the ideal receiver exhibits the same thresholds for stimuli that have equal bandwidths but different center frequencies.

As the ideal receiver filters in the frequency domain, so is it selective in time. Stimulus energy is measured only during the two observation intervals -- the only time periods when the signal may occur. Since energy present at other times is ignored, it makes no difference to the ideal receiver whether the signal is added to a continuous masker

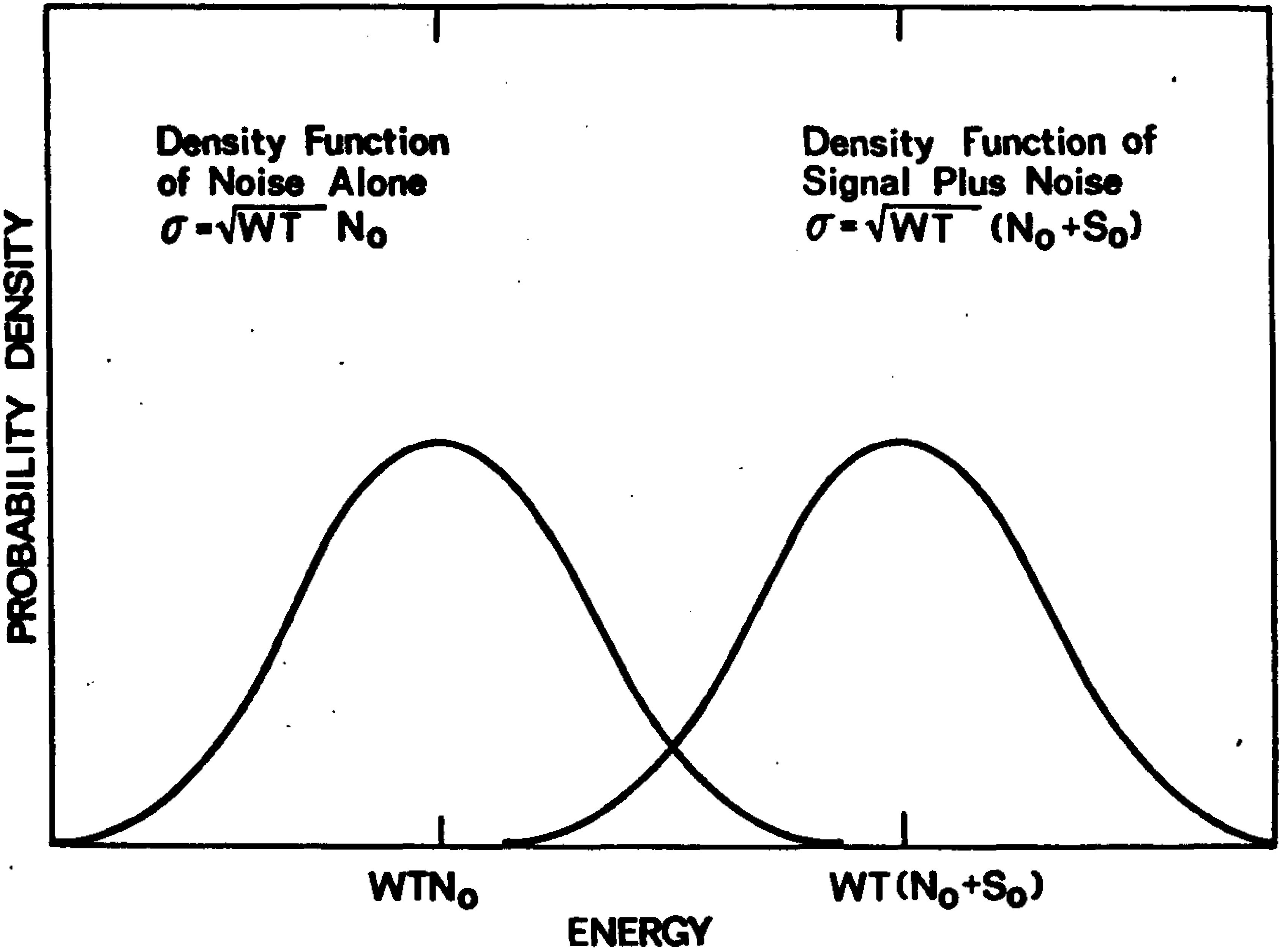
(Green, 1960) or to a gated masker (Raab and Goldberg, 1975).

In the 2IFC experiment, the interval containing the signal will, on the average, have the greater energy. However, statistical fluctuations will sometimes cause the the interval with the masker alone to have more energy than the interval with signal-plus-masker. Although an optimal detection strategy is employed, sample-to-sample variability of the noise nevertheless results in less than perfect performance. While it is more probable that the interval with the greater stimulus energy includes the signal, it is not certain.

Figure 1-1 shows the energy distributions conditional on either signal being presented along with the masker, or the masker present alone. The receiver functions as a statistical hypothesis-tester, measuring the stimulus energy during each of the observation intervals and reporting that the signal occurred in the interval with the greater energy. In deriving the means and variances of these distributions (as shown in the figure) Green makes certain simplifying assumptions about the nature of the random noise process. The noise source is assumed to be Gaussian with a uniform spectral-power density. The continuous waveform of the noise sample is then represented by a discrete approximation, using a finite series of $2W_sT$

Figure 1-1

Theoretical energy distributions for signal-plus-masker and masker alone. S_O and N_O are, respectively, average power per Hz for signal and for masker. The signal and masker waveforms are statistically independent (average r = 0).


Density Function of Noise Alone
$\sigma = \sqrt{WT}\ N_o$
Density Function of Signal Plus Noise
$\sigma = \sqrt{WT}\ (N_o + S_o)$
PROBABILITY DENSITY
WTN_o
$WT(N_o + S_o)$
ENERGY

terms in a Fourier expansion (where W_s is the signal bandwidth in Hz, and T is the signal duration in seconds). Green notes that the energy distributions in Figure 1-1 may be approximated by normal distributions if $2W_sT$ is greater than 30.

For the forced-choice paradigm the decision rule for optimal detection is to report the interval having the larger energy as the one containing the signal. The probability of a correct response by the ideal receiver is the likelihood of a random sample drawn from the signal-plus-masker distribution being greater than one selected from the distribution of masker energy alone. This probability is computed by considering the theoretical distribution of the set of differences between samples taken from the distributions of signal-plus-masker, and masker alone. Since both of these energy distributions are approximately normal, this difference distribution is also approximately normal. The mean of the difference distribution is equal to the difference between the means, and, since the noise samples in the two observation intervals are independent, the variance is simply the sum of the two variances. The normalized mean of the difference distribution is

$$M = \frac{\sqrt{W_s T}}{\sqrt{2}} \cdot \frac{S_o}{N_o} \cdot \frac{1}{\sqrt{1 + S_o/N_o + 1/2\ (S_o/N_o)^2}}, \qquad (1\text{-}1)$$

where S_0 and N_0 are the spectral power densities of the signal and maskers waveforms, respectively. For $S_0/N_0 << 1$, Equation 1-1 is approximated by

$$M \approx \frac{\sqrt{W_s T}}{\sqrt{2}} \cdot \frac{S_0}{N_0} . \qquad (1-2)$$

Thus: (1) The psychometric function -- percent correct as a function of S_0/N_0 -- is generated by the upper half of a normal ogive, since the difference distribution is approximately Gaussian. (2) The Weber fraction (S_0/N_0), for constant detectability, is determined by signal bandwidth (W_s) and duration (T). Furthermore, Weber's Law holds true. (3) There is perfect reciprocity between W_s and T; neither "M" nor the Weber fraction is affected by trading W_s and T for each other. (4) For fixed N_0, and constant detectability, the reciprocity between S_0 and either W_s or T is such that a tenfold increase in either W_s or T yields a half-log unit improvement in the Weber fraction.

The psychoacoustic literature on noise-intensity discrimination is reviewed in the next section of this chapter. First, the form of the Weber function is considered for both narrowband and wideband stimuli. Under what conditions is Weber's Law obtained? What are the effects of the mode of the masker (continuous vs. gated)? Does the form of the Weber function depend on the bandwidth conditions (i.e., whether $W_s = W_n$, or whether $W_s < W_n$)? Second, the literature on the reciprocity between signal intensity and duration is examined. The effects of masker-mode and bandwidth conditions on intensity-duration reciprocity are noted. Finally, data on the effect of bandwidth are reviewed. That both filtering and mode of masker influence intensity-bandwidth reciprocity is suggested from the experiments of Green (1960) and Raab and Goldberg (1975) previously cited.

B. Intensity-Discrimination Functions for Noise Stimuli

The form of the Weber function has long been of interest to psychophysicists. Conventionally, the Weber fraction is plotted as a function of stimulus intensity. Weber's Law is evidenced if the data are well fitted by a horizontal line.

Alternatively, the results can be plotted as an "intensity-discrimination function." Consider one generalized form of the Weber function,

$$\Delta I = kI^m . \tag{1-3}$$

Taking logarithms of both sides,

$$\log(\Delta I) = m \log(I) + \log(k) \ . \qquad (1-4)$$

This function is linear on a log-log plot and values for m and k can be estimated from experimental results using standard regression techniques.

The slope, m, of Equation (1-4) is found to equal unity for a variety of intensive continua (Fechner, 1860/1965). This is Weber's Law. That the Weber fraction decreases with intensity for pure-tone stimuli is, however, well established (Dimmick and Olson, 1941; Campbell, 1966; Campbell and Lasky, 1967; McGill and Goldberg, 1968 a, b; Viemeister, 1972; Schacknow and Raab, 1973; Penner, Leshowitz, Cudahy, and Ricard, 1974). Intensity discrimination functions for sinusoidal stimuli have slopes between 0.80 and 1.00. This so-called "near-miss" to Weber's Law has been used to support a neural counting model of detection (McGill, 1967).

The situation with respect to noise stimuli is somewhat more complicated. A number of studies have shown that the intensity difference-limen for wideband noise is independent of the level of the masker. Miller (1947) presented listeners with a continuous noise background to which a signal was added periodically. Signal and masker bandwidth were the same, 6850 Hz; signal duration equalled 1.5 seconds. Signal-to-masker ratios for fifty percent correct responses were interpolated from "yes"/"no" psychometric functions. Weber's Law was exhibited for intensities greater than 30 dB sensation level (SL). Discrimination thresholds were -9 dB to -10 dB. Harris (1950; see also Harris, 1963, pp. 40-41) essentially replicated Miller's experiment and obtained similar results. Pollack (1951) employed the method of limits in a decrement-detection experiment with broadband maskers ($W_s = W_n$). Subjects heard a five-second presentation of continuous, uninterrupted noise, which was alternated with a five-second presentation of periodically decremented noise. Decrements were 55 msec in duration and were preceded and followed by 45 msec of the standard noise. The size of the decrement was adjusted (in ascending and descending fashion) until subjects could not distinguish between the interrupted noise and a continuous noise of the same intensity. The Weber fraction was constant at -10 dB for noise intensities greater than 35 dB SPL (sound pressure level, or dB re 0.0002 microbar). Raab, Osman, and Rich (1963) used a 2IFC procedure to determine thresholds for 500-msec increments in a continuous noise masker. Signal and masker bandwidth were equal, 6900 Hz. The slope of the intensity discrimination function for the data as given in their

Figure 1 (for masker intensities greater than 16 dB SL) is 1.02; Weber's Law held true ($\Delta I/I$) = -9.2 dB) over a 60 dB range of stimulus intensities.

Intensity-discrimination functions for wideband noise have also been obtained using gated maskers. Postman (1946) studied the effect of changing the interstimulus interval (ISI) on intensity-discrimination at several levels of masker. Stimuli were wideband ($W_s = W_n = 2500$ Hz) noise bursts of one second duration. Psychometric functions were generated by the method of constant stimulus differences and DL's were obtained by interpolation. For ISI's between 1 and 2 seconds, the Weber fraction was about -10 dB over the range of intensities employed. Harris (1950; 1963, pp. 40-41) determined the form of the Weber function for one-second bursts of white noise bandlimited only by the response of the PDR-8 headphones worn by the listeners. Threshold S/N was constant at approximately -9 dB for masker levels greater than 10 dB SL. Small, Bacon and Fozard (1959) used the method of limits to obtain thresholds for alternating bursts (T = 1 second) of random noise presented at three levels: 5, 20, and 50 dB SL. Several bandwidths and center frequencies were utilized. The Weber fraction was essentially the same at the two higher levels of masker. For example, threshold S/N was about -8.4 dB for noise with an 8033-Hz bandwidth, at both 20 and

50 dB SL. For technical reasons, their 127-Hz band of noise could not be presented over a broad range of intensities; as a result, the experiment tells us little about the form of the Weber function for narrowband noise. Viemeister (1974) measured discrimination thresholds for 200-millisecond, wideband bursts of noise using a 2IFC tracking method. Stimulus bandwidth was determined by the frequency response of the TDH-39 headphone. Weber's Law held over at least an 80 dB range of masker spectrum-level. Moore and Raab (1975) also employed the 2IFC psychophysical procedure and obtained thresholds for noise bursts of 10 and 250 msec. Again, the stimuli were wideband, limited only by the response of the Sennheiser HD-414 headphone. They reported slopes of intensity-discrimination functions close to unity for both burst durations.

The Viemeister (1974) and Moore and Raab (1975) studies also provide data for the intensity discrimination of gated noise bands in the presence of bandstop background noises. In the Viemeister study the background was gated together with the signal and masker; in the Moore and Raab study the background was on continuously. In both experiments, the noise spectrum-level within the passband of the bandstop background was at least 10 dB more intense than the standard burst. Both studies reported Weber's Law for "notches" varying in width from about 100 Hz to 4000 Hz.

In an experiment by Zwicker (1956), subjects were asked to detect the presence of amplitude (envelope) variations in a noise-band carrier that was sinusoidally modulated at the rate of 3 Hz. The depth of modulation at threshold was used as an index of differential sensitivity. Zwicker reported constant detectability for masker levels greater than 30 dB SPL with wideband noise ($W_s \geq 2000$ Hz). The center frequency of the noise band was unimportant. Rodenburg (1972 a, b) confirmed Zwicker's finding using a white-noise carrier that was sinusoidally modulated at the rate of 10 Hz. Weber's Law was found with all listeners for noise intensities ranging from 20 to 60 dB SL. The average depth of modulation at threshold was approximately 3 percent. This value corresponds to a signal-to-masker ratio of about -9 dB.

With two exceptions, the experiments we have reviewed all provide support for Weber's Law with wideband noise. Green and Sewall (1962) reported slightly enhanced differential sensitivity at higher levels in a 2IFC experiment with continuous maskers. The increment signal lasted 100 msec; signal and masker bandwidths were the same, 4000 Hz. Thresholds were estimated from psychometric functions obtained at several masker levels. A 2 dB improvement in threshold S/N was noted over a 40 dB range of masker SPL. Viemeister (1974) plotted Weber functions for intensity discrimination of bandpass noise (650 Hz to 2000 Hz). Stimuli were 200 millisecond bursts of noise; thresholds were determined with a 2IFC tracking procedure. Weber fractions were found to improve slightly with increasing masker intensity.

The two intensity-discrimination experiments that have been performed employing narrowband noise differ with respect to the matter of Weber's Law. Bos and de Boer (1966) used a Bekesy audiometer to control the intensity of a noise signal (T = 125 msec) that was added periodically to a continuous background. Weber functions were determined separately for two bands of noise (200 Hz and 800 Hz) which were both centered at 1000 Hz. Threshold S/N varied inversely with masker intensity, although the effect was more pronounced for the narrower bandwidth. Maiwald (1967) used the amplitude-modulation technique with a 127-Hz band of noise centered at 1000 Hz. The sinusoidal modulation rate was 4 Hz. Detectability was independent of the level of the carrier.

In summary, four types of experiments have been performed to determine intensity difference-limens for noise. In the continuous-masker paradigm, subjects must choose the temporal interval believed to contain a signal that has been added to (or subtracted from) a background of continuous noise. With gated-maskers the listener's task is to select the more intense of two noise bursts. The third procedure employs a relatively intense bandstop noise to regulate the bandwidth of the signal and masker. This bandstop background may be presented either continuously or gated with the stimulus bursts. In the two studies reviewed above, the masker was gated together with the increment signal. The fourth method, that of amplitude-modulation, requires the subject to detect the presence of envelope fluctuations in a noise-band carrier. In all four types of studies, the bandwidths of the signal and masker were identical. The experiments employing amplitude-modulation used flutter rates of 10 Hz or less.

With wideband noise stimuli Weber's Law was obtained in all cases but two, Green and Sewall (1962), and Viemeister (1974). Differential sensitivity was found to be independent of masker level for all four psychophysical procedures.

With narrowband noise, the evidence for Weber's Law is not consistent. On the one hand, a "near-miss" to Weber's Law is found with continuous maskers, especially for the more narrowband stimuli. On the other hand, the amplitude-modulation technique yields Weber's Law for noise bandwidths as narrow as 127 Hz. No experiments have been performed with gated stimuli.

C. Intensity-Duration Reciprocity

Green (1960) studied the effect of duration on detection of a noise signal presented in a continuous masker (spectrum-level, 50 dB SPL). The signal and masker had equal bandwidths, 3862 Hz. For stimuli lasting between 3 and 300 msec, a plot of 10 log S_0/N_0 against duration had a slope of approximately -5 dB per tenfold increase in signal duration. Plots such as this are called "intensity-duration functions." Slopes of these functions have the dimension of dB/log-unit of T. Campbell (1963) replicated Green's experiment. Using maskers that were continuous and broadband, he found that a log-unit increase in duration produced an approximately 5.5 dB decrease in threshold S/N. Signal and masker bandwidths were equal, 5000 Hz; masker spectrum-level was 50 dB SPL.

Some experimenters have reported slopes of intensity-duration functions that are less than that predicted by the energy-detector model. A study by Macmillan (1973) using stimuli with a 5000-Hz bandwidth ($W_s = W_n$) gave intensity duration trades of -4.1 and -3.5 dB/log-unit of T for the detection of noise increments and decrements, respectively. Spectrum-level of the continuous masker equalled 62 dB SPL.

Raab and Goldberg (1975) presented their listeners with gated noise-maskers. The subjects showed an average improvement of about 3.7 dB in threshold S_o/N_o for a decade increase in duration with broadband stimuli ($W_s = W_n = 5000$ Hz). The corresponding intensity-duration function for narrowband noise ($W_s = W_n = 500$ Hz) had a slope of approximately -3.5 dB per log-unit of T.

The psychoacoustic literature also contains three studies which reported intensity-duration functions whose slopes are steeper than -5 dB/log-unit of T. Raab, Osman, and Rich (1963) used continuous maskers which were presented over a large range of intensities. Signal power needed to maintain 75 percent correct detection decreased at the rate of about 7 dB per log-unit of duration. Signal and masker bandwidths were both 6900 Hz. Rochester (1971) obtained a slope of about -8 dB per log-unit of T for the intensity-duration function. She employed continuous maskers at two spectrum-levels, 54 and 64 dB SPL. Rodenburg (1972) used gated maskers at 30 dB SPL. Both narrowband noise ($W_s = W_n = 300$ Hz) at several center frequencies and one relatively wide band of noise (equal to the passband of the headphones employed) were utilized. We have computed the slopes of intensity-duration functions for the data obtained at burst durations between 25 msec and 100 msec. Intensity-duration reciprocity, averaged across subjects and center frequencies, was -7.4 dB per log-unit of T for the narrowband stimuli. For the wideband noise the corresponding value, averaged across subjects, was -10 dB/log-unit of T.

An intensity-duration trade of -10 dB in signal power for a decade increase in signal duration indicates a complete reciprocity between S_o and T; performance is not affected by trading signal power and duration. Perfect energy-integration (such as was exhibited by Rodenburg's subjects listening to wideband stimuli) has often been reported in studies measuring absolute threshold (c.f., Olson and Carhart, 1966), but is not noted in any of the other studies on intensity-discrimination reviewed in this section.

To summarize, several studies using either continuous or gated maskers provide intensity-duration functions with slopes that are equal to or greater than that given by the energy-detection model. On the other hand, both Raab and Goldberg (using gated stimuli) and Macmillan (in his decrement-detection paradigm) found slopes that were appreciably shallower than predicted. There is no obvious way of reconciling these divergent findings with ideal receiver theory; the optimum-detector does not distinguish between increments and decrements, nor among the different psychophysical procedures employed.

D. Intensity-Bandwidth Reciprocity

Recall that the energy-detector model predicts improved discrimination as the bandwidth of the stimulus is increased. The principle involved is statistical; as the noise bandwidth is increased so is the number of Fourier components used to approximate its waveform. As a result, the relative variability (sigma-to-mean ratio) of the noise energy, measured from trial-to-trial, decreases as the square-root of bandwidth increases. The principle is the same as that involved in increasing the "power" or "sensitivity" of common tests of significance; the standard error of a statistic is inversely proportional to the square-root of sample size. Thus for constant detectability, the ideal receiver has an intensity-bandwidth reciprocity (or bandwidth effect) of -5 dB in signal power for a tenfold increase in signal bandwidth.

Studies of the magnitude of the bandwidth effect for Gaussian noise have employed a variety of experimental procedures. Green (1960) asked his subjects to indicate which of two temporal intervals contained a noise signal added to a broadband (W_h = 5143 Hz), continuous masker. Signal-to-masker ratios for 75 percent correct detections were computed by interpolation from psychometric functions.

Three values of signal bandwidth were used: 655 Hz, 3862 Hz, and 5143 Hz. While the absolute value of 10 log S_o/N_o necessary for 75 percent correct detections fell short of the model's predictions by about 5 to 6 dB, the observed change in detectability as a function of bandwidth was in reasonable agreement with the theory: about -4.3 dB in S_o per log-unit of signal bandwidth. Green concluded that the center frequency of the signal band had no effect on the shape or location of the psychometric function. We note again that the receiver of the ideal model both ignores stimulus energy outside the signal passband and listens only during the observation intervals; the results of Green's experiment support the notion that real observers are capable of doing these same things.

The 655-Hz noise bands were presented at several center frequencies; for this bandwidth, Green reports threshold S_o/N_o averaged across all center frequencies. Unfortunately, signal duration was 100 msec for the 655-Hz bands and 250 msec for the two wider bands. Green "adjusted" the thresholds for the 100-msec (655-Hz) signals, in order to compare them with those obtained with the 250-msec signals. Finally, the masker spectrum-level for the 655-Hz noise bands was 10 dB higher than the spectrum-level for the 3862-Hz and 5143-Hz bands. It is from these data -- given in Green's Table II (p. 128) --

that we have computed the value of -4.3 dB/log-unit of W_s for the intensity-bandwidth reciprocity. (Data for two subjects were averaged.) Needless to say, this value may not reflect the effect of only signal bandwidth on intensity discrimination.

Campbell (1964) also used a continuous masker that had a wider bandwidth (W_n = 4940 Hz) than the noise signals. Four narrowband signals were employed; each had a duration of one second and a bandwidth of 700 Hz. Signal passbands were centered at 500, 1000, 2000, and 3000 Hz. A wideband signal of 3200 Hz was also utilized. Discrimination thresholds for the 700-Hz signals depended on both the masker level and center frequency. At moderate intensities, the magnitude of the bandwidth effect compared favorably with the model's predictions. For example, the model forecasts a 3.3 dB lowering of threshold S/N when changing the signal bandwidth from 700 Hz to 3200 Hz; the observed shift in threshold was about -3.5 dB (at a masker sensation-level of 60 dB). At this sensation-level, performance was independent of center frequency.

Bos and de Boer's (1966) listeners heard continuous noise maskers, although the design of their experiment involved the use of a secondary masking source as well. The bandwidths of the signal and (primary) masker were identical; these stimuli were, in fact, generated from the same noise source, and had a uniform spectral-power density. A secondary, wideband-masker was presented at an intensity 20 dB below that of the primary masker (as measured in a band 1/3-octave wide surrounding the center frequency of the signal passband). The secondary masker was white below 500 Hz; above 500 Hz the spectrum-level of the secondary masker was attentuated at the rate of 3 dB/octave (pink noise). The experimenters felt that this low-level masking stimulus would prevent "any effect of distortion, etc., from creeping in ..." (p. 712), so that the influence of non-linearities in the auditory system would thereby be minimized. A Békésy audiometer was used to control the level of the signal (T = 250 msec). Noise bandwidth ranged from 10 to 10,000 Hz, each band being presented at each of five center frequencies: 500, 1000, 2000, 4000, and 8000 Hz. Two findings are of interest here. First, difference limens were independent of center frequency for all but the 8000-Hz stimuli. Second, the trade of signal power with signal bandwidth was not as great as that predicted by Green's model. We have computed the magnitude of the bandwidth effect for the data of subject EdB (see Figure 7, p. 713). For stimulus bandwidths between 300 Hz and 10,000 Hz -- where the trade is fairly linear on a log-log plot -- S_o decreased by approximately 2 dB per decade increase in W_s. (This value is based on data averaged over all center frequencies except 8000 Hz.) This intensity-bandwidth reciprocity is considerably different from the value of -5 dB/log-unit of W_s obtained by both Green (1960) and Campbell (1964) who used continuous maskers that were broader in bandwidth than the signal. In the Bos and de Boer study, signal and masker bandwidths were equal, if one ignores the "secondary," pink-noise stimulus.

Several researchers have used gated maskers in experiments on the bandwidth effect. Small, Bacon, and Fozard (1959) presented subjects with bands of noise which changed in intensity each second. Listeners were asked to adjust the intensity of the "variable" noise (which appeared in alternate seconds) until the loudness difference between the bursts vanished and the stimulus seemed to be continuous. The method of limits (both ascending and descending) was employed to adjust the loudness of the variable bursts. Three octave bands (127-255 Hz; 1040-2080 Hz; 4080-8160 Hz) and one "wideband" (127-8160 Hz) noise were employed, each at several sensation levels. For technical reasons, not all passbands could be used at all masker levels. We have computed the intensity-bandwidth reciprocity for the data from their highly practiced subjects at a masker intensity of 20 dB SL (see Figure 2, p. 509). All four bands of noise were used at this masker level, and Weber's Law holds true in this intensity region for the three widest bands of noise. At this intensity, threshold signal power traded with stimulus bandwidth at the rate of approximately -2.7 dB/log-unit of bandwidth.

Moore (1975) conducted an experiment similar to the study of Small et al. (1959), except that a 2IFC task was used with gated maskers (T = 300 msec). Stimuli were 1/3-octave bands of noise at center frequencies of 1000, 4000, and 6300 Hz. Five masker levels were employed; the bandwidths of the signal and masker were equal. The mean (across levels) intensity-bandwidth reciprocity was -2.7 dB/log-unit of bandwidth -- similar to the value obtained in the Small et al. (1959) study. Note, however, that the Moore (1975) and Small et al. (1959) experiments may not describe the effect of only stimulus bandwidth on intensity discrimination. Consider, first, that the center frequency of the passband had to vary as the bandwidth was changed. There are no data as to whether or not the center frequency of a noise-band, *per se*, is important when gated maskers are used. Second, since the overall sensation level of each noise band was matched (e.g., 20 dB SL) for each of the different passbands, the spectrum-level (N_0) of the masker had to decrease as the bandwidths grew. While Weber's Law holds for the ideal receiver, differential sensitivity of real observers may be a function of masker spectrum-level for some bandwidths. If one is concerned with studying the effect of bandwidth on intensity-discrimination, then an experiment where both center frequency and masker spectrum-level are held constant as bandwidth is varied is much to be preferred.

De Boer (1965) generated psychometric functions using gated maskers in a 2IFC experiment. Subjects judged which of two bursts of noise (T = 400 msec) contained the increment signal. Stimuli were bands of noise filtered so as to contain equal power per octave-band; i.e., they were pink noises. Thus, masker spectrum-level was not constant, N_o being more intense for lower frequency components in the passband than for higher frequency components. The center frequency of the passbands was fixed at 1000 Hz; signal and masker bandwidths were the same. Four bands of noise -- 63 Hz, 250 Hz, 1000 Hz, and 4000 Hz -- were used with subject GR, and all but the widest band were also presented to listener HV. Signal-to-masker ratios for approximately 75 percent correct detections were estimated from the psychometric functions (see de Boer's Figures 1 and 2). Using these values, the calculated reciprocities are -4.4 dB and -5.5 dB per log-unit of W for subjects GR and HV, respectively. The mean value of -5.0 dB/log-unit of W agrees with the prediction of the energy-detector model, but is steeper than the reciprocities obtained by Moore (1975) and Small et al. (1959) with gated maskers.

Raab and Goldberg (1975) also studied intensity-bandwidth reciprocity with gated noise-maskers. Two bands of noise -- 500 Hz and 5000 Hz (f_c = 1000 Hz) -- were employed, each at two spectrum-levels of the masker. The computed reciprocities, averaged across masker-levels and subjects, are -0.9 dB/log-unit of W for bursts of 10 msec duration, and -1.1 dB/log-unit of W for 100 msec bursts. With stimuli that were gated together and filtered together, Raab and Goldberg found little effect of bandwidth on intensity-discrimination. This outcome contrasts with that of the de Boer (1965) study, where a much greater bandwidth effect was obtained. We note, however, that while the stimuli were gated together and filtered together in both experiments, Raab and Goldberg employed white noise and de Boer used pink noise.

Moore and Raab (1975) determined intensity-bandwidth reciprocities for gated bursts of noise in the presence of a continuous, bandstop-filtered background, whose spectrum level in the passband was 10 dB above that of the masker. (See their Figure 1 for details of the stimulus situation.) They computed an average trade of -2.5 dB in signal power per decade increase in "notch" bandwidth, over a 40 dB range in masker spectrum-level.

Intensity-bandwidth reciprocity has also been examined using the amplitude-modulation technique. Zwicker (1956) employed white noise carriers, modulated sinusoidally at the rate of 3 Hz. Difference limens were constant at approximately -5.7 dB for masker bandwidths wider than 2000 Hz, and intensities greater than 30 dB SPL (see Figure 14, p. 373). With noise bands less than 2000 Hz wide, discrimination became poorer as the passband was narrowed. Specifically, changing, the masker bandwidth by a factor of ten (from 1000 Hz to 100 Hz) produced a 5.6 dB increase in the threshold for detecting noise-amplitude fluctuations. The effect was subsequently confirmed by Zwicker and Feldtkeller (1967). In that experiment, the modulation rate was 4 Hz. The center frequency of the noise-band was 6000 Hz (see Figure 38.1). The intensity-bandwidth reciprocity was about -5.4 dB/log-unit of W.

Maiwald (1967) determined the depth of modulation for flutter thresholds of sinusoidally-modulated (4 Hz), high-pass noise, which had a fixed low-frequency cut-off of 6400 Hz. Note that since the low-frequency cut-off was held constant, the center frequency of the passband changed as the bandwidth of the noise carrier was varied. From the data in Maiwald's Figure 17 (p. 205), we compute a trade of about -5.5 dB in signal power per decade increase in noise bandwidth.

The two Zwicker studies and the Maiwald experiment support the square-root reciprocity of the ideal receiver.

Rodenburg (1972) also used the amplitude-modulation procedure to study the effect of bandwidth on noise-intensity discrimination. Depth of modulation at threshold was determined as a function of carrier bandwidth for three center frequencies: 500, 2000, and 8000 Hz. The modulation frequency was 10 Hz, a rate more than double that employed in the Zwicker studies or in the Maiwald experiment. Rodenburg replicated Zwicker's (1956) finding that thresholds improve as noise bandwidth is increased until some critical value is reached, beyond which thresholds remain consant. These "critical" values are different for each center frequency and are approximately twice as large as the generally accepted estimates of critical bands (cf., Scharf, 1970, p. 162). We computed intensity-bandwidth reicprocities separately for each of Rodenburg's subjects, and for each of the center frequencies employed. (Only those data for noise bandwidths between 100 Hz and the empirical "critical" values were used in the computations.) The bandwidth effect, averaged across subjects and center frequencies, is -13.4 dB/log-unit of W. This value is considerably larger than the intensity-bandwidth trade of -5 to -6 dB/log-unit of W obtained in earlier experiments using amplitude-modulation (Zwicker, 1956; Zwicker and Feldtkeller, 1967; Maiwald, 1967). Perhaps the nature of the perceptual task varies as a function of the different modulation rates employed from experiment to experiment.

A summary of the experiments reviewed in this section is given in Table 1-1. Intensity-bandwidth reciprocity accords with the predictions of the model when maskers are continuous and $W_s < W_n$ (Green, 1960; Campbell, 1964); the degree of reciprocity is less when the background is continuous and the signal and masker have the same bandwidth (Bos and de Boer, 1966). Gated bands of white noise yield a relatively small bandwidth effect when $W_s = W_n$ (Small et al., 1959; Moore, 1975; Raab and Goldberg, 1975; Moore and Raab, 1975), although with pink noise stimuli, de Boer (1965) observed the -5 dB trade that is predicted by the energy-detector model. No experiments have been undertaken using gated stimuli with signal bandwidth smaller than masker bandwidth. Except for Rodenburg's (1972) experiment, the studies employing the amplitude-modulation procedure confirm the square-root reciprocity of the ideal receiver (Zwicker, 1956; Zwicker and Feldtkeller, 1967; Maiwald, 1967).

E. Plan of Research

Previous experiments attempting to specify the effect of bandwidth on noise intensity-discrimination have not

Table 1-1
Summary of Studies on the Bandwidth Effect.

Study	Bandwidth Conditions	Mode of Masker	Cen. Fre. (a)	Recip. (b)
Green, 1960	Ws ≤ Wn	Contin.	D	-4.3
Campbell, 1964	Ws < Wn	Contin.	D	-5.3
Bos & de Boer, 1966	Ws = Wn (c)	Contin.	I	-2.0
Small et al., 1959	Ws = Wn	Gated	D	-2.7
Moore, 1975	Ws = Wn	Gated	D	-2.7
de Boer, 1965 (d)	Ws = Wn	Gated	I	-4.4
Raab & Goldberg, 1975	Ws = Wn	Gated	I	-1.0
Moore & Raab, (1975)	Ws = Wn (e)	Gated	I	-2.5
Zwicker, 1956	Ws = Wn	3 Hz AM (f)	(g)	-5.6
Zwicker & Feldtkeller, 1967	Ws = Wn	4 Hz AM (f)	(g)	-5.4
Maiwald, 1967	Ws = Wn	4 Hz AM (f)	(g)	-5.5
Rodenburg, 1972	Ws = Wn	10 Hz AM (f)	(g)	-13.4

(a) Was center frequency independent (I) of, or dependent (D) on, bandwidth?

(b) Intensity-bandwidth reciprocity (dB/log-unit of Ws).

(c) Primary masker: white noise; secondary (low-level) masker: pink noise.

(d) Stimuli were bands of pink-noise.

(e) Continuous bandstop background was used to vary stimulus bandwidth; see text for details.

(f) Amplitude-modulation technique; rate of sinusoidal modulation is given in parentheses.

(g) Not specified in the paper.

yielded a single value for the degree of intensity-bandwidth reciprocity. No experiment has been designed to explore systematically the separate contributions of mode of masker, bandwidth conditions, and spectrum-level of the masker.

Reported in this dissertation are the results of just such a study. The experiment was conducted in four parts as outlined in Table 1-2. To assess the effect of masker spectrum-level on intensity-bandwidth reciprocity, and to investigate the form of the Weber function, each part of the experiment employed three intensities of masker. Noise bandwidth was varied independently of spectrum-level (N_0). Unfortunately, most earlier studies had allowed N_0 to change as the stimulus bandwidth was manipulated.

Existing evidence is conflicting as to whether the center frequency of a noise band does (Small et al., 1959; Campbell, 1964; Rodenburg, 1972) or does not (Green, 1960; Bos and de Boer,1966; Zwicker, 1956; Zwicker and Feldtkeller, 1967; Maiwald, 1967) affect intensity-discrimination. As a result, we chose to use a single center-frequency (1000 Hz) for our noise bands. The study included noise passbands as narrow as 100 Hz and as wide as 10,000 Hz.

One hundred milliseconds was selected as the stimulus duration for two reasons. First, it is shorter than the

Table 1-2

The Four Principal Experimental Conditions

Ws = Wn Masker: Continuous	Ws = Wn Masker: Gated
Ws < Wn Masker: Continuous	Ws < Wn Masker: Gated

maximum duration for which the auditory system can integrate stimulus energy. This is generally reported to be between 200 and 300 msec for noise bands (Green, 1960; Raab, Osman, and Rich, 1963; Campbell, 1964). Second, filtering or critical band mechanisms involved in the perception of the noise stimuli might require some minimum time to become fully operative. Opinions differ as to the minimum response-time, but all estimates agree that 100 msec would be long enough for such frequency-selective mechanisms to be activated (see Scharf, 1970, pp. 179-188; Zwicker and Fastl, 1972).

The chapters that follow describe the design of the study, present experimental findings, and discuss the present work in relation to theories of intensity-discrimination.

Chapter II

METHOD

An experiment was performed to study intensity discrimination of band-limited, Gaussian noise signals presented in maskers of various bandwidths. The noise masker was either presented continuously throughout an experimental session or gated during the observation intervals. Forced-choice thresholds were obtained at three levels of noise masker.

A. Subjects

One male undergraduate student (MB) and the author (PS) served as subjects. Both had clinically normal audiograms and received 15-20 hours of training before any data were recorded.

B. Apparatus

For those experimental conditions where the signal and masker bandwidths were identical, a single General Radio (1390-B) noise generator provided the noise source. Its output was bandlimited by means of a Rockland (1042-F) electronic filter whose settings were adjusted so that the passband was centered at 1000 Hz for all bandwidths used.

Table 2-1 lists the various bandwidths used, as measured by the half-power points. Equivalent rectangular bandwidths (ERB) were calculated for each passband using the procedure given by Beranek (1949, pp. 564-565). The 100-Hz passband was obtained by first passing the noise generator output through a UTC BML-1000 passive filter and then into the Rockland filter set for the 10,000 Hz bandwidth. (The Rockland filter provided the high-impedance load required by the UTC filter.) Response curves for the filters are shown in Figure 2-1. Note that the shape of the passband for the 100-Hz filter is different from the other curves. The attenuation-slope of the UTC filter is not as steep as that of the Rockland filter at frequencies well removed from the center of the passband. Bandwidths are henceforth reported as half-power bandwidths (HPB) unless otherwise noted.

The filtered output of the noise generator was divided and led to two channels -- one for the increment signal (ΔV) and one for the noise masker (V). Each channel contained an amplifier (Scott 140 B) and attenuators for level adjustment. Trimming capacitors were used for phase-balancing of the channels. The magnitude of the signal could be changed between blocks of trials by means of a Lehigh Valley (1427) two-way stepping switch and a series of 12 attenuators connected in cascade. The signal channel

Table 2-1

Passbands Used in the Experiment

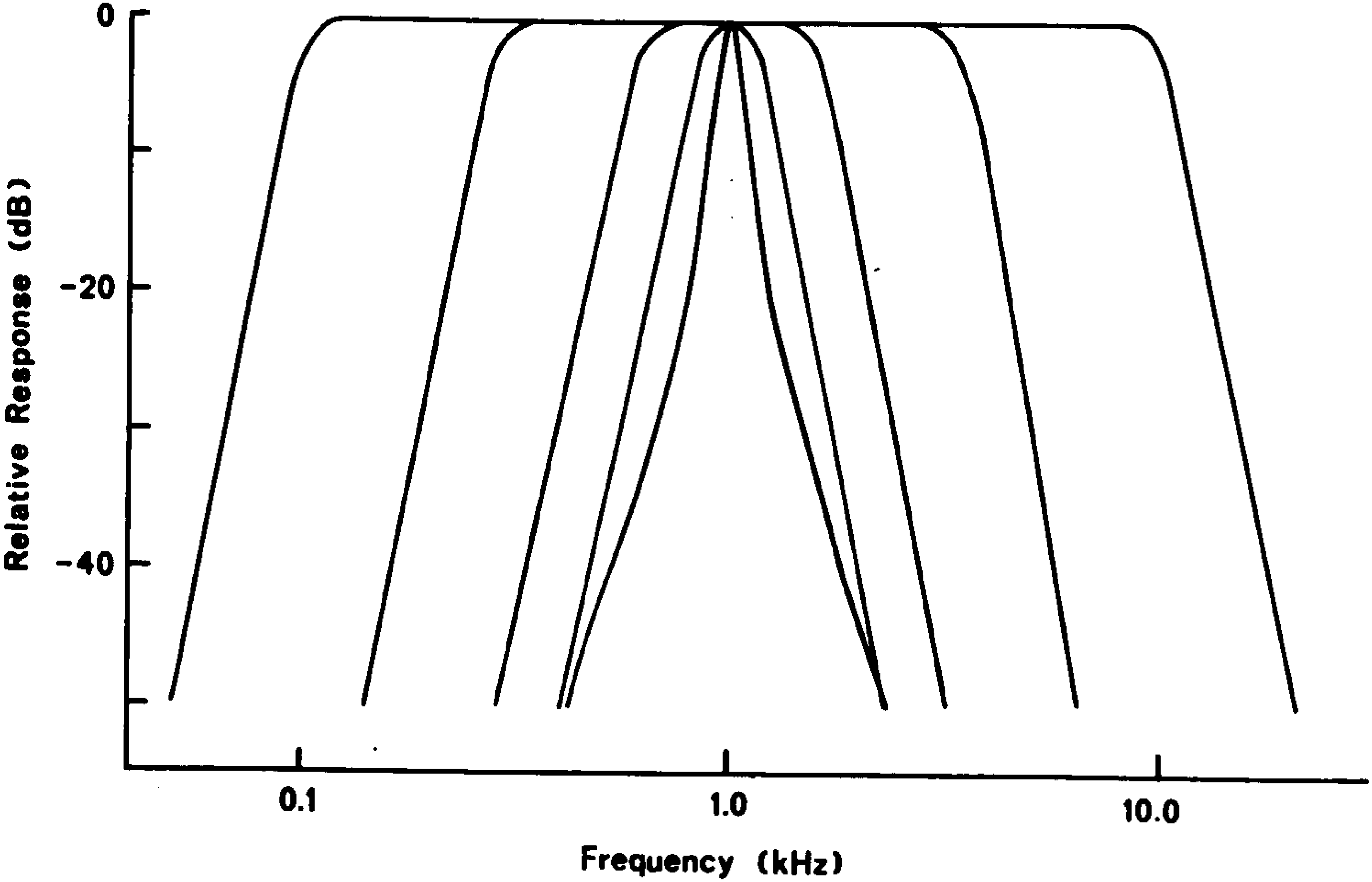
Half-power Bandwidth (Passband)	Equiv. Rect. Bandwidth (Passband)
100 (951 - 1051)	119 (942 - 1061)
316 (854 - 1170)	344 (843 - 1187)
1000 (618 - 1618)	1013 (615 - 1628)
3160 (290 - 3450)	3206 (286 - 3492)
10,000 (99 - 10,099)	10,051 (99 - 10,150)

Note: All frequencies are in Hz.

Center frequency equals 1000 Hz.

Figure 2-1

Response curves of the bandpass filters listed in Table 2-1.


Relative Response (dB)
0
-20
-40
0.1
1.0
10.0
Frequency (kHz)

contained a relay whose closure placed the ΔV in one of the two temporal intervals comprising a trial. Activation of this relay was controlled by a BRS PP1 probability generator.

The noise masker was presented to the subject either continuously or gated with the signal by means of an electronic switch (Grason-Stadler 829B). By powering the switch from an external regulated supply (Kepco KR2 M), hum and noise in the instrument were significantly reduced and the stability of the pedestal balance adjustment was markedly increased (see Raab and Schacknow, 1973).

A block diagram of the apparatus used in the continuous masker conditions is given in Figure 2-2. The increment signal was passed through the electronic switch and then added coherently to the noise masker by means of a resistive mixing network. Summation accuracy of better than 0.1 percent was achieved through the use of precision resistors. The sum was passed through a master attenuator, patched into a soundproof room (IAC 1200 SP), and delivered, finally, to the subject's right earphone, a Sennheiser HD-414. The Sennheiser Corporation provided frequency-response curves of this earphone based on both "real ear" and "artificial ear" measurements. These are shown in Figure 2-3.

The subject wore a PDR-10 earphone in an MX/41-AR

Figure 2-2

Block diagram of the apparatus used when the maskers were continuous. With the switch in position A, $W_s < W_n$; with the switch in position B, $W_s = W_n$.

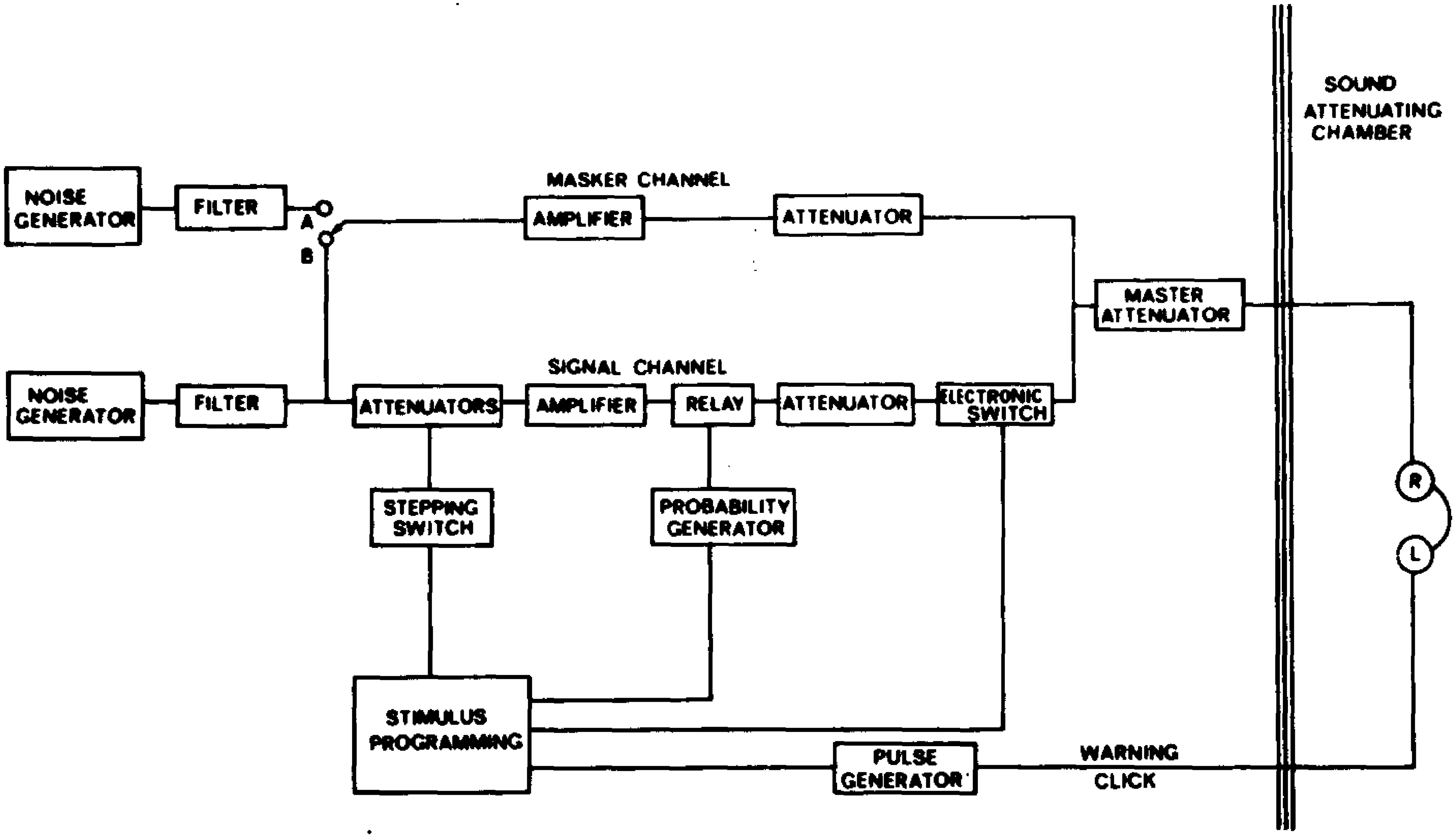
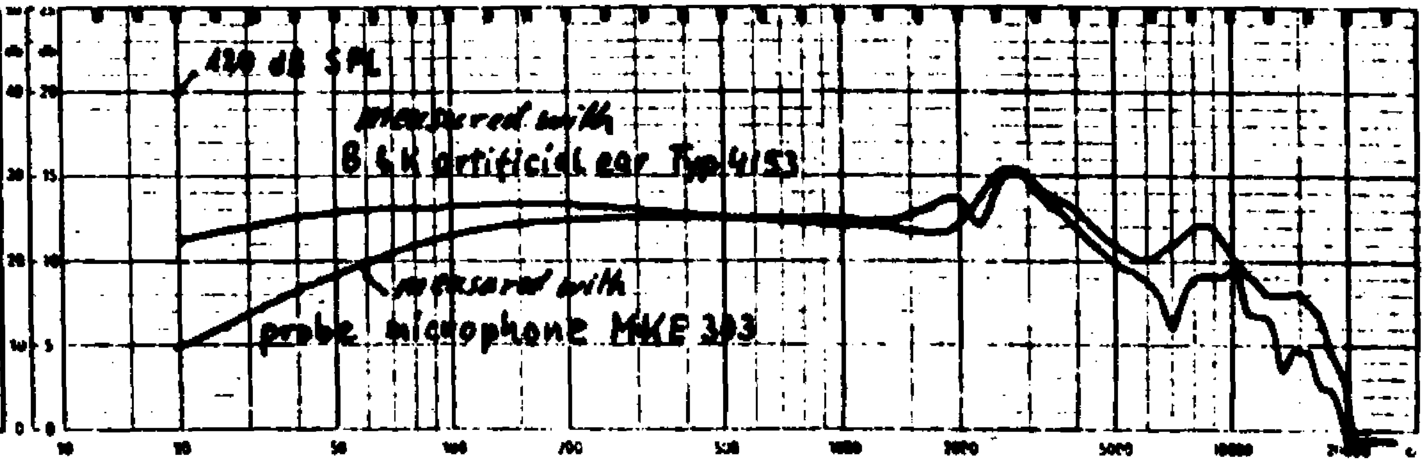

SOUND ATTENUATING CHAMBER
NOISE GENERATOR
FILTER
A
B
MASKER CHANNEL
AMPLIFIER
ATTENUATOR
MASTER ATTENUATOR
SIGNAL CHANNEL
NOISE GENERATOR
FILTER
ATTENUATORS
AMPLIFIER
RELAY
ATTENUATOR
ELECTRONIC SWITCH
R
L
STEPPING SWITCH
PROBABILITY GENERATOR
STIMULUS PROGRAMMING
PULSE GENERATOR
WARNING CLICK

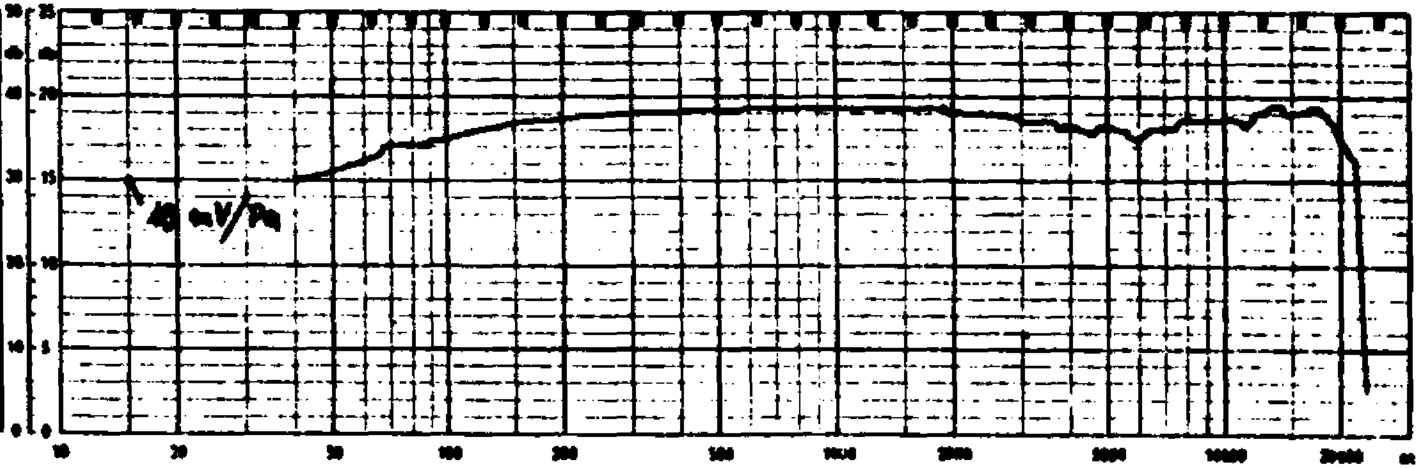
Figure 2-3

Response curves of the Sennheiser HD 414 earphone used in the experiment. The lower graph is a calibration curve of the microphone used to make the "real ear" measurements.

SENNHEISER electronic		
*		
Typ: HD 414 (L)		
Prüffeld	Pot:	25dB ☐ 50dB ☒
Sign. Mi	Dat: 12.5.73	



SENNHEISER electronic		
* 90° Freq. Resp. of probe micr.		
Typ: MKE 303		
Prüffeld	Pot:	25dB ☐ 50dB ☒
Sign. Mi	Dat: 12.5.73	



cushion over his left ear. This served to attenuate airborne sounds resulting from the "open-air" design of the Sennheiser earphone.

For the gated masker conditions, where the signal and masker had equal bandwidths, signal and masker waveforms were first added in phase and then passed through the electronic switch to the master attenuator. Figure 2-4 shows this experimental apparatus.

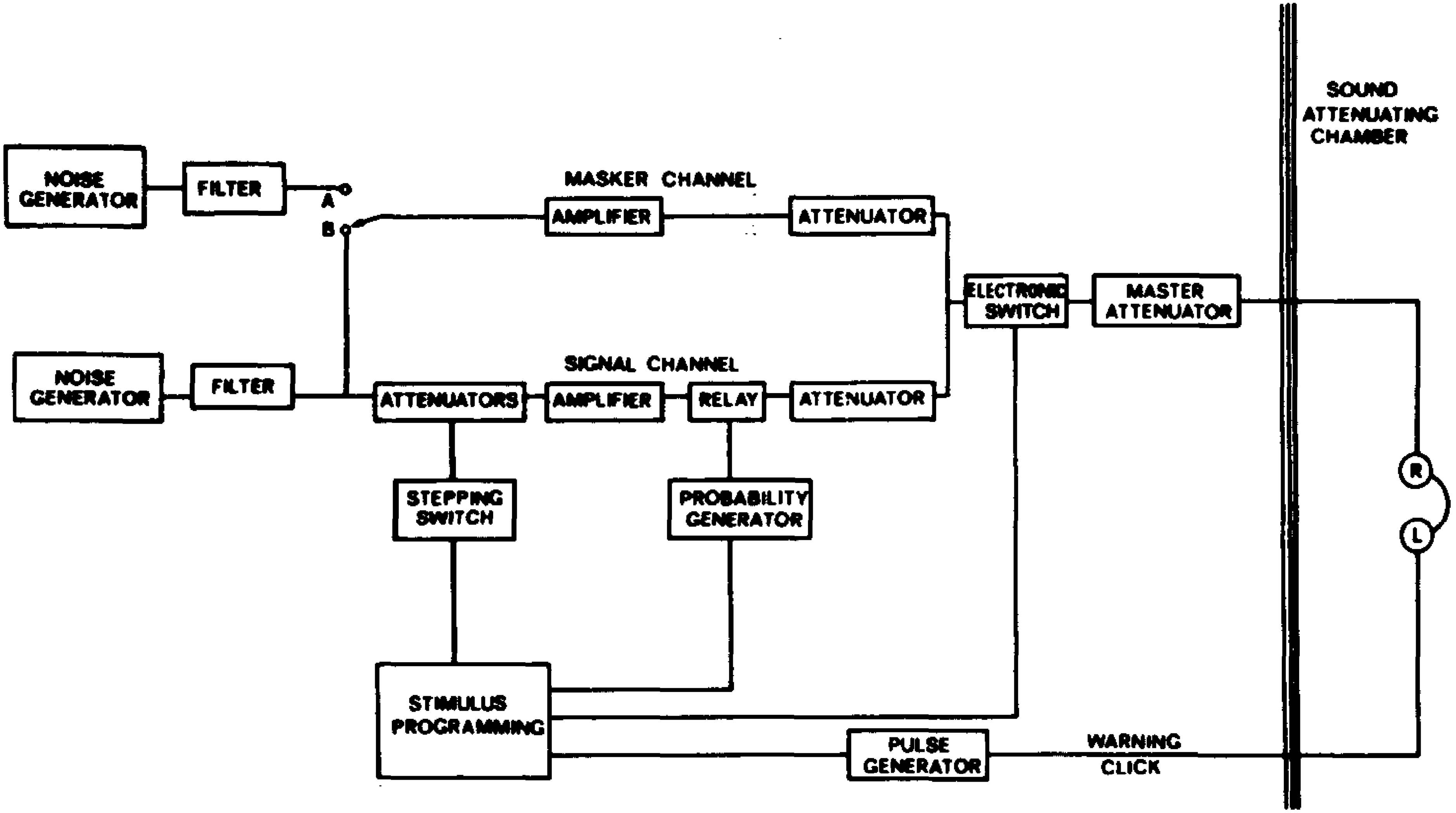
When the experiment required the signal and masker bandwidths to be different, two General Radio noise generators and two Rockland filters were employed. One generator-filter combination fed the signal channel and one combination was connected to the masker channel. In all other respects the equipment was the same as for the "equal-bandwidth" conditions.

An electrical signal of 0.4 volts RMS, as measured by a Ballantine (320) voltmeter, produced an acoustic output of approximately 91 dB SPL from the Sennheiser earphone. Sound pressure levels given in this dissertation are all referred to 0.0002 microbar.

An Iconix (6255-6010) digital timing system and several Tektronix 160-Series waveform and pulse generators were used to generate the stimulus sequences as required. Responses were tabulated automatically by means of LVE (1425-10) electromechanical counters.

Figure 2-4

Block diagram of the apparatus used when the maskers were gated. With the switch in position A, $W_s < W_n$; with the switch in position B, $W_s = W_n$.


NOISE GENERATOR
FILTER
A
B
MASKER CHANNEL
AMPLIFIER
ATTENUATOR
NOISE GENERATOR
FILTER
SIGNAL CHANNEL
ATTENUATORS
AMPLIFIER
RELAY
ATTENUATOR
ELECTRONIC SWITCH
MASTER ATTENUATOR
SOUND ATTENUATING CHAMBER
STEPPING SWITCH
PROBABILITY GENERATOR
STIMULUS PROGRAMMING
PULSE GENERATOR
WARNING CLICK
R
L

C. Procedure

1. Psychophysical Method

Intensity-discrimination thresholds were determined using a two-interval, forced-choice (2IFC) variation of the staircase technique. Each trial began with a faint "ready" click presented to the subject's left earphone. The increment signal, ΔV, was placed with equal probability in one of two observation intervals, the first of which began one second after the "ready" click. A neon lamp was lighted to mark the observation periods, whose onsets were spaced 300 msec apart. The noise masker was either presented throughout an experimental run ("continuous condition") or switched on only during the two observation intervals ("gated condition"). The electronic switch was pulsed to yield a power envelope whose "equivalent rectangular duration" was calculated to be 100 msec. (Nominal rise/fall times of 10 msec were employed.) The subject indicated the interval containing the signal by pressing one or the other of two microswitch buttons. Immediate knowledge of results was furnished by red and green pilot lamps. Trials were self-paced and occurred approximately once every five seconds.

Each determination of a threshold began with the increment signal, ΔV, easily detectable. If the subject responded correctly on five out of six trials for a given level of signal, the signal was attenuated for the next block of six trials. If the subject voted incorrectly on two of the six trials in a block, ΔV was increased.

When the signal and masker bandwidth were different, ΔV was changed in steps of 1.5 dB. Since signal and masker waveforms were uncorrelated, the change in increment power (ΔI) was also 1.5 dB. When the signal and masker bandwidths were the same, ΔV was varied in 3 dB steps. With correlated addition of the waveforms, ΔI changed in steps of approximately 1.5 dB over most of the range of thresholds.

This blocked-trials staircase procedure (c.f., Campbell and Lasky, 1968) allows the subject to cross and recross his threshold (the value of ΔV yielding approximately 75 percent correct decisions) many times during an experimental run. At the end of 100 trials the median value of attenuation in the signal channel (after the first reversal), ΔV, was computed and then converted to increment power, ΔI. The ratio of signal power to noise power in a 1-Hz band, S_0/N_0, was calculated. This quantity, expressed in decibels ($10 \log S_0/N_0$), is used as an index of intensity discrimination.

2. Experimental Design

The experiment was conducted in two parts. First, intensity discrimination was investigated for noise bands where the signal bandwidth (W_s) and the masker bandwidth (W_n) were equal ("homogeneous" conditions). The five pairs of signal and masker bandwidth are listed in Table 2-2. Second, subjects listened to combinations of W_s and W_n where the signal bandwidth was smaller than the masker bandwidth ("heterogeneous" conditions). Table 2-3 shows the heterogeneous bandwidth combinations that were utilized.

The presentation of bandwidth combinations was randomized and was different for the two subjects. Pairs of consecutive days were used to study each combination of W_s and W_n, the masker being presented continuously on one of the days, and gated on the other. During one day's session, the bandwidth combination was presented several times at each of three masker levels (5 dB, 25 dB and 45 dB SPL).

Three thresholds (each based on 100 2IFC trials) were first determined for each experimental condition. After data had been collected for all 90 conditions, two more thresholds were determined for each condition in an order

Table 2-2

Bandwidths (in Hertz) Employed in the Experiment When $W_s = W_n$

W_s	W_n
100	100
316	316
1,000	1,000
3,160	3,160
10,000	10,000

Table 2-3

Bandwidths (in Hertz) Employed in the Experiment When $W_s < W_n$

W_s	W_n
100	316
100	1,000
100	3,160
100	10,000
316	1,000
316	3,160
316	10,000
1,000	3,160
1,000	10,000
3,160	10,000

counterbalancing the original sequence. Thus, each threshold is based upon 500 trials. A daily experimental session lasted approximately 1.5 hours and consisted of either 6 or 9 threshold determinations separated by rest periods.

Chapter III

RESULTS

A. Intensity Discrimination of Noise Bands for the Homogeneous Conditions

The effect of bandwidth on intensity discrimination for the homogeneous conditions can be seen in Figure 3-1, where 10 log S_o/N_o is plotted as a function of the common equivalent rectangular bandwidth (ERB) of the signal and masker. The data presented in the figure have been averaged across the two listeners; mean values of S_o/N_o were calculated before taking logarithms. Tables 3-1 and 3-2 list the results for each observer separately. The parameters of the plots in Figure 3-1 are the spectrum levels of the masker, and the mode of masker presentation (continuous or gated). The solid diagonal plot shows the performance of the ideal receiver as given by Green's model (see Equation 1-1). The theoretical reciprocity of S_o/N_o and W_s is given by the slope of this plot. If we make the assumptions underlying Equation 1-2, we may approximate the theoretical function with a linear plot, with slope of -5 dB per decade increase in signal bandwidth.

The line best-fitting the results at each level of masker was calculated separately for each subject by the

Figure 3-1

Noise-intensity discrimination as a function of equivalent rectangular bandwidth, when $W_s = W_m$. The results have been averaged across listeners. The parameters are masker spectrum-level (⬟ = 5 dB; ● = 25 dB; ■ = 45 dB) and mode of the masker (solid lines: continuous; dashed lines: gated). The solid line without data points is the theoretical function derived from Equation 1-1.

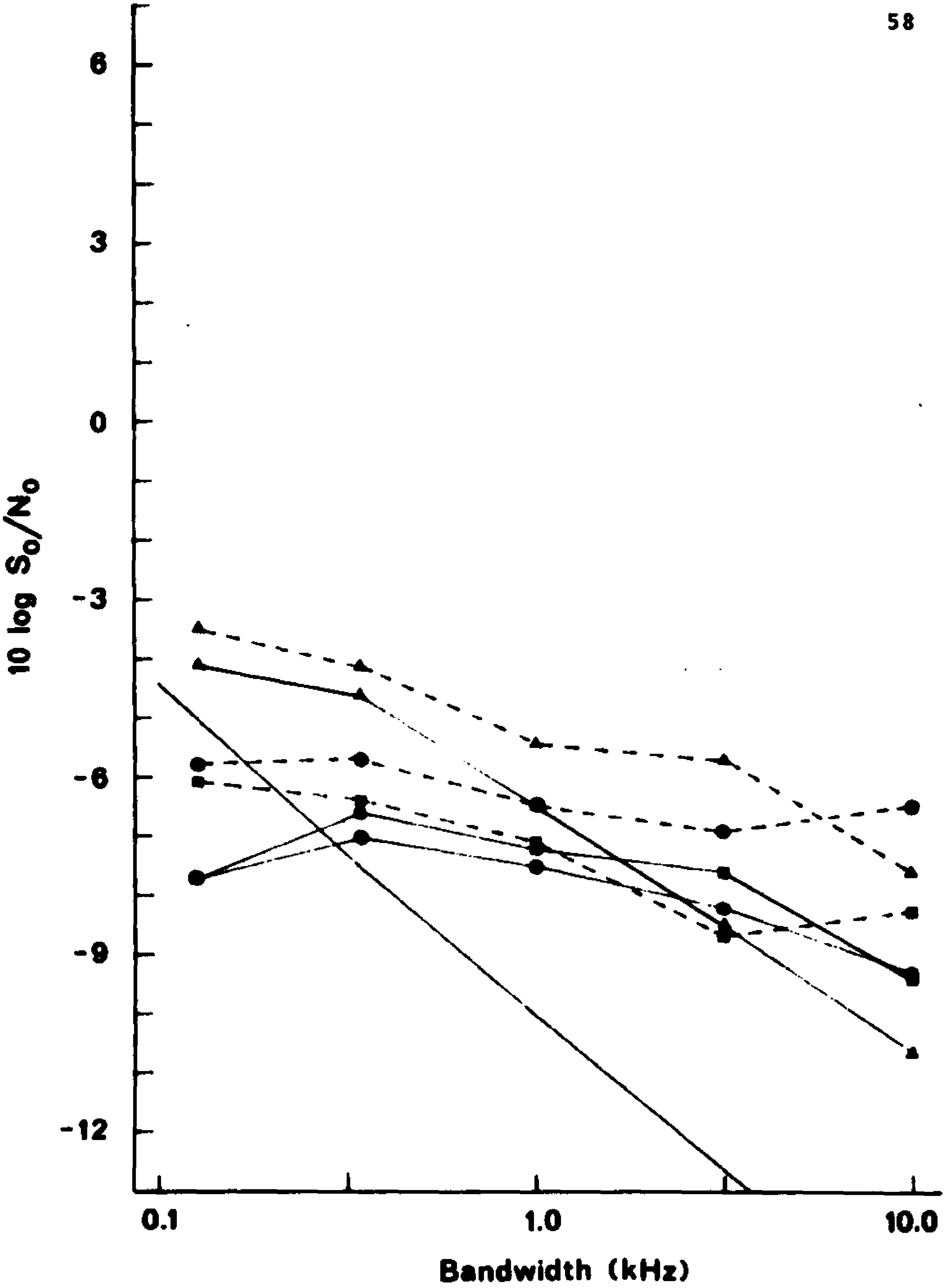

6
3
0
-3
-6
-9
-12
10 log S_o/N_o
0.1
1.0
10.0
Bandwidth (kHz)

Table 3-1

Noise Intensity-Discrimination as a Function of Bandwidth (HPB) When $W_s = W_n$. Data for Subject PS.

Masker Spectrum-level (dB SPL)	Half-power Bandwidth (Hz) 100	316	1000	3160	10,000
C 45 dB	-8.0	-6.7	-7.5	-7.2	-9.9
C 25 dB	-7.6	-6.9	-8.0	-8.4	-9.6
C 5 dB	-4.6	-4.2	-5.7	-7.9	-10.4
G 45 dB	-7.4	-6.7	-8.3	-9.5	-8.9
G 25 dB	-6.9	-6.8	-6.4	-7.3	-8.5
G 5 dB	-3.4	-4.4	-6.2	-7.3	-7.6

Note: Results are given as threshold values of 10 log S_o/N_o.
C indicates continuous maskers.
G indicates gated maskers.

Table 3-2

Noise Intensity-Discrimination as a Function of Bandwidth (HPB) When $W_s = W_n$. Data for Subject MB.

Masker Spectrum-level (dB SPL)	Half-power Bandwidth (Hz) 100	316	1000	3160	10,000
C 45 dB	-7.3	-6.4	-6.9	-8.1	-9.0
C 25 dB	-7.8	-7.1	-7.0	-8.0	-9.1
C 5 dB	-3.6	-5.2	-7.5	-9.1	-10.9
G 45 dB	-5.2	-6.1	-6.2	-8.0	-7.7
G 25 dB	-4.9	-4.8	-6.5	-6.5	-5.1
G 5 dB	-3.5	-3.7	-4.7	-5.3	-7.6

Note: Results are given as threshold values of 10 log S_o/N_o.
C indicates continuous maskers.
G indicates gated maskers.

method of least-squares. Slopes were converted to "reciprocity-factors" and are given in Table 3-3. (The reciprocity-factor is defined as the change, in decibels, of S_o/N_o resulting from a log-unit increase in W_s.) Reciprocity-factors, averaged across masker levels, are shown in the last two rows of the table. For the continuous masker conditions, the mean reciprocity-factor was calculated to be -1.8 for subject PS and -1.9 for subject MB. With gated maskers, the mean reciprocity-factors were -1.4 and -1.3 for subjects PS and MB, respectively.

The data presented thus far confirm and extend the Raab and Goldberg (1975) finding of a small bandwidth effect for gated maskers when W_s and W_n are equal. With continuous maskers, the bandwidth effect is slightly greater. In both cases, stimulus bandwidth has a much smaller effect on discrimination than is predicted by Green's model. (It should be noted that the degree of reciprocity depends slightly on the intensity of the masker. Both observers show greatest reciprocity-factors with maskers presented at a 5 dB spectrum-level.)

Figure 3-1 shows that except for the narrowest bandwidth, real observers do more poorly than the model, the discrepancy in performance increasing directly with bandwidth. With the 100-Hz noise band, our listeners exhibit better performance than the ideal receiver at the

Table 3-3

Reciprocity-factors for the Results with Homogeneous Bandwidths

Masker Spectrum-level (dB SPL)	Continuous	Gated
5	-3.2	-2.1
	-3.8	-2.0
25	-1.2	-0.8
	-0.7	-0.4
45	-0.9	-1.2
	-1.1	-1.4
Mean	-1.8	-1.4
	-1.9	-1.3

Note: For each condition the upper value refers to subject PS; the lower value to subject MB.

25 dB and 45 dB masker levels, for both continuous and gated maskers. Green's ideal receiver makes its decision on a basis that is monotonic with likelihood ratio, viz., by comparing the noise energies during the two observation intervals comprising a trial. Clearly, several of the assumptions underlying the ideal model must not hold for some of the experimental conditions employed in our study. We shall discuss this matter in Chapter IV.

In summary, we have found that when the signal and the masker are filtered together, intensity discrimination of noise bands is relatively independent of both noise bandwidth and presentation mode of the masker. We have noted that the model of optimal performance fails to account for the small effect of bandwidth. A second theoretical problem is posed by the finding of better-than-energy-detector performance in some experimental conditions with the 100-Hz signal.

B. Intensity Discrimination of Noise-Bands for the Heterogeneous Conditions

Our experimental situation most similar to Green's (1960) paradigm is the heterogeneous condition with continuous masker. Results obtained with continuous maskers are presented in Figures 3-2 thru 3-5, together with

Figure 3-2

Noise-intensity discrimination as a function of signal ERB, when $W_s \leq W_n$. Masker bandwidth equals 344 Hz. The results have been averaged across listeners. The parameters are masker spectrum-level (▲ = 5 dB; ● = 25 dB; ■ = 45dB) and mode of masker (solid lines: continuous; dashed lines: gated). The solid line without data points is the theoretical function computed from Equation 1-1; the dotted line without data points is the theoretical function computed from Equation 3-1.

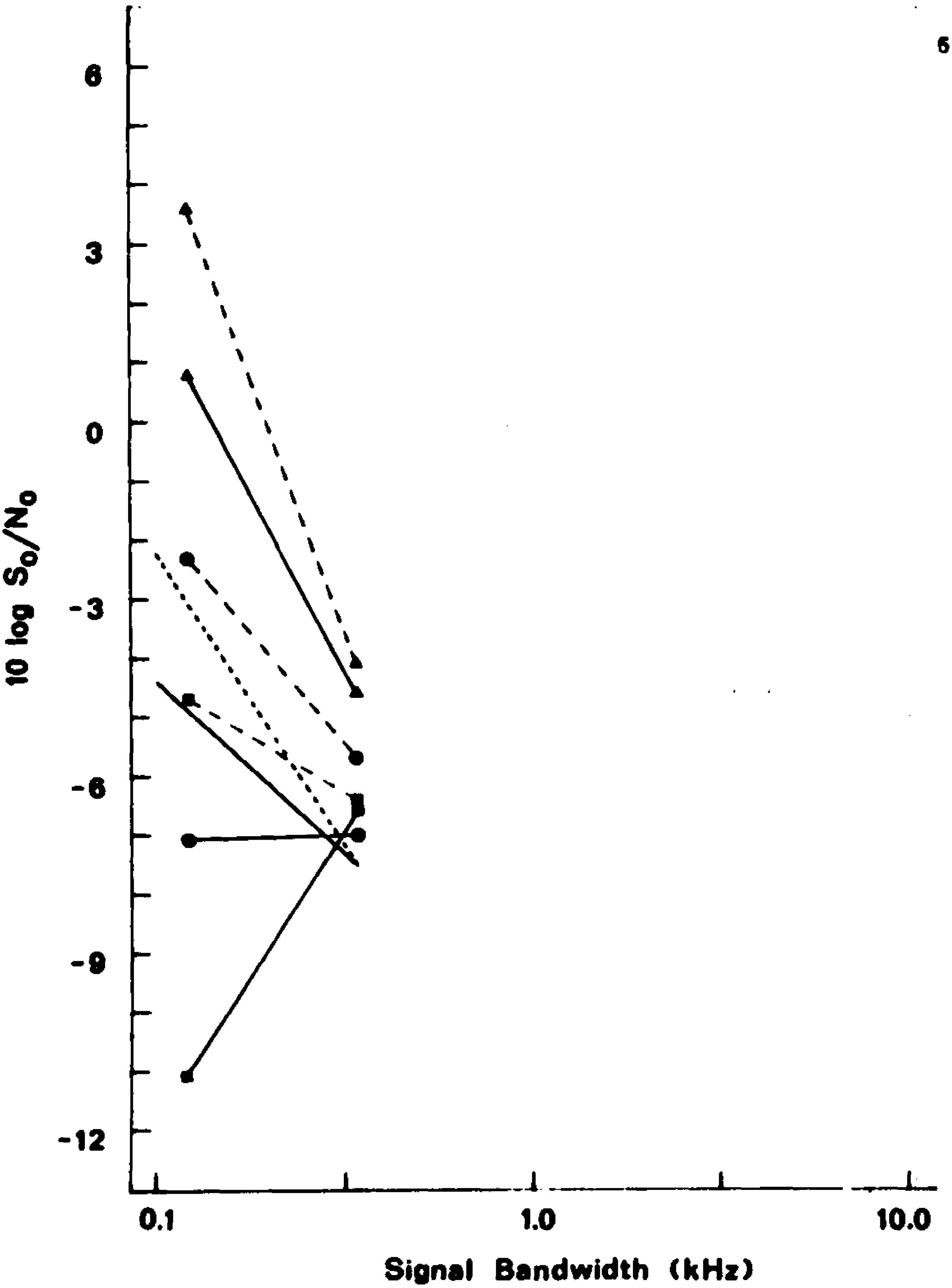

6
3
0
-3
-6
-9
-12
10 log S_O/N_O
0.1
1.0
10.0
Signal Bandwidth (kHz)

Figure 3-3

Noise-intensity discrimination as a function of signal ERB, when $W_s \leq W_n$. Masker bandwidth equals 1013 Hz. The results have been averaged across listeners. The parameters are masker spectrum-level (▲ = 5 dB; ● = 25 dB; ■ = 45dB) and mode of masker (solid lines: continuous; dashed lines: gated). The solid line without data points is the theoretical function computed from Equation 1-1; the dotted line without data points is the theoretical function computed from Equation 3-1.

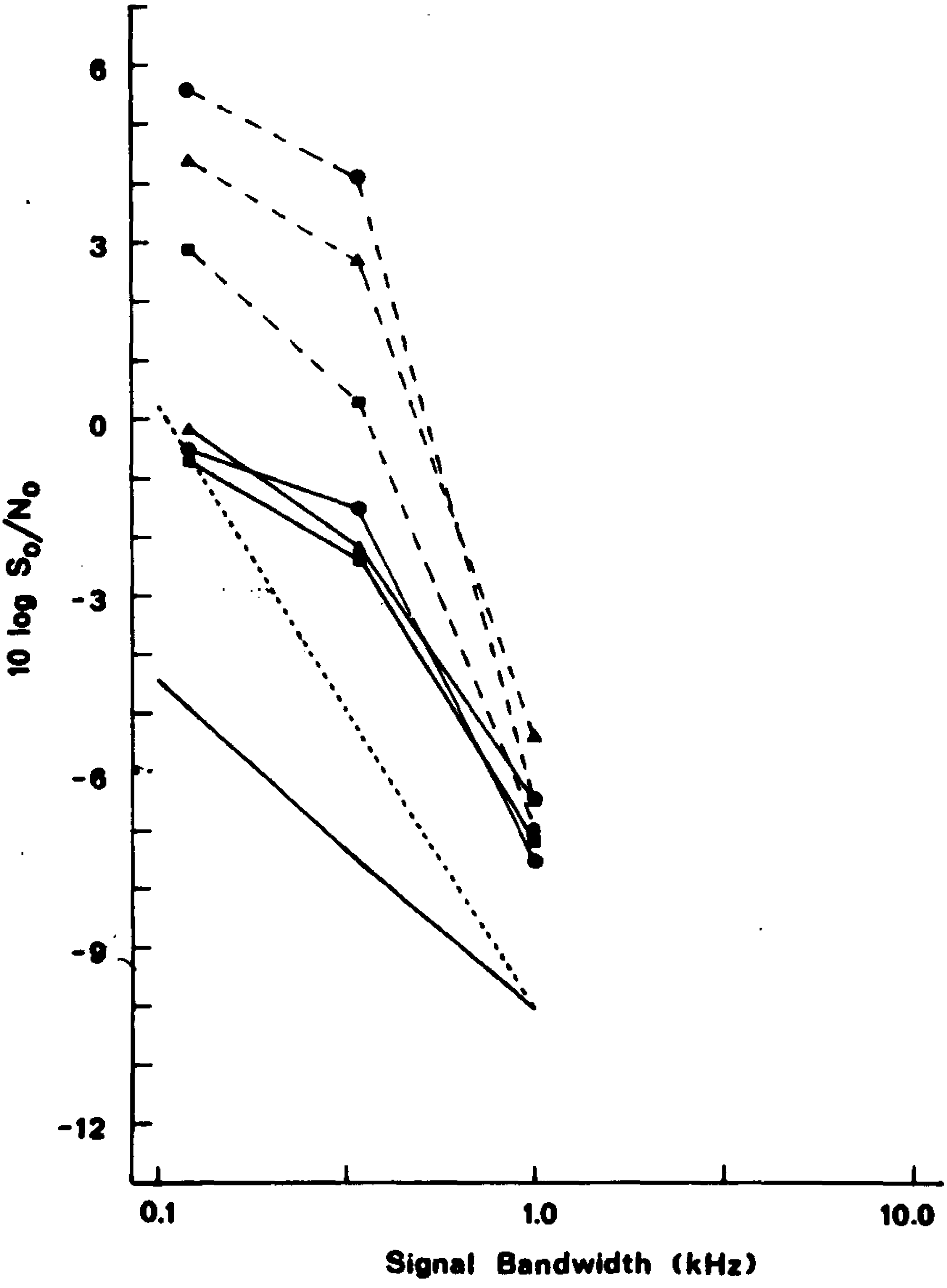

10 log So/No
6
3
0
-3
-6
-9
-12
0.1
1.0
10.0
Signal Bandwidth (kHz)

Figure 3-4

Noise-intensity discrimination as a function of signal ERB, when $W_s \leq W_n$. Masker bandwidth equals 3206 Hz. The results have been averaged across listeners. The parameters are masker spectrum-level (▲ = 5 dB; ● = 25 dB; ● = 45dB) and mode of masker (solid lines: continuous; dashed lines: gated). The solid line without data points is the theoretical function computed from Equation 1-1; the dotted line without data points is the theoretical function computed from Equation 3-1.

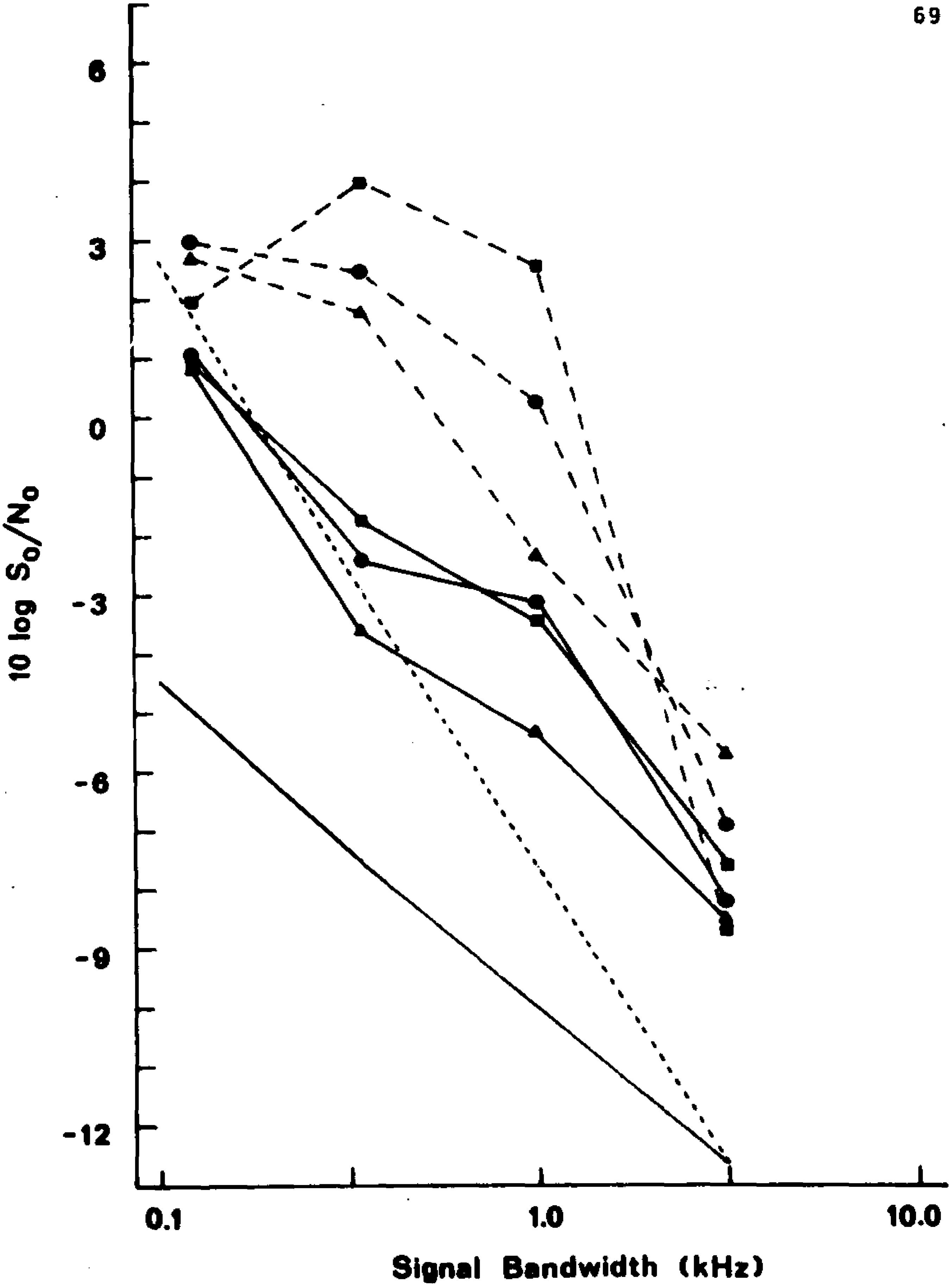
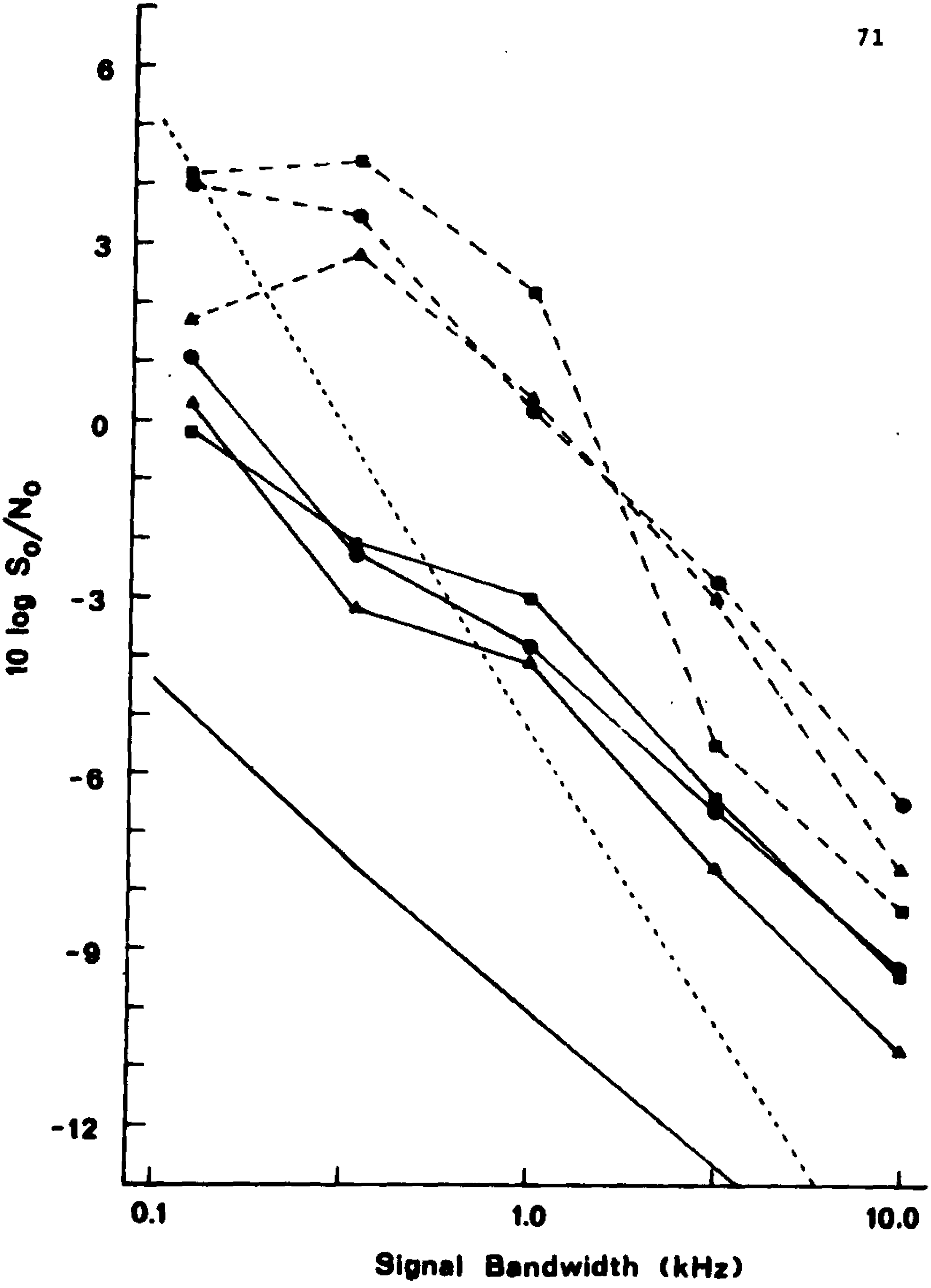

6
3
0
-3
-6
-9
-12
10 log So/No
0.1
1.0
10.0
Signal Bandwidth (kHz)

Figure 3-5

Noise-intensity discrimination as a function of signal ERB, when $W_s \leq W_n$. Masker bandwidth equals 10,051 Hz. The results have been averaged across listeners. The parameters are masker spectrum-level (▲ = 5 dB; ● = 25 dB; ■ = 45dB) and mode of masker (solid lines: continuous; dashed lines: gated). The solid line without data points is the theoretical function computed from Equation 1-1; the dotted line without data points is the theoretical function computed from Equation 3-1.


6
3
0
-3
-6
-9
-12
10 log S_o/N_o
0.1
1.0
10.0
Signal Bandwidth (kHz)

thresholds obtained with gated maskers. The data have been averaged for the two subjects. (Tables 3-4 and 3-5 contain the results for the two listeners separately.) Each figure presents results for a single ERB of masker. Except for the right endpoint of each plot, the masker bandwidth is greater than the signal bandwidth. Each figure shows how intensity discrimination varies for signals of different bandwidth detected in a masker of fixed bandwidth (where $W_s < W_n$). The solid diagonal line in each figure shows theoretical values of S_o/N_o (in dB) calculated from Green's model. It should be noted, again, that this model assumes that the receiver filters the input ("rectangularly") to match the bandwidth of the signal; frequency components of the masker outside the signal band are infinitely attenuated. (The diagonal line composed of short dashes is also theoretical and will be referred to later.)

Since the trends in the data are essentially the same for Figures 3-3 thru 3-5, Figure 3-5 (where W_n = 10,000 Hz) will be used to illustrate the general findings. (Figure 3-2 displays thresholds for the 100-Hz signal detected in narrow-band maskers. These data will be discussed in the next chapter.) Table 3-6 gives reciprocity-factors for lines best-fitting the data in Figure 3-5. The results indicate that intensity-discrimination thresholds for noise signals ($W_s < W_n$)

Table 3-4

Noise Intensity-Discrimination as a Function of Signal Bandwidth (HPB) When $W_s < W_n$. Data for Subject PS.

Wn (Hz)	Masker Spectrum-level (dB SPL)	Signal Bandwidth (Hz)			
		100	316	1000	3160
316	C 45 dB	-11.6			
316	C 25 dB	-9.5			
316	C 5 dB	+1.1			
316	G 45 dB	-7.9			
316	G 25 dB	-5.6			
316	G 5 dB	+4.1			
1000	C 45 dB	-1.0	-2.2		
1000	C 25 dB	-0.4	-0.7		
1000	C 5 dB	+0.5	-1.3		
1000	G 45 dB	+2.5	-0.7		
1000	G 25 dB	+4.3	+4.3		
1000	G 5 dB	+5.0	+2.7		
3160	C 45 dB	+0.5	-2.1	-4.8	
3160	C 25 dB	+1.3	-2.0	-1.9	
3160	C 5 dB	+0.8	-3.6	-4.8	
3160	G 45 dB	+2.4	+6.0	+2.4	
3160	G 25 dB	+4.0	+3.6	+0.1	
3160	G 5 dB	+2.2	+3.4	-1.3	
10,000	C 45 dB	-0.4	-2.6	-5.2	-7.1
10,000	C 25 dB	+0.4	-2.8	-4.8	-5.9
10,000	C 5 dB	+0.4	-3.6	-5.8	-7.5
10,000	G 45 dB	+5.2	+6.1	+1.0	-7.7
10,000	G 25 dB	+5.0	+5.7	+1.0	-2.6
10,000	G 5 dB	+2.2	+5.0	+1.7	-3.1

Note: Results are given as threshold values of 10 log S_o/N_o.
C indicates continuous maskers.
G indicates gated maskers.

Table 3-5

Noise Intensity-Discrimination as a Function of Signal Bandwidth (HPB) When $W_s < W_n$. Data for Subject MB.

W_n (Hz)	Masker Spectrum-level (dB SPL)	Signal Bandwidth (Hz)			
		100	316	1000	3160
316	C 45 dB	-10.7			
316	C 25 dB	-5.6			
316	C 5 dB	+0.5			
316	G 45 dB	-2.9			
316	G 25 dB	-0.5			
316	G 5 dB	+2.9			
1000	C 45 dB	-0.3	-2.7		
1000	C 25 dB	-0.7	-2.6		
1000	C 5 dB	-1.0	-3.3		
1000	G 45 dB	+3.4	+1.1		
1000	G 25 dB	+6.6	+3.8		
1000	G 5 dB	+3.6	+2.7		
3160	C 45 dB	+1.3	-1.3	-2.4	
3160	C 25 dB	+0.9	-2.1	-4.7	
3160	C 5 dB	+0.8	-3.6	-5.8	
3160	G 45 dB	+1.6	+0.2	+2.8	
3160	G 25 dB	+1.6	+1.0	-0.4	
3160	G 5 dB	+3.1	-0.8	-3.4	
10,000	C 45 dB	-0.0	-1.7	-1.5	-5.9
10,000	C 25 dB	+1.6	-1.9	-3.0	-7.3
10,000	C 5 dB	+0.2	-2.9	-2.8	-7.7
10,000	G 45 dB	+2.9	+1.3	+3.1	-4.1
10,000	G 25 dB	+2.5	-0.9	-0.9	-2.8
10,000	G 5 dB	+1.2	-1.8	-1.3	-2.9

Note: Results are given as threshold values of 10 log S_0/N_0.
C indicates continuous maskers.
G indicates gated maskers.

Table 3-6

Reciprocity-factors for the Results Presented in Figure 3-5

Masker Spectrum-level (dB SPL)	Continuous Masker	Gated (1) Masker	Gated (2) Masker
5	-5.5	-5.1	-7.1
25	-5.2	-5.6	-6.7
45	-4.7	-7.3	-9.3
Mean	-5.1	-6.0	-7.7

Note (1): Computation of best-fitting line included data for W_n = 100 Hz.

Note (2): Computation of best-fitting line omitted data for W_n = 100 Hz.

presented in a continuous masker of fixed bandwidth (W_n = 10,000 Hz), vary as a function of W_s in a manner similar to that reported by Green (1960).

The mean reciprocity-factor, averaged across masker spectrum-levels, was -5.1 for the continuous conditions. Gated maskers yielded an average reciprocity-factor of -6.0. Regression lines were also determined for the gated conditions omitting the left endpoint of each plot, i.e., for all signal bandwidths greater than 100 Hz. The table shows that the reciprocity-factors for these lines are clearly larger (negatively) than -5.0, the value predicted by Green's model. Thus we see that signal bandwidth has a much greater effect on discrimination performance in the heterogeneous conditions, than in the homogeneous conditions.

Real observers show poorer discrimination than the optimal model. The 5 to 6 dB difference in threshold S_o/N_o between theory and experiment that was observed by Green with continuous maskers (W_s < W_n) is also seen in our results (e.g., see Figure 3-5). Furthermore, performance is clearly worse with gated maskers than with continuous maskers. The optimal model does not, however, distinguish between continuous and gated conditions; predicted thresholds are identical for both modes of masker. The ideal receiver has precise knowledge of signal onset and termination and "filters" in the time domain, by listening only during the observation periods. One would suppose that these assumptions about timing information are better satisified for real observers when the stimuli are gated. One would therefore expect performance to be better with gated than with continuous maskers. Our results fail to confirm this notion; discrimination is poorer with gated maskers.

To summarize, increasing signal bandwidth results in better discrimination performance in heterogeneous conditions with both continuous and gated maskers. For all masker bandwidths, therefore, the threshold value of S_o/N_o is least when $W_s = W_n$ (the homogeneous condition). With continuous maskers the effect of signal bandwidth on intensity discrimination was found to agree with both theory and data as reported by Green (1960). Gated maskers are, however, everywhere more effective than continuous maskers for the heterogeneous conditions ($W_s < W_n$). Both this finding and the fact that gated bursts of noise yield reciprocity-factors greater than -5.0, present difficulties for the ideal receiver model.

C. Factors Influencing the Bandwidth Effect

Our research has confirmed the reports of both Raab and

Goldberg (1975) and Green (1960). When signal and masker are gated together and filtered together (Raab and Goldberg), bandwidth has little effect on discrimination. On the other hand, when noise signals are presented in continuous broadband maskers (as in Green's experiments), the reciprocity of S_o/N_o with W_s approximates that given by the optimal decision model. These two experimental designs (homogeneous-gated and heterogeneous-continuous) are, of course, equivalent for the ideal receiver. For real observers they are not.

Should the difference in findings between the Green experiment and the Raab and Goldberg study be attributed to the mode of presentation of the noise masker? Or, is the difference a consequence of the bandwidth conditions, in that the bandwidths were homogeneous in one study and heterogeneous in the other? Unfortunately, the relative importance of the two factors cannot be assessed by comparing the two experiments since confounding is complete. Here, however, we have varied the two factors separately and are in a position to understand why Green differs from Raab and Goldberg with respect to the effect of bandwidth on intensity discrimination.

We analyze our results as follows. The mode of the noise masker has only a minor influence on the magnitude of the bandwidth effect for the homogeneous conditions;

reciprocities are similar for both continuous and gated maskers (see Table 3-3). However, for the heterogeneous conditions that utilized continuous maskers, the data show reciprocity-factors of about -5.0, whereas the results with gated maskers show an even larger bandwidth effect (see Table 3-6). Thus the mode of the masker has little influence on the degree of reciprocity for the homogeneous conditions, but does affect the magnitude of the bandwidth effect when $W_s < W_n$. Mode is a factor in determining the reciprocity of S_o/N_o with W_s, but since its effect depends on the bandwidth conditions, the two factors obviously interact.

Bandwidth conditions also affect the degree of reciprocity. Changing from homogeneous to heterogeneous conditions increases reciprocity-factors, the magnitude of the change depending upon the mode of the masker.

We see then, that the effect of signal bandwidth on intensity discrimination is not a simple one. The magnitude of the bandwidth effect depends on both the mode of the masker, and on bandwidth conditions (homogeneous or heterogeneous). The findings of Green, and of Raab and Goldberg, though contradictory, are both confirmed; the degree of reciprocity of S_o/N_o with W_s results from the interaction of both factors.

Our subjects behaved like the ideal receiver with respect to changes in signal bandwidth only when the masker was presented continuously, with W_s smaller than W_n (Green's 1960 experimental procedure). The other conditions yield reciprocities different from the predictions of the model. Green's finding of a reciprocity-factor of about -5 was in some sense fortuitous; had he employed any of the other three procedures he would have failed to confirm the theory with respect to the effect of signal bandwidth.

D. The "Masker-Bandwidth Model" for Noise-in-Noise

Green's ideal receiver adjusts its filter to match the bandwidth of the signal (W_s). Components of the masker which lie outside the signal passband (as when $W_n > W_s$) play no part in decision making. Thus, for a signal of specified bandwidth, performance is identical for the homogeneous and the heterogeneous conditions. The data from our experiment indicate that human observers do not filter the noise input to match the signal bandwidth; the presence of masking energy outside the signal passband results in elevated discrimination thresholds. That is to say, for a signal of bandwidth W_s, the threshold value of S_0/N_0 depends on the bandwidth (W_n) of the masker presented with it.

Given these results, it seems worthwhile to examine an extension of Green's model which treats the case of a receiver whose bandwidth equals or exceeds that of the masker (the "masker-bandwidth model"). This model, which has been derived by Raab (unpublished), is presented in Appendix I. Explicit expressions are given for the mean and variance of the density function for noise energy conditional on one of two hypotheses, either "signal plus masker" present, or "masker" present alone, during the observation interval. For a 2IFC experiment, the model yields "M," the normalized mean of the difference distribution, as given by Equation 3-1:

$$M = \frac{\sqrt{W_s T}}{\sqrt{2}} \cdot \frac{S_o}{N_o} \cdot \frac{1}{\sqrt{W_n/W_s + S_o/N_o + 1/2(S_o/N_o)^2}} . \qquad (3\text{-}1)$$

This equation corresponds to Equation (1-1) of Green's model (the "signal bandwidth model").

The equations are identical when $W_s = W_n$ -- the homogeneous conditions; both models predict the same threshold value of S_o/N_o when the signal and the masker have the same bandwidth. If we assume that $S_o/N_o \ll W_n/W_s$, Equation 3-1 may be approximated by

$$M \approx \frac{W_s}{\sqrt{W_n}} \cdot \frac{\sqrt{T}}{\sqrt{2}} \cdot \frac{S_o}{N_o} . \qquad (3\text{-}2)$$

This equation is analogous to Equation 1-2 for Green's model, where it is assumed that $S_o/N_o << 1$.

The signal-bandwidth model ("W_s-model") generates a square-root reciprocity between S_o/N_o and W_s, i.e., a reciprocity-factor of -5.0. Equation 3-2 of of the masker-bandwidth model ("W_n-model") shows that S_o/N_o and W_s trade equally (i.e., the reciprocity-factor equals -10.0) for signals presented in a masker of fixed and broader bandwidth. It is worth noting that the derivation of the W_n-model incorporates the same statistics of noise-energy fluctuations as the W_s-model. Nevertheless, the two models yield different intensity-bandwidth reciprocities. The performance predicted by the masker model is the same as that which would occur if energy fluctuations did not exist. In this respect, the finding of complete reciprocity between intensity and bandwidth parallels the intensity-duration trades described in classical psychophysics.

We can now identify the dashed theoretical lines in Figures 3-2 thru 3-5. They are plots of threshold values of 10 log S_o/N_o as a function of W_s, computed from Equation 3-1 of the masker-bandwidth model. It is apparent from the figures that the signal-bandwidth model predicts smaller thresholds than the masker bandwidth model whenever $W_n > W_s$. A receiver that does not adjust its filter to match the signal bandwidth performs more poorly than one that does.

How do the results of our experiment compare with the predictions of the W_n-model with respect to the effect of changing signal bandwidth? It will be recalled that the obtained reciprocity-factors for the homogeneous conditions are between -1 and -2 with both continuous and gated maskers. In the heterogeneous conditions the reciprocity-factors are approximately -5 when the noise masker is presented continuously and between -5 and -10 when the masker is gated with the signal. When bandwidths are homogeneous, neither the W_s-model nor the W_n-model adequately describes the effect of bandwidth on intensity discrimination. The results for the heterogeneous conditions with continuous maskers show a bandwidth effect which accords with the predictions of the W_s-model. The data for the heterogeneous conditions with gated maskers give reciprocities more in line with the W_n-model's assumption that the receiver's input filter has a bandwidth greater than W_s.

Let us summarize some of the difficulties with both models. First, our observers perform better than the ideal receivers when signals are narrow-band. Clearly some of the assumptions of both models do not apply in these instances. Second, for signal bandwidths greater than some minimum value, intensity discrimination is worse than predicted by both models. Third, while mode of masker presentation does affect the level of performance in certain conditions, the models do not distinguish between continuous and gated maskers. Fourth, our results show that the magnitude of the bandwidth effect depends on both the mode of the masker and the bandwidth conditions. The receiver of the W_s-model is insensitive to all these changes in procedure and predicts a reciprocity-factor of -5 for all four conditions. The W_n-model also ignores the mode of masker presentation and yields different reciprocity-factors for the homogeneous and heterogeneous conditions (-5 and -10, respectively). In summary, both ideal receiver models, which are based solely on the statistical properties of noise, fail in several respects to account for the results of our experiment. We shall discuss other approaches to modeling noise-intensity discrimination in Chapter IV.

E. Filtering by Human Observers

We seek now to determine the input passbands actually used by our subjects for each of the various signal bandwidths. For this purpose the results of our experiment have been replotted in Figures 3-6 thru 3-9. Each figure shows how discrimination varies for a signal of fixed bandwidth (W_s), as a function of the bandwidth (W_n) of the masker. Both signal and masker bandwidths are given as equivalent rectangular bandwidths. Also plotted are theoretical values of 10 log S_o/N_o for both the W_s-model (solid line) and the W_n-model (dashed line). Since stimulus energy outside the receiver's passband has no influence on intensity discrimination, plots of the kind shown in these figures will have zero slope for bandwidths greater than the passband being used by the receiver. Fletcher (1940) used a similar method of analysis to calculate the widths of the critical bands for tones masked by noise.

What are the forms of theoretical plots yielded by the two models using this presentation? The receiver of the signal-bandwidth model is unaffected by noise energy outside its passband (W_s); plots of its theoretical thresholds are, therefore, horizontal lines. For the masker-bandwidth model, Equation 3-2 gives a square-root trade between S_o/N_o and W_n (for fixed W_s and constant detectability). That is to say, this model predicts elevated threshold values of S_o/N_o as the receiver listens with a wider and wider passband.

If our human observers were either adjusting their

Figure 3-6

Noise-intensity discrimination for a signal of 119 Hz ERB, as a function of masker bandwidth. The parameters are masker spectrum-level (▲ = 5 dB; ● = 25 dB; ■ = 45 dB) and mode of masker (solid lines: continuous; dashed lines: gated). The solid line without data points is the theoretical function computed from Equation 1-1; the dotted line without data points is the theoretical function computed from Equation 3-1.

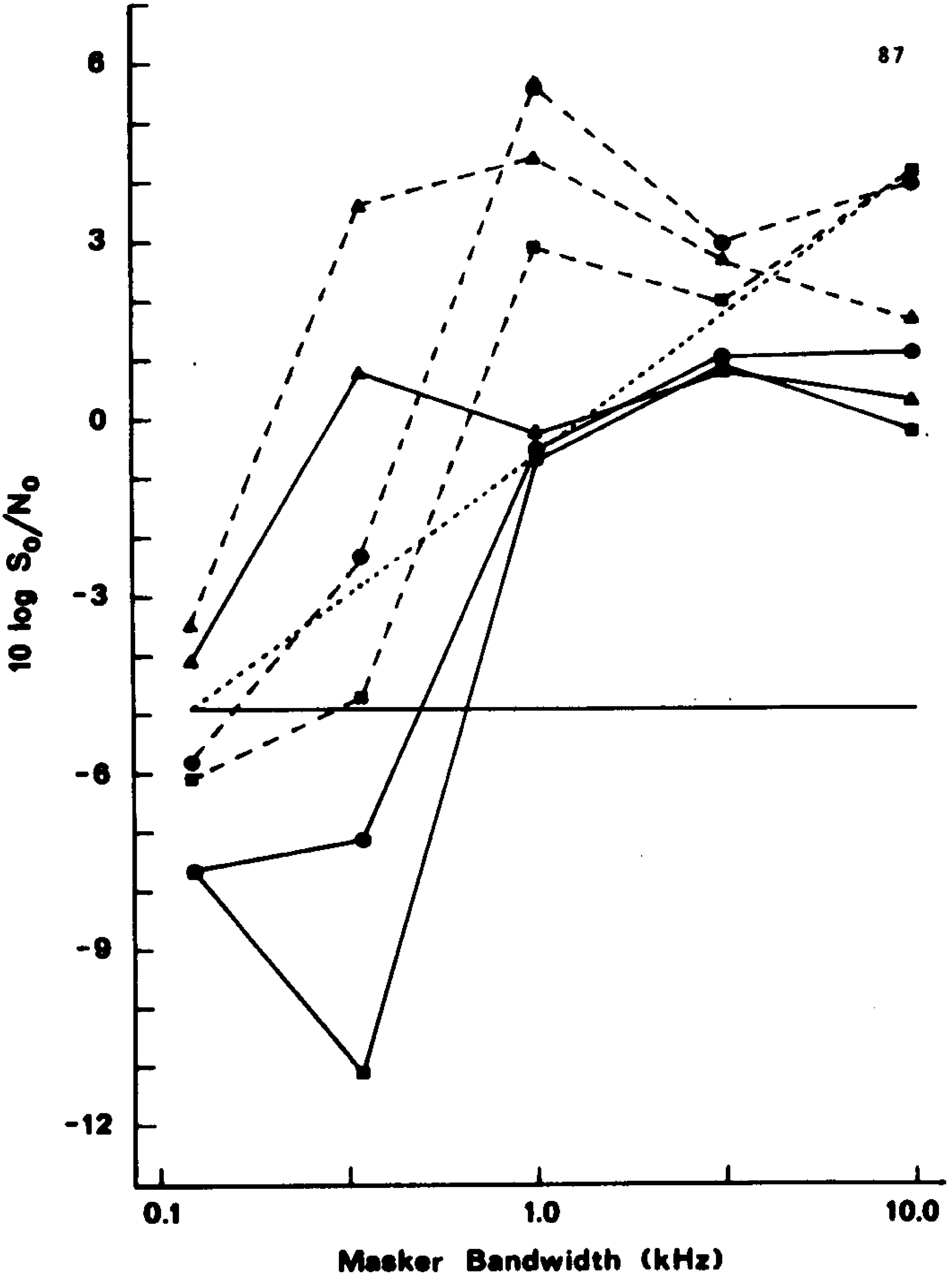
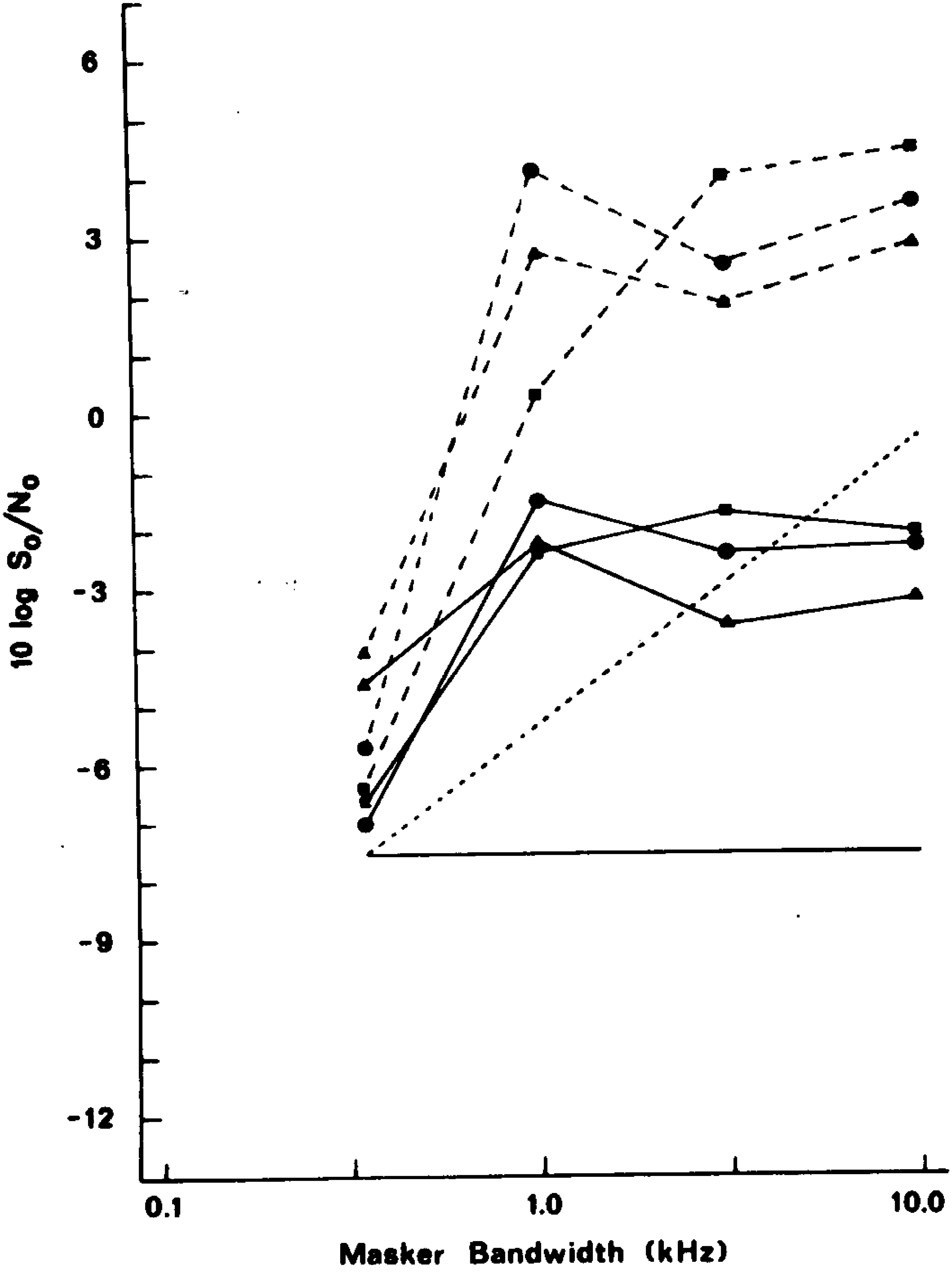

10 log S_0/N_0
6
3
0
-3
-6
-9
-12
0.1
1.0
10.0
Masker Bandwidth (kHz)

Figure 3-7

Noise-intensity discrimination for a signal of 344 Hz ERB, as a function of masker bandwidth. The parameters are masker spectrum-level (▲ = 5 dB; ● = 25 dB; ■ = 45 dB) and mode of masker (solid lines: continuous; dashed lines: gated). The solid line without data points is the theoretical function computed from Equation 1-1; the dotted line without data points is the theoretical function computed from Equation 3-1.



6
3
0
-3
-6
-9
-12
10 log S_0/N_0
0.1
1.0
10.0
Masker Bandwidth (kHz)

Figure 3-8

Noise-intensity discrimination for a signal of 1013 Hz ERB, as a function of masker bandwidth. The parameters are masker spectrum-level (▲ = 5 dB; ● = 25 dB; ■ = 45 dB) and mode of masker (solid lines: continuous; dashed lines: gated). The solid line without data points is the theoretical function computed from Equation 1-1; the dotted line without data points is the theoretical function computed from Equation 3-1.

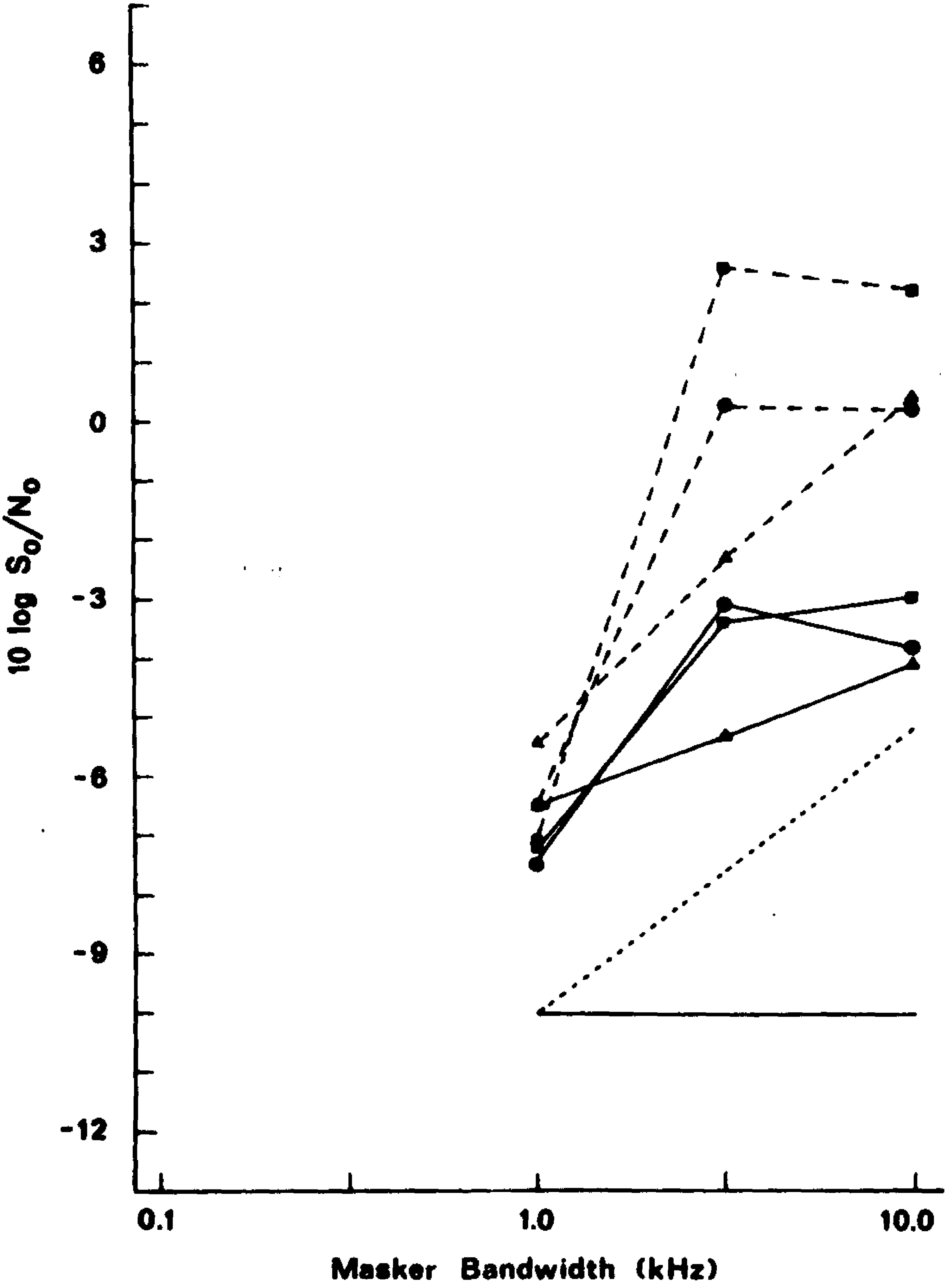
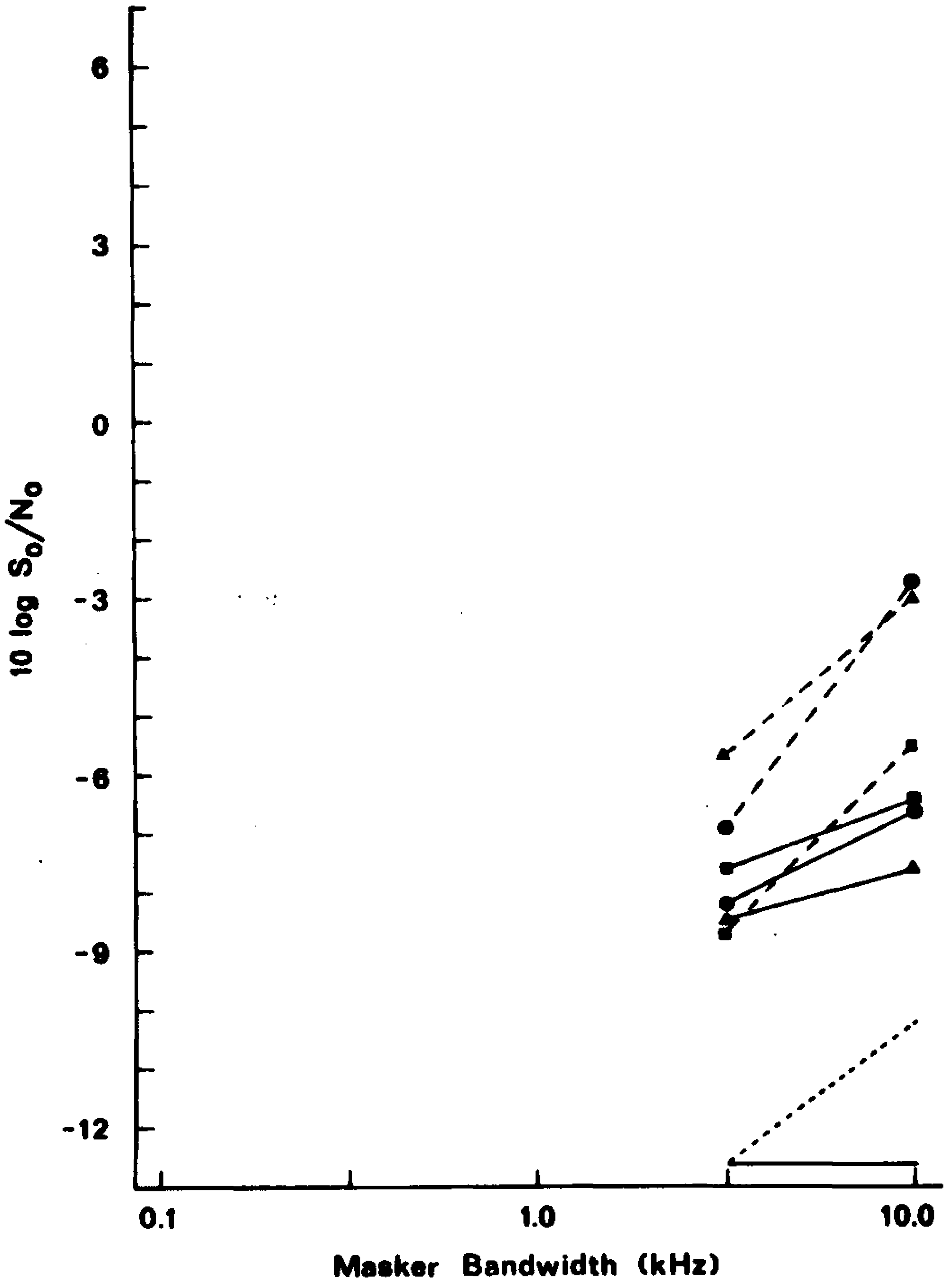

10 log S_o/N_o
6
3
0
-3
-6
-9
-12
0.1
1.0
10.0
Masker Bandwidth (kHz)

Figure 3-9

Noise-intensity discrimination for a signal of 3206 Hz ERB, as a function of masker bandwidth. The parameters are masker spectrum-level (▲ = 5 dB; ● = 25 dB; ■ = 45 dB) and mode of masker (solid lines: continuous; dashed lines: gated). The solid line without data points is the theoretical function computed from Equation 1-1; the dotted line without data points is the theoretical function computed from Equation 3-1.


10 log S_o/N_o
6
3
0
-3
-6
-9
-12
0.1
1.0
10.0
Masker Bandwidth (kHz)

input filters to match the passband of the masker, or listening with a wide open passband, then we should expect their performance to worsen as W_n grew larger. The data in Figures 3-6 thru 3-9 show that threshold values of S_o/N_o are in fact relatively constant beyond some "critical" value of masker bandwidth. This is so for both continuous and gated maskers.

It is difficult to determine precisely the passbands used for each signal. While we have used noise covering a two-decade range of bandwidths, only five values of bandwidth were employed. Interpolation between these coarsely spaced (1/2 log-unit) stimuli is risky. Furthermore, while both this method of analysis and the models we have been considering assume a rectangular passband for the input filter, it is unlikely that such an "ideal" filter is utilized by real listeners. Swets et al. (1962) have shown how estimates of the bandwidth of the listener's filter depend on the assumed "shape" of its passband. Since the data can provide no clue as to the type of filter used by our subjects, it is impossible to determine the actual bandwidths used. Nevertheless, the plots in Figures 3-6 thru 3-9 do permit some characterizations of the filtering process. First, it is clear that real observers are doing some filtering of the stimulus; they are not listening to all frequencies in the masker. Second, they apparently do not narrow their filters sufficiently to match the signal bandwidth. Third, input passbands are different for each value of signal bandwidth; the horizontal portion of each plot begins at greater values of W_n as W_s increases. Fourth, observers are able to set and maintain filter passbands greater than one critical band (160 Hz for a center frequency of 1000 Hz; see Scharf, 1970, p. 162). Fifth, for a given signal, the input passband appears to depend somewhat on both the mode and the spectrum-level of the masker.

F. Intensity-Discrimination Functions for Bands of Noise

Intensity-discrimination functions were determined for each combination of signal and masker bandwidth employed in the experiment. Specifically, plots of threshold S_o (in dB SPL) against N_o (in dB SPL) were fitted by straight lines using a least-squares criterion. Presented this way, a slope of unity indicates a finding of Weber's Law. Tables 3-7 and 3-8 list the slopes of these intensity-discrimination functions for the two subjects.

We shall first discuss the results for the conditions where signal and masker bandwidths are equal. Weber's Law fails to describe intensity discrimination when the noise is

Table 3-7

Slopes of Best-Fitting Lines for Intensity-Discrimination Functions. Data for Subject PS.

W_s (Hz)	Mode	Masker Bandwidth (Hz)				
		100	316	1000	3160	10,000
100	C	0.92	0.68	0.96	0.99	0.98
100	G	0.90	0.70	0.94	1.00	1.07
316	C		0.94	0.98	1.04	1.03
316	G		0.94	0.91	1.07	1.03
1000	C			0.96	1.00	1.02
1000	G			0.95	1.09	0.98
3160	C				1.02	1.01
3160	G				0.92	0.89
10,000	C					1.01
10,000	G					0.97

Note: C indicates continuous masker.
G indicates gated masker.

Table 3-8

Slopes of Best-Fitting Lines for Intensity-Discrimination Functions. Data for Subject MB.

W_s (Hz)	Mode	Masker Bandwidth (Hz)				
		100	316	1000	3160	10,000
100	C	0.91	0.72	1.02	1.01	0.99
100	G	0.96	0.85	0.99	0.96	1.04
316	C		0.97	1.02	1.06	1.03
316	G		0.94	0.96	0.99	1.08
1000	C			1.01	1.09	1.03
1000	G			0.96	1.16	1.11
3160	C				1.03	1.05
3160	G				0.94	0.97
10,000	C					1.05
10,000	G					1.00

Note: C indicates continuous masker.
G indicates gated masker.

narrow-band. This is so for both modes of the masker. The computed slopes are less than unity; discrimination is more acute for higher spectrum-levels of the masker (the "near-miss" to Weber's Law.) In the continuous condition, the slopes increase as the bandwidth of the stimulus is broadened. Indeed, at the two widest bandwidths -- 3160 Hz and 10,000 Hz -- the slopes just exceed unity, for both observers. Stimulus bandwidth has a much smaller effect on the slope of the intensity-discrimination function when the noise-bands are gated. Additionally, slopes are smaller when the maskers are gated then when they are continuous, with the result that Weber's Law is nowhere obtained except perhaps for the 10,000 Hz band of noise. Thus both bandwidth and the mode of the masker affect the slope of the intensity-discrimination function for the homogeneous condition.

The slopes for the heterogeneous conditions can be compared by reading across the rows of the tables. The mode of the masker apparently has little influence on the slope of the intensity-discrimination function when the bandwidth of the masker is greater than the bandwidth of the signal. In some cases the slope for the continuous condition is larger than the slope for the corresponding gated condition; for other bandwidth combinations, the reverse is true. Slopes are close to or slightly greater than unity for the heterogeneous conditions, with the exception of one bandwidth combination. Pairing signals of 100 Hz bandwidth with maskers of 316 Hz bandwidth results in intensity-discrimination functions with slopes considerably smaller than unity (the range across observers being 0.68 to 0.85). This is found with both continuous and gated maskers. An explanation for this finding will be offered in the next chapter, when we examine possible mechanisms of intensity discrimination.

Both the W_s-model and the W_n-model predict that the slope of the intensity-discrimination function is unity. Furthermore, both ideal models hold that Weber's Law is true whether maskers are homogeneous or heterogeneous. Our results show, however, that not only does Weber's Law fail to hold for some experimental conditions, but also that the mode of the masker and the bandwidth conditions do affect the slope of the intensity-discrimination function.

In summary, when $W_s = W_n$, narrow-band stimuli yield intensity-discrimination functions with slopes less than unity for both modes of the masker. As the noise bandwidth increases in the homogeneous condition, slopes of intensity-discrimination functions approach or exceed unity with the continuous maskers, and tend to remain less than unity with the gated maskers. For the heterogeneous conditions, we see that intensity-discrimination functions have slopes equal to or slightly greater than unity when a noise signal is detected in the presence of a wide-band masker (W_n > 1000 Hz). This is so for both continuous and gated versions of the masker. Finally, both ideal receivers fail to account for the observed effects of both masker mode and bandwidth conditions on the slopes of intensity-discrimination functions.

Chapter IV

DISCUSSION

This chapter is divided into two sections. First, the experimental findings are compared with the results of the studies reviewed in the Introduction (Chapter I). Second, discrepancies between the energy-detector theories (W_s-model and W_n-model) and the data are examined. Several modifications of the ideal models are proposed.

A. Comparisons with Earlier Studies of Noise-Intensity Discrimination

1. The Bandwidth Effect for Noise-Intensity Discrimination

The experimental results presented in the preceding chapter demonstrate that the magnitude of the bandwidth effect is a function of both mode of masker and bandwidth conditions. (Comparison of the present research findings with the literature reviewed in Chapter I will be facilitated by referring to Table 1-1, which summarizes studies of the bandwidth effect.) Green (1960) and Campbell (1964) used continuous maskers to obtain detection thresholds as a function of signal bandwidth. In both experiments, masker bandwidth was fixed and broadband (heterogeneous-continuous conditions). Reciprocity-factors computed from their data accord with our results as well as with the energy-detector model (W_s-model). Note that signal bandwidth varied independently of center frequency in the present study and covaried with center frequency in the Green and Campbell experiments. Bos and de Boer (1966) employed continuous maskers, but kept W_s and W_n equal as stimulus bandwidth changed. The intensity-bandwidth reciprocity observed in that experiment (which used pink noise as a secondary masker) is in agreement with the magnitude of bandwidth effect we obtained under the homogeneous conditions with continuous maskers.

This dissertation provides the only data on the bandwidth effect for gated maskers when $W_s < W_n$. Subjects exhibit a greater degree of intensity-bandwidth reciprocity than is described by the W_s-model, although reciprocity-factors are smaller than those given by the W_n-model. Several experimenters have studied the bandwidth effect with gated maskers and homogeneous conditions. Raab and Goldberg (1975) found that noise bandwidth had little influence on detection -- a result confirmed by our study. Both Small et al. (1959) and Moore (1974) obtained slightly greater intensity-bandwidth trades than reported in the two preceding studies. In the Small et al. and Moore experiments W_s and f_c covaried, while in the Raab and Goldberg study and in the present experiment f_c was fixed as W_s varied. De Boer's (1965) data yield an even larger intensity-bandwidth reciprocity, one that is close to the prediction of the W_s-model. De Boer employed pink noise stimuli; his experiment, therefore, is not altogether comparable with the others. (Moore and Raab, 1975, employed a continuous bandstop background to vary the bandwidth of gated noise-bursts; they obtained reciprocities "shallower" than -5 dB/log-unit of bandwidth. The significance of this experiment will be explored later in the chapter.) With the exception of the de Boer results, it is clear that bandwidth has a smaller effect on intensity-discrimination, under homogeneous conditions with gated maskers, than is given by either of the energy-detection schemes (W_s-model, W_n-model).

Experiments employing the amplitude-modulation technique provide additional data on the bandwidth effect. A problem arises in trying to categorize the "mode" of the masker under this procedure. It could be argued, that detecting a low rate of sinusoidal flutter of a noise carrier is akin to the discrimination of increments and/or decrements in a noise background. Thus the AM procedure could be considered a variant of the configuration we have called "homogeneous-continuous." Unfortunately, the reciprocity-factors computed from the data of Zwicker (1956), Zwicker and Feldtkeller (1967), and Maiwald (1967) resemble those found for heterogeneous conditions and continuous maskers. Why Rodenburg (1972) obtained an average reciprocity-factor of -13.4 is not clear at all, since he used essentially the same AM procedure employed in the previous studies. (The modulation rate he chose was, however, about three times greater than the rates used in the Zwicker and Maiwald experiments.) That manipulating bandwidth affects performance under the AM paradigm is obvious -- whether the two ideal models should be applied to this class of experiments is not so apparent. Therefore, the remainder of this discussion deals only with the more conventional procedures employing continuous and gated maskers.

2. Intensity-Discrimination Functions for Noise Bands

With the exception of experiments by Green and Sewall (1962), and Viemeister (1974), Weber's Law has been reported for intensity discrimination of "wideband" noise. This is true for continuous maskers (Miller, 1947; Harris, 1950; Pollack, 1951; Raab, Osman and Rich, 1963); for gated maskers (Postman, 1946; Harris, 1950; Small, Bacon and Fozard, 1959; Viemeister, 1974; Moore and Raab, 1975); and for the study employing the amplitude-modulation technique

(Zwicker, 1956). In all these studies, signal and masker bandwidth were equal (homogeneous conditions).

The data of Bos and de Boer (1966) exhibit a "near-miss" to Weber's Law for noise bands of 200 Hz and 800 Hz (continuous maskers, $W_s = W_n$). This is contradicted by Maiwald (1967), who, using the AM method, found that performance is independent of level for a narrow band (127-Hz) of noise. (As we have previously noted, the AM experiment employs a masker that is not simply classified as either continuous or gated.)

It would seem that when $W_s = W_n$, "wideband" stimuli yield Weber's Law, whereas discrimination improves with increasing level for "narrowband" stimuli. Noise bands are not "wide" or "narrow" in any absolute sense, of course, but only in relation to one another. Intensity-discrimination functions obtained in the present study under homogeneous conditions have slopes that increase towards unity as stimulus bandwidth increases (see Tables 3-7 and 3-8). It is not surprising, therefore, that Weber's Law has been reported for "wideband" stimuli. Indeed, our results show slopes increasing with bandwidth from values below 1.0 to values exceeding 1.0. With the widest passbands, performance worsens with increasing level.

Ours is the only experiment yielding intensity-discrimination functions for heterogeneous bandwidth conditions. Slopes close to or exceeding unity are evidenced for most combinations of signal and masker bandwidth. (The major exception occurs when $W_s = 100$ Hz and $W_n = 316$ Hz. More will be said about this later.) Furthermore, the mode of the masker apparently has little effect on the slope of the intensity-discrimination function. For some pairs of W_s and W_n the slope for the continuous condition is greater than the slope for the corresponding gated condition; for other pairs the reverse is true.

To summarize, when signal and masker bandwidths are equal, slopes of intensity-discrimination functions range from about 0.90 to 1.05, increasing as a function of stimulus bandwidth. For heterogeneous conditions, most combinations of W_s and W_n yield slopes equal to or greater than unity, regardless of masker mode.

C. Data and Theory: Energy Detector Models

1. Differential Sensitivity

The W_s-model describes a truly optimal receiver for white Gaussian noise. It is impossible to develop a better detection strategy for this kind of stimulus than measuring and comparing the energies within the signal passband during the observation periods. If the receiver does not or cannot set a rectangular input filter to match W_s, but listens instead with a bandwidth as large as that of the masker, then the W_n-model predicts the best performance obtainable. Once again the decision strategy employed is energy detection.

a. Differential Sensitivity: Homogeneous Conditions

It is instructive to compare the obtained Weber fractions with those generated by the W_s-model or the W_n-model. Consider, first, the results for the homogeneous conditions (Figure 3-1; Tables 3-1 and 3-2). Here the W_s-model and the W_n-model are indistinguishable and we will simply refer to the W_s-model. For the 100-Hz noise bands, subjects exhibit Weber fractions (S_o/N_o) that are "impossible," i.e., better than energy detector performance. With gated maskers they are about 1 dB more acute than predicted (averaged across subjects for the two higher masker levels); with continuous maskers they are approximately 2.5 dB better than given by theory. Obtained thresholds are poorer than those of the ideal receiver for all other (homogeneous) bandwidths used in the experiment. If energy detection is the optimal stimulus processing technique for noise bands, how, then, could our subjects ever achieve performance superior to the ideal model? If they can perform better than "ideal" for some bandwidths, why are empirical thresholds higher than predicted for other passbands?

For energy detector models, performance in a discrimination task is limited solely by the statistical fluctuations inherent in the noise stimuli. The derivation of the W_S-model incorporates the "energy statistics" for Gaussian noise with a rectangular power spectrum (white noise). Unlike such "ideal" (white noise) stimuli, the noise bands used in our experiment did not have uniform power spectra, i.e., they were "tinted." Deriving unique ideal-detector models for each of our noise bands is not necessary. To employ Equation 1-1 of the W_s-model with a tinted noise band, we must first calculate the "equivalent statistical bandwidth (ESB)" of the stimulus. It is "the bandwidth of a hypothetical rectangular filter which would pass a signal with the same mean square value (of) statistical error as the actual filter when the input is white noise" (Bendat and Piersol, 1971, p. 278). Specifically,

$$\mathrm{ESB} = \frac{\left[\int_0^\infty |H(f)|^2 df\right]^2}{\int_0^\infty |H(f)|^4 df} , \qquad (4\text{-}1)$$

where $|H(f)|$ is the magnitude of the filter transfer function (in voltage) at any frequency, f. The ESB may then be directly substituted for the stimulus bandwidth -- W_s -- in Equation 1-1.

The approximate width of the ESB for each of the filters used in the experiment was computed by numerical integration. Table 4-1 lists these values along with the corresponding half-power (HPB) and equivalent rectangular (ERB) bandwidths of the filters taken from Table 2-1. The equivalent rectangular bandwidth is used to calculate stimulus spectral density (i.e., N_o and S_o), while the equivalent statistical bandwidth is the parameter for determining the percentage of correct decisions for the energy detector. In each case, ESB > ERB > HPB for our tinted noise bands. Had our stimuli been truly white, the three measures of stimulus bandwidth -- HPB, ERB, and ESB -- would have been identical. Consequently, an energy detector will exhibit lower discrimination thresholds for one of our tinted noise bands with an ERB equal to W, than for a white noise band with the same ERB (i.e., when ERB = W). Mathews and Pfafflin (1965) have presented a similar analysis for an energy detector which processes broadband noise shaped by a single-tuned filter.

Table 4-1

Alternate Specifications of the Stimulus Bandwidths Employed in the Present Experiment.

Half-Power Band. (HPB)	Equiv. Rect. Band. (ERB)	Equiv. Stat. Band. (ESB)
100	119	186
316	344	481
1000	1013	1158
3160	3206	3399
10,000	10,051	10,471

Note: Bandwidths are given in Hz.

Each plot of the performance of the W_s-model appearing in the figures in Chapter III was determined by substituting the ERB of each noise band for W_s in Equation 1-1. The assumption implicit in these calculations is that the stimuli are "ideal" (i.e., white) noise bands. Table 4-2 gives the degree of improvement in the theoretical thresholds when the computations are made utilizing the ESB of the stimuli rather than the ERB of the noise bands. With the narrowest noise-band employed, for example, the energy detector actually exhibits thresholds about 1 dB smaller than given by the theoretical plot for the receiver of the W_s-model. Thus, the discrepancies between our obtained thresholds for the 100-Hz stimuli and the predictions of the energy detector as displayed in Figure 3-1 are reduced. (The gap between theoretical and empirical thresholds increases somewhat for each of our other noise bands, although the increase in separation is less for the greater bandwidths.) While the 1 dB correction may bring the average empirical thresholds for the 100-Hz bands within the performance limits of the energy detector under the gated conditions, the thresholds with continuous maskers are still about 1.5 dB "better than energy detection."

Stimuli entering the receiver of the W_s-model undergo three stages of processing before a decision variable is computed (Green and Swets, 1966, p. 211). First, the

Table 4-2

Theoretical Thresholds for the Energy-Detector Model When Stimulus Bandwidth is Specified as Equivalent Statistical Bandwidth (ESB) and Equivalent Rectangular Bandwidth (ERB).

ESB	10 log S_O/N_O	ERB	10 log S_O/N_O
186	-6.01	119	-4.89
481	-8.29	344	-7.50
1158	-10.32	1013	-10.01
3399	-12.75	3206	-12.62
10,471	-15.24	10,051	-15.15

Note: All bandwidths given in Hz.

external noise is shaped by an input filter with a rectangular passband. Next, the output of this filter is fed to a square-law device which computes the power spectrum of the stimulus. Finally, the output of the square-law device is passed to an integrating mechanism, which computes a decision variable corresponding to the original stimulus.

The energy detector itself comprises only the second and third stages of the receiver. If the stimulus is white noise, and the receiver has a rectangular input filter with its passband matched to that of the stimulus, then optimal decisions can be made. For tinted noise bands, our analysis has shown that discrimination thresholds will be smaller if the stimulus is not filtered before it is fed to the energy detector, than if the receiver has a rectangular input filter with its passband matched to the ERB of the external noise. (Recall that ESB > ERB for these stimuli.) However, while listening to the tinted bands "wide-open" is a better strategy than employing a rectangular filter (as the W_S-model does), it is not the optimal method of stimulus processing.

What, then, is the optimal technique for processing homogeneous bands of Gaussian noise having a non-uniform spectral distribution? Consider a filter transfer function with less than infinitely steep skirts. In theory the filter will pass some energy at all possible frequencies. In practice, of course, the residual noise of the filter, and other system components, will "swamp" the filter output for frequencies far from the cut-off frequencies. We define that band of frequencies with spectral power densities greater than the spectrum level of the system noise as the "effective passband" of the filter; the difference between the highest and lowest frequencies within the effective passband is defined as the "effective bandwidth" of the filter. It can easily be demonstrated that the relative variability (sigma-to-mean ratio) of <u>white</u> Gaussian noise with bandwidth W, is less than the relative variability of Gaussian noise (effective bandwidth = W) with any other spectral energy distribution. (The system noise itself contributes some variability to the noise fed to the energy detector. The "contribution" from the system noise can be reduced to an arbitrarily small proportion of the total variability by choosing a somewhat smaller value for the effective bandwidth than specified by the definition.)

To optimize performance (by minimizing the relative variability of the stimulus) we require a device which will operate on the tinted noise and produce "ideal" (i.e., white) noise which is then fed to the energy detector (square-law device and integrator). This type of transformation is called "prewhitening" by communication engineers (Blackman and Tukey, 1958).

Under the homogeneous conditions a single filter is employed for stimulus generation on both halves of a 2IFC trial. Consequently, a mechanism for accomplishing prewhitening is easily specified. The input filter of the receiver should have a transfer function with the "inverse" (reciprocal) spectral characteristics of the stimulus.

Since white noise has a flat spectrum the transfer function of an "inverse filter" used with this stimulus will also be rectangular. Obviously, passing noise which is already white through such a filter has no affect on the relative variability of the stimulus. This simply confirms that the W_S-model (with its rectangular input filter) describes the optimal receiver for white noise.

The effects of prewhitening on discrimination performance for the 100-Hz stimulus are shown in Table 4-3. The table lists the effective bandwidths of broadband noise passed through the 100-Hz filter for various assumed levels of system noise. Included are threshold signal-to-masker ratios for energy detection of such stimuli after prewhitening. (The small increase in stimulus variability due to system noise is neglected.) These thresholds are compared, in the last column of the table, with the performance of an energy detector receiving white noise with

Table 4-3

Theoretical Thresholds for the Energy-Detector Model When Stimulus Bandwidth Is Specified as Effective Bandwidth. Stimulus ERB: 119 Hz; Theoretical Threshold: -4.89 dB.

System Noise dB re $\|H_m\|$	Effective Passband	Effective Bandwidth	10 log S_O/N_O	Improvement re -4.89 dB
-10	890 - 1117	227	-6.50	-1.61
-15	844 - 1175	331	-7.41	-2.52
-20	791 - 1250	459	-8.19	-3.30
-25	733 - 1352	619	-8.88	-3.99
-30	666 - 1485	819	-9.53	-4.64
-35	601 - 1660	1059	-10.12	-5.23
-40	534 - 1875	1341	-10.66	-5.77
-45	471 - 2117	1646	-11.12	-6.23
-50	427 - 2388	1961	-11.51	-6.62

Note: All frequencies given in Hz.

a bandwidth equal to the equivalent rectangular bandwidth of the 100-Hz filter (ERB = 119 Hz; 10 log S_O/N_O = -4.89 dB). For example, threshold signal to masker ratios are reduced by more than 3 dB if system noise limits the prewhitening process to those frequency components that are not more than 20 dB below the maximum response (|Hm|) of the filter. This degree of improvement in 10 log S_O/N_O is enough to reconcile the empirical thresholds of our subjects (for the 100-Hz bands, homogeneous conditions) with the theoretical performance of the energy detector. We have thus "salvaged" the energy detector by adding a stage of preprocessing. Note, also, that for any fixed level of system noise, prewhitening is less important for those stimuli with the larger ERB's. This is because the proportion of stimulus information -- energy -- outside the ERB of the filter decreases as the bandwidth (ERB) increases.

In order to prewhiten our noise stimuli (and thereby optimize decision making) we have postulated an "inverse" filtering mechanism to serve as the input stage of an energy detector. This would require a unique filter for each spectrally different stimulus that is to be detected. That so flexible a mechanism exists within the human auditory system is unlikely. How, then, might real listeners accomplish the task of reducing the relative variability of the stimuli?

All of the models presented so far (W_s-model, W_n-model, Mathews and Pfafflin "single-tuned" model, "inverse filter" model) are stimulus oriented in their approach to detection. All of them develop mathematical receivers limited in performance solely by fluctuations in the stimuli. Real observers, however, cannot make decisions solely on the basis of the physical stimulus. Stimulus energy is transduced by auditory receptors into nerve impulses. It is the "neural effect" generated by the stimulus that serves as the input to the observer's decision making apparatus. The behavior of real observers is, therefore, more adequately described by models which consider the neural correlates of stimulus events, and which specify the nature of the transformation of the stimuli to neural events. Models which incorporate these features are called "hybrid models" by Raab and Goldberg (1975), a term which we shall also employ. Examples of the hybrid approach to modeling in audition include papers by Siebert (1965,1968), McGill (1967; McGill and Goldberg, 1968a, 1968b), Luce and Green (1972), and Penner (1972).

It is generally accepted that stimulus energies are not transduced into neural effects in a linear fashion. As Zwislocki (1966, p. 23) has stated, "The neural response grows less rapidly than the stimulus intensity whereby a substantial compression of the useful intensity range is achieved." For instance, Hind et al. (1967), working with primary neurons in the auditory nerve of the squirrel monkey, present data showing that the firing rate (spikes *per second*) increases by only a factor of 4 for a 60 dB increase in the intensity of a 2000 Hz tone. Kiang (1965) had earlier provided similar data for the cat.

Neural compression of stimulus intensity provides a partial analog of the prewhitening process. Compression gives more weight to frequency components with a lower average power (i.e., those near the edges of the effective passband of the stimulus) than to those with a higher average power. The compression resulting from neural transduction does not "whiten" the stimulus as completely as if an "inverse filter" were used. Nevertheless, a considerable reduction in the relative variability of the neural effect evoked by the stimulus is obtained as a consequence of compression. (This is similar to the action of automatic volume control circuitry which is used to keep the instantaneous power of an amplifier close to the mean output power.) While the thresholds exhibited by our subjects for the 100-Hz bands of noise are indeed "impossible" for the receiver of the W_s-model (with its rectangular input filter matched to the ERB of the stimulus), they are entirely consistent with the performance of an energy detector model where the input is partially or completely prewhitened.

The experimental results show that, with the exception of the 100-Hz bands of noise, real listeners exhibit higher thresholds than those calculated for the two ideal-observer theories (W_s-model, inverse-filter model) under the homogeneous conditions. The combined effects of all those factors within an organism which degrade detection performance relative to the stimulus oriented models are generally lumped together under the rubric of "internal" or "biological" noise. Any process which reduces the information content of the stimulus by adding uncertainty (variability) is a type of internal noise. Green (1960) invokes a constant attenuation factor (for a fixed level of detectability) to reduce the efficiency of the Ws-model and thereby to reconcile the theory with his subjects' data. Although no physiological mechanism is specified, this is a reasonable thing to do, since each of his obtained signal-to-masker ratios (for fixed detectability) is about 5-6 dB larger than predicted by the W_s-model over the major range of signal bandwidths and durations employed in the experiment. The data plotted in Figure 3-1, do not, however, simply parallel the theoretical line for the energy detector -- the difference between empirical and theoretical thresholds increases with stimulus bandwidth. Thus our results cannot be predicted merely by reducing the efficiency of the W_s-model by a constant factor (i.e., a factor independent of bandwidth) as did Green.

For the receiver of the W_S-model, performance improves with increasing bandwidth since the relative variability of the stimulus decreases. The empirical results, however, show only a small bandwidth effect. This suggests that the relative variability of the test statistic used by the subject changes only slightly over a two-decade range of bandwidth. It would appear that the relative contribution of internal (additive) noise, to the relative variability of the test statistic, must decrease with stimulus bandwidth. Models which incorporate explicit specifications of internal noise mechanisms are considered later in the chapter.

What follows is a brief summary of some of our observations and conclusions on differential sensitivity under the homogeneous conditions: (1) An energy detector with a rectangular input filter set to match the stimulus passband is the optimal receiver for white Gaussian noise. (2) For Gaussian noise with a non-uniform spectral distribution, prewhitening of the stimulus before its power spectrum is computed improves detectability relative to thresholds for non-processed noise. The degree of improvement varies inversely with the level of system noise. (3) Through "neural compression" the human auditory system performs a partial prewhitening of noise stimuli. This serves to reduce the relative variability of the stimuli and thereby improve their discriminability. (4) Thresholds exhibited by our subjects for the 100-Hz stimuli are well within the theoretical performance limitations of an energy detector fed by a mechanism which "prewhitens" the stimulus ("inverse filter" model). That these thresholds are better than predicted by the W_s-model tends to support the analogy between "neural compression" and "prewhitening."

b. Differential Sensitivity: Heterogeneous Conditions

Three features of the data are noteworthy with respect to differential acuity for the heterogeneous conditions. First, empirical thresholds are better than those of the W_s-model when $W_s = 100$ Hz and $W_n = 316$ Hz (see Figure 3-2). Under these conditions subjects exhibit performance that is "impossibly" acute for a simple energy detector. On the other hand, subjects performed more poorly than the W_s-model when masker bandwidth was greater than 316 Hz (see Figures 3-3, 3-4, 3-5). Finally, it is significant, that, with the exception of the 100-Hz band of noise, a particular signal is always easier to detect under homogeneous conditions, than under heterogeneous conditions.

To explain these results it is necessary to explore in some detail the nature of the noise stimulus for each of the experimental procedures we employed. When a single filter is used to produce both the signal and the masker, as in our homogeneous conditions, the power spectra of the stimuli are identical (on the average) for both halves of a 2IFC trial. This would be true even if the filter generated white rather than tinted noise. Because S_o/N_o is the same in all frequency regions, noise components which are strongly attentuated by the filter are as important for decision making as components near the center of the passband. Thus it is to the receiver's advantage to listen as wideband as possible, constrained only by system noise.

While S_o/N_o remains constant throughout the stimulus spectrum under the homogeneous conditions, this is not the case for the heterogeneous conditions. The analysis is straight-forward if truly rectangular filters are used to generate the noise bands. For example, the power transfer function --$|H_s(f)|^2$-- of a hypothetical filter used to generate a 100-Hz signal is:

$$\begin{aligned} |H_s(f)|^2 &= 0; \quad f < f_1 \\ &= 0; \quad f > f_2 \\ &= 1; \quad f_1 < f < f_2 \end{aligned}$$

$$|H_s(f_c)|^2 = 1; \quad f_c = 1000 \text{ Hz}$$

$$W_s = f_2 - f_1 = 100 \text{ Hz},$$

where f_1 and f_2 are the lower and upper cut-off frequencies, respectively.

Similarly, for a hypothetical rectangular-filter generating a 316-Hz masker,

$$
\begin{aligned}
|H_n(f)|^2 &= 0; \quad f < f_3 \\
&= 0; \quad f > f_4 \\
&= 1; \quad f_3 < f < f_4
\end{aligned}
$$

$$|H_n(f_c)|^2 = 1; \quad f_c = 1000 \text{ Hz}$$

$$W_n = f_4 - f_3 = 316 \text{ Hz},$$

where f_3 and f_4 are the lower and upper cut-off frequencies, respectively.

For the compound stimulus (signal plus masker), the ratio S_o/N_o at any frequency, f, is directly proportional to the quotient of the filter transfer functions. That is,

$$\frac{S_o}{N_o} = k \cdot \frac{|H_s(f)|^2}{|H_n(f)|^2}$$

where k is a constant of proportionality. To simplify the analysis, we set "k" to unity and assume that S_O and N_O are equal at the common center frequency of 1000 Hz. Then for the hypothetical filters described above, S_O/N_O is constant and equal to unity within the signal passband, and equal to zero outside the band-limits of the signal over the range of frequencies encompassed by the masker. (The value of S_O/N_O is undefined, and of no interest, beyond the upper and lower cut-off frequencies of the masker.)

Given this distribution of S_O/N_O with frequency, the receiver should weight each stimulus component within the signal passband equally, and a null weighting factor should be assigned to stimulus components everywhere else. A simple mechanism for accomplishing this weighting with white noise stimuli is to pass the input to the receiver through a rectangular filter with its passband matched to that of the signal. The weighted stimulus is then fed to the energy detector. The receiver of the W_s-model employs just this method of stimulus processing.

Next, consider the response characteristics of the two filters used to generate the 100-Hz (HPB) and 316-Hz (HPB) noise bands actually employed in the experiment (c.f., Figure 2-1). The filters are obviously not "rectangular." Moreover, the shapes of their transfer functions are not the same. The compound (heterogeneous) stimulus is obtained by summing the outputs of the two filters when they are both fed from sources of broadband white noise. (Again, the analysis is simplified by assuming $S_0 = N_0$ at the common center frequency.) With these two filters, S_0/N_0 is distributed as follows: (1) Within the frequency limits of the half-power passband of the signal, $1/2 \leq S_0/N_0 \leq 1$. (2) As we move outside this region, S_0/N_0 rapidly decreases towards relative minima of approximately 0.06 and 0.04 at frequencies of 790 Hz and 1250 Hz, respectively. (That these minima are not equal is a consequence of a slight asymmetry in the transfer characteristic of the 100-Hz filter.) (3) Extrapolation of the curves in Figure 2-1 indicates that for frequencies either greater than 1250 Hz, or less than 790 Hz, S_0/N_0 increases rapidly, equalling, and, finally exceeding, unity.

For white noise stimuli under heterogeneous conditions, S_0/N_0 is unity within the signal passband and zero at all other frequencies where stimulus energy is present. Thus all information about the presence or absence of the signal is contained within the limits of the signal passband. For the tinted stimuli we have been examining, some information is present at all frequencies. While signal-to-masker ratios are moderate within the 100 Hz band centered at 1000 Hz, they are by far larger at frequencies more than 0.3 log units on either side of the center frequency. (When extrapolated, the transfer functions of the two filters cross at these points; see Figure 2-1.)

Can real listeners make use of signal-information at frequencies outside the nominal passband of the 100-Hz signal, where stimulus components are well below their spectrum levels near the center frequency? A paper by Leshowitz and Wightman (1971) suggests that this may be possible. These investigators examined the masking of tonal signals by continuous sinusoids of the same frequency as the signal (1000 Hz). The oscillator used to produce the signal generated rectangular bursts of tone. Consequently, while most of the signal's energy was concentrated near the signal frequency, about ten percent of the total signal energy was "splattered" over frequencies more than 1/T Hz on either side of the signal frequency. In contrast the spectral energy distribution of the continuous sinusoidal masker is approximated by a line at the signal frequency. Larger ratios of signal to masker energy are found, therefore, at frequencies somewhat removed from the signal frequency.

Note, however, that stimulus components that are "off-frequency" contain relatively little energy as compared to those near the signal frequency. Leshowitz and Wightman provide data showing that human observers extract useful information from the stimulus at frequencies "where the signal energy is as much as 40 dB down from the peak" (p. 1180).

Leshowitz and Wightman developed a "simple filter model" to account for their results. To optimize performance, they propose that the location of a band-pass input-filter is adjusted to yield the maximum ratio of signal energy to masker energy at the input of an energy detector. According to this model, detection of tonal increments is better accomplished when the observer centers his auditory filter at frequencies other than 1000 Hz, where higher signal-to-masker ratios are found.

The "simple filter-model" proposed for tone intensity discrimination may be extended to the present experiment. A subject seeks to optimize performance by setting his auditory filter so that the overall signal-to-masker ratio at its output is maximized. For the stimulus configuration we have been examining (100-Hz signal with 316-Hz masker), larger values of S_0/N_0 are found outside the nominal signal passband than within it. Thus the subject would position his auditory filter at a region remote from the signal center-frequency rather than at 1000 Hz. The location selected would depend on the passband characteristics of the auditory filter (including critical bandwidth considerations), the attenuation slopes of the stimulus-generating filters, audibility constraints, and the level of residual noise in the stimulus-production system.

Leshowitz and Wightman (1971) obtained data from their tone-in-tone experiment suggesting that "observers probably monitor energy changes in the low frequency regions of the spectrum" (p. 1186). Unfortunately, whether this is also true for our 100-Hz signal and 316-Hz masker combination cannot be deduced from our results. Further research employing secondary maskers of high-and low-pass filtered noise should help to clarify this matter.

It is reasonable to expect that a subject attending to stimulus components outside the 100-Hz passband of the signal, where signal-to-masker ratios are large, would be able to perform better than the receiver of the W_s-model which restricts its input to the nominal signal passband. The empirical thresholds plotted in Figure 3-2 are by no means theoretically unattainable, since the W_s-model is optimal only for rectangular noisebands. The "impossible" sensitivity shown by our observers is a consequence of the particular way signal and masker energies are packaged under this stimulus condition. It is worth reiterating here that these thresholds are "impossible" only in the context of the W_s-model. As Green and Swets (1966, p. 177) point out, radically different results are produced if the 2WT sampling theorem is not employed to represent a finite noise waveform.

Note that the empirical thresholds in Figure 3-2 decrease monotonically with increasing masker level for both continuous and gated conditions. While S_o/N_o is high at remote frequencies, stimulus components in these regions are well below 0 dB SPL when masker spectrum-level is low. Those stimulus components which are inaudible (i.e., effectively masked by biological noise) are clearly of no use in decision making. Only at high levels of the stimulus is it profitable to attend to frequencies outside the half-power passband of the 100-Hz signal. As the audibility of stimulus components varies with changes in the spectrum-level of the stimulus, the auditory filter is adjusted to maximize signal-to-masker ratio at its output.

If sensitivity is so acute for the combination of 100-Hz signal and 316-Hz masker, why then is discrimination so much poorer than the predictions of the W_s-model under the remaining heterogeneous conditions (see Figures 3-3 thru 3-5)? Consider the pairing of the 100-Hz filter, as a signal source, with the output of either the 1000 Hz, 3160 Hz, or 10,000 Hz filters as masking agent (see Figure 2-1). Within the half-power passband of the signal, S_o/N_o has a value between one-half and unity. Outside this frequency region the transfer functions of any of these filter-pairs rapidly diverge, with the result that S_o/N_o moves towards zero.

Extrapolation of the curves in Figure 2-1 shows that the transfer function of the 100-Hz "signal" filter eventually crosses the transfer function of each of the "masker" filters. At frequency regions greatly removed from the common center frequency, S_o/N_o far exceeds unity. Note, however, that the relative (extrapolated) output of the individual filters past these cross-over frequencies is considerably below the maximum response. Although this analysis is _post-hoc_, it appears that stimulus components at frequencies far outside the nominal signal passband are not used by the listener. First, the "extrapolated" output of the signal filter in very remote regions is surely swamped by the residual electrical noise of the stimulus-generating system. Second, those stimulus components which are both above the system noise, and which have high signal-to-masker ratios, are found at frequencies where they are most likely too weak to be heard by the listener.

If the observer is unable to make use of stimulus components at frequencies where S_o/N_o is very large, then on what part of the stimulus should the listener concentrate? Certainly, it is important to attend to stimulus frequencies within the nominal signal passband, where $S_o/N_o \leq 1/2$. But should information processing also include frequencies just outside the half-power passband of the signal, where stimulus components are audible, but where signal-to-masker ratios are quite small?

Because Fourier components in these regions contain some signal energy, their inclusion in the sample fed to the energy detector does result in increasing the separation between the means of the "signal-plus-masker" and "masker alone" energy distributions. (The masker energy of each Fourier component increments the two distributions equally, on the average, and thus has no effect on their relative separation.) However, this tendency toward enhanced sensitivity comes at the cost of a concomittant growth in the variances of the two energy distributions, since the variances of Fourier components within and without the nominal signal passband are summed. Whether discrimination performance is improved or degraded by widening the auditory filter much beyond the nominal signal passband, depends on the relative effect of these opposing factors.

To calculate the exact input bandwidth which results in the smallest threshold value of 10 log S_0/N_0 would require precise knowledge of the shape of the auditory filter. An approximate solution to this problem may be attempted by using semi-quantitative arguments. Assume that both the auditory filter and the 100-Hz signal filter have rectangular transfer functions, and further assume that the passbands of the two filters are matched. Extending the auditory passband slightly above and below the band-limits of the signal would result in a decreased percentage of correct responses. This is because the variances of the theoretical energy distributions would be increased by the additional masker energy, but there would be no change in the separation of the two distributions, i.e., there is no increase in signal energy. Furthermore, the higher the spectrum-level of the "masker-only" stimulus components, the more deleterious would be the effect of their inclusion in the noise sample fed to the energy detector.

With the experimental stimuli we have been examining ("100-Hz" signal, and either the "1000-Hz," "3160-Hz," or "10,000-Hz" masker), frequencies just outside the nominal signal passband (but before the cross-over points of the transfer functions) do contain a small amount of signal energy. (In these regions, $0 < S_O/N_O << 1$.) Widening the auditory filter to include some of these stimulus components results in a slight increase in the distance between the theoretical energy distributions. It is likely, however, that this apparent gain in sensitivity is more than offset by the variance contributed by the "new" components to the total variance of the decision statistic. This is especially true if stimulus components outside the half-power signal passband have relatively high spectrum-levels, as they surely do up to the nominal band-limits of the masker. It would appear, then, that setting the input filter to a bandwidth equal to 100 Hz (or perhaps a little wider) is the best strategy.

Similar analyses hold for the remaining combinations of filters under the heterogeneous conditions. By way of example, consider the signal and masker pair where W_s = 1000 Hz and W_n = 10,000 Hz (half-power passbands). For this combination S_O/N_O varies between one-half and unity within the half-power passband of the signal. Immediately outside the nominal signal passband S_o/N_o drops precipitously. Signal-to-masker ratio continues to decrease as the half-power band-limits of the masker filter are approached. Outside the nominal masker passband S_o/N_o is constant, since the attenuation skirts of the signal and masker filters are parallel at these frequencies. In these regions there is proportionately little signal energy, i.e., $S_o/N_o << 1$. Reasoning as before, it is probable that widening the auditory filter much beyond the nominal signal passband results in an increase in the relative variability of the test statistic used by the observer. Differential sensitivity suffers as a consequence. The data in Figures 3-7, 3-8, and 3-9, suggest that real observers do in fact filter out most stimulus energy outside the nominal signal passband.

Under the heterogeneous conditions it is only the combination of the 100-Hz signal and the 316-Hz masker that results in our subjects performing better than the W_s-model. As shown above, the superior performance for this particular combination of signal and masker may be attributed to two factors: (1) Signal-to-masker ratio is very high at frequency regions outside the half-power band-limits of the signal filter. (2) Stimulus components at frequencies where S_o/N_o is large are above absolute threshold, at least for the higher stimulus levels. Either or both of these conditions do not hold for the other heterogeneous stimuli employed in the experiment.

The thresholds plotted in Figures 3-3, 3-4, and 3-5 are poorer than those computed for the receiver of the Ws-model. It has been demonstrated earlier that under these conditions, subjects should confine their listening to the immediate neighborhood of the half-power signal passband. Thus the W_s-model provides an approximate lower bound on the thresholds we can expect to obtain with real listeners. The actual performance exhibited by our subjects with these stimuli is, of course, worse than calculated from Equation (1-1) of the W_s-model. Once again, biological noise is invoked as the agent degrading the performance of real observers in comparison with the ideal model.

Although the receiver of the W_s-model makes no distinction between the homogeneous and heterogeneous conditions, the performance of real listeners is affected by bandwidth conditions. The results plotted in Figures 3-7 thru 3-9 indicate that, for each noise signal, the minimum threshold value of 10 log S_o/N_o was obtained when the signal and masker passbands were identical. (The thresholds for the 100-Hz signal, as shown in Figure 3-6, are anomalous in this respect. The circumstances leading to the especially fine sensitivity observed when the 100-Hz signal was paired with the 316-Hz masker have already been described. Here our discussion is confined to the other signal-bands employed in the heterogeneous conditions.) Recall that for the homogeneous conditions optimal performance is possible only if the tinted noise is not filtered prior to energy detection. Because S_0/N_0 is the same throughout the stimulus spectrum, any filtering of the auditory input removes valuable information about the occurrence of the signal. Listening "wideband" is the preferred strategy. Under the heterogeneous conditions, however, some filtering of the stimulus is desirable. The notion that it is worthwhile to attend to all stimulus frequencies, where even a slight amount of signal energy may be present, was shown to be incorrect. With these stimuli, theoretical thresholds are lowest when the input is restricted (approximately) to the noiminal band-pass of the signal filter. This is because the test-statistic used in decision making, is calculated with more sample values in the homogeneous conditions, than in the heterogeneous conditions. (Since the "extra" Fourier components have signal-to-masker ratios equal to those found within the nominal signal passband, their addition serves to reduce the relative variability of the test-statistic.) To put it another way, observers are able to make more reliable determinations of stimulus energy under the homogeneous conditions, than under the heterogeneous conditions. Thus, best thresholds for a given signal are found with the homogeneous stimuli.

We now compare the effects of stimulus-prewhitening (and its biological analog, neural compression) on intensity-discrimination under the homogeneous and the heterogeneous conditions. When the same filter generates both signal and masker noise-bands, the stimuli presented during the two halves of an experimental trial have identical power spectra (on the average). It is possible, therefore, for a single inverse-filter to whiten the stimulus, whether it consists of signal energy plus masker energy ("S+N"), or of masker energy alone ("N"). As described previously, the relative variability of a tinted noise-band is reduced by "whitening," with a consequent increase in the accuracy of decisions made in the 2IFC task.

Unfortunately, the effects of prewhitening are not as beneficial under the heterogeneous conditions. Assume that the observer matches his input filter to the half-power passband of the signal, the procedure suggested earlier. The transfer characteristics of both the signal and the masker filters are relatively flat within this frequency region. Thus the power spectra of the filtered "S+N" and "N" stimuli that are passed to the inverse-filter are approximately rectangular. These stimuli would undergo almost no change with respect to their relative variability, since they are virtually "white" before inverse-filtering. Prewhitening, then, has little influence on performance under heterogeneous conditions, if the noise input is first filtered to the nominal bandwidth of the signal.

If the observer does not set his auditory filter to the nominal band-limits of the signal, then the situation is more complex. For example, suppose that all stimulus components within the half-power passband of the masker are fed through the auditory filter. First, irrespective of prewhitening, the additional stimulus components outside the nominal signal passband tend to degrade performance, as previously described. Second, prewhitening of both the "S+N" and "N" stimuli cannot be accomplished with a single inverse-filter -- on "N" halves of an experimental trial the stimulus spectrum is roughly flat, while on "S+N" presentations the spectrum-level is greatest at frequencies within the midrange of the signal passband. To whiten each of these stimuli a different inverse-filter is needed. To decide which inverse-filter must be employed on a given half of an experimental trial requires exact knowledge of the observation interval containing the increment-signal. Obviously, the intensity-discrimination task is trivial if the observer has such information. Employing the "wrong" inverse-filter on some trials introduces additional variance to the decision process which raises thresholds.

Moreover, numerical examples have shown that even if a single inverse-filter is used to preprocess the noise (e.g., one that would whiten the "S+N" stimulus completely), sensitivity is poorer then if attempts at prewhitening are ignored altogether for these stimuli. Thus prewhitening of the stimuli under the heterogeneous conditions either has little effect on performance (when the input-bandwidth is restricted to the nominal bandwidth of the signal) or, an adverse effect on sensitivity (when stimulus components outside the nominal signal passband are included in the noise sample fed to the energy detector.)

c. Differential Sensitivity: Mode of Masker

It is generally accepted that gated sinusoidal maskers produce significantly more masking of a pure tone signal than do continuous sinusoidal maskers (Campbell, 1966; Campbell and Lasky, 1967; Green, 1969; Leshowitz and Cudahy, 1975). When the stimuli are not tones, but bands of noise, the effect of masker mode on intensity discrimination depends on the bandwidth conditions. In the homogeneous conditions there is little difference in the effectiveness of continuous and gated maskers. With the heterogeneous stimuli, sensitivity is everywhere poorer with gated maskers, mimicking the tone-in-tone data.

Under heterogeneous conditions, the continuous masker may provide clues for the optimal location of the auditory filter. The increased uncertainty with gated maskers, where the observer must rely to some extent on auditory memory, may result in raised thresholds. In the homogeneous conditions, subjects listen "wide-band" with both continuous and gated maskers; in this case information about the center frequency of the stimulus is relatively unimportant. These suggestions are, of course, <u>post-hoc</u> and untested. The question of why gated maskers produce more masking than continuous maskers, but only under heterogeneous bandwidth conditions, is unresolved at present.

2. Noise-Intensity Discrimination as a Function of Stimulus Bandwidth

a. The Bandwidth Effect: Homogeneous Conditions

The reciprocity-factor was defined in Chapter III as "the change, in decibels, of S_o/N_o resulting from a log-unit increase in W_s." Reciprocity-factors for the homogeneous conditions (see Table 3-3) were calculated by determining best-fitting linear functions for the obtained differential-thresholds plotted against the equivalent rectangular bandwidths of the stimulus filters. We now demonstrate that reciprocity-factors computed in this manner are somewhat misleading, since they do not fully describe the effect of changing stimulus bandwidth on auditory intensity-discrimination with tinted bands of noise. Specifically, we show that theoretical plots of threshold 10 log S_o/N_o versus stimulus ERB, yield slopes that are shallower than -5 dB per log-unit of bandwidth with the homogeneous stimuli used in the experiment.

As noted previously, "effective passband" is more properly specified as stimulus bandwidth in the homogeneous conditions, than is the ERB of the noise-band, when the stimulus does not have a uniform spectral power-density. Prewhitening within the effective passband, then passing the noise to the energy detector, is the optimal information-processing technique. The intensity-bandwidth reciprocity of this "modified " energy-detection scheme is the same as that of the simpler W_s-model; a tenfold change in bandwidth produces a 5 dB change in threshold 10 log S_o/N_o. This is because once the tinted noise is whitened, the energy statistics of the two models are the same.

In our experiment, the widest filter used, 10,000 Hz (ERB = 10,051 Hz), had an equivalent rectangular bandwidth 84.5 times larger than that of the narrowest filter employed 100 Hz (ERB = 119 Hz). The ratio of the widest to narrowest effective passband of the homogeneous stimuli depends, of course, on the level of system noise. This ratio ranges from 50.8 to 10.6, for spectrum-levels of system noise that are 10 dB and 50 dB below maximum filter output, respectively (see Table 4-4). Consequently, switching from one stimulus filter to another should not produce as large a variation in threshold values of 10 log S_0/N_0 as the corresponding change in stimulus ERB might lead us to expect.

Although effective bandwidth is the proper theoretical parameter, the reciprocity-factors given in Table 3-3 were computed using the equivalent rectangular bandwidths of the stimuli. (This is the correct procedure for noise-bands with white spectra, since effective bandwidth and ERB are equal for these stimuli.) These reciprocity-factors should not, therefore, be compared with the value of -5 for the energy-detector model, which results from employing the same definition of bandwidth in calculations of both thresholds and intensity-bandwidth reciprocities. More appropriate yardsticks for comparison are, however, readily determined. Table 4-5 lists theoretical thresholds for the homogeneous sitmuli for several possible levels of system noise. The calculations assume that the stimuli are completely whitened within their effective passbands, then passed to the energy-detector. Regression lines were determined -- at each level of system noise -- by pairing

Table 4-4

Ratio of the Widest to Narrowest Effective Passbands for the Homogeneous Stimuli at Various Levels of System Noise.

System Noise dB re $\lvert H_m \rvert$	Bandwidth Ratio
-10	50.8
-20	29.1
-30	18.9
-40	13.4
-50	10.6

the computed thresholds in Table 4-5 with their corresponding equivalent rectangular bandwidths. The slopes of these lines, multiplied by ten, are the theoretical analogs of the reciprocity-factors presented in Table 3-3 (which were computed from the data of Tables 3-1 and 3-2). Thus, plotting thresholds calculated using effective bandwidth, against the ERB of the stimuli, yields "reciprocity-factors" that are smaller (in magnitude) than -5; this is based on the assumption of optimal processing of the stimuli, viz., whitening followed by energy-detection.

Several points should be considered when evaluating the bandwidth effects obtained for our listeners (Table 3-3) in comparison with these theoretical "reciprocity-factors." First, that portion of the 10,000 Hz (HPB) noise-band that is useful to the subject may not be as wide as is the effective passband of the stimulus at low levels of system noise. This is because frequency components at the edges of the passband are probably below audiometric thresholds. The truly "effective" passband of this stimulus is likely to be independent of the intensity of the system noise. This tends to make the stimulus bandwidths more alike, for real listeners, especially if system noise is low. The expected bandwidth effect is likewise diminished. Next, note that the largest reciprocities are found at the weakest masker spectrum-level employed. Here, it is reasonable to assume

Table 4-5

Theoretical "Reciprocity-Factors" for the Homogeneous Conditions at Several Assumed Levels of System Noise.

System Noise: -10 dB re $|H_m|$
Reciprocity-factor: -4.6

ERB (Hz)	119	344	1013	3206	10,051
Eff. Band. (Hz)	227	594	1337	3770	11,536
10 log S_o/N_o	-6.5	-8.8	-10.7	-13.0	-15.5

System Noise: -20 db re $|H_m|$
Reciprocity-factor: -3.9

ERB (Hz)	119	344	1013	3206	10,051
Eff. Band. (Hz)	459	912	1709	4438	13,376
10 log S_o/N_o	-8.2	-9.8	-11.2	-13.3	-15.8

System Noise: -30 dB re $|H_m|$
Reciprocity-factor: -3.4

ERB (Hz)	119	344	1013	3206	10,051
Eff. Band. (Hz)	819	1249	2117	5202	15,501
10 log S_o/N_o	-9.5	-10.5	-11.7	-13.7	-16.1

System Noise: -40 dB re $|H_m|$
Reciprocity-factor: -3.0

ERB (Hz)	119	344	1013	3206	10,051
Eff. Band. (Hz)	1341	1612	2750	6077	17,957
10 log S_o/N_o	-10.7	-11.1	-12.1	-14.0	-16.4

System Noise: -50 dB re $|H_m|$
Reciprocity-factor: -2.8

ERB (Hz)	119	344	1013	3206	10,051
Eff. Band. (Hz)	1961	2010	2078	7081	20,797
10 log S_o/N_o	-11.5	-11.6	-12.5	-14.4	-16.8

that biological noise masks stimulus components at the edges of the filter passbands, thereby limiting the "effective" bandwidths of the noise-bands. This in turn leads to a greater bandwidth effect. Finally, neural compression of stimulus energy does not whiten a noise-band as efficiently as does an inverse-filter. As a result, stimulus components at frequencies remote from the center of the passband are not weighted as heavily as they should be for optimal decision making. This tends to accentuate differences in stimulus bandwidth and acts to increase the observed degree of intensity-bandwidth reciprocity.

The small effect of bandwidth on intensity-discrimination found for our subjects under homogeneous conditions, is not completely explained by arguing that the overall change in the effective bandwidths of the stimuli is less than the change in the equivalent rectangular bandwidths of the noise-bands. Raab and Goldberg (1975), who reported similar "shallow" reciprocity-factors with homogeneous stimuli (they employed gated maskers), explored the possibility that additive internal noise reduces the magnitude of the bandwidth effect from that anticipated for the W_s-model. Specifically, they demonstrated that if internal variance is proportional to stimulus energy, an assertion which "explains" Weber's Law, then intensity-bandwidth reciprocities are predicted which are comparable to those exhibited by both their subjects and ours. Raab and Goldberg also developed a single-channel, Poisson counting model (c.f., McGill and Goldberg, 1968a, b) which yields a small bandwidth effect when stimulus energy is heavily compressed during neural transduction. Unfortunately, their derivation applies only to pseudorandom noises, whose waveforms vary between trials, but not within trials.

b. The Bandwidth Effect: Heterogeneous Conditions

Our data indicate that bandwidth has a greater effect on intensity-discrimination in the heterogeneous conditions than in the homogeneous conditions. (For example, larger reciprocity-factors are found in Table 3-6, than in Table 3-3. In all cases, reciprocity-factors were calculated using signal ERB.) This outcome results from the difference in filtering strategies adopted by the subjects under the two bandwidth conditions.

With homogeneous stimuli, optimal information-processing requires that the auditory filter be set "wide-open." Neural compression of stimulus energies acts to reduce differences in stimulus bandwidth. This theory is consistent with the relatively small bandwidth effect observed empirically. On the other hand, listening is confined to the neighborhood of the nominal signal passband in the heterogeneous conditions (see Figures 3-6, 3-7, and 3-8). Here "steeper" reciprocities are obtained than in the homogeneous conditions. We suggest that this is because the noise signals, as processed by the subject, are more dissimilar with respect to their bandwidths under the heterogeneous conditions than under the homogeneous conditions. The essential point is that in the heterogeneous conditions, listeners cannot make use of signal energy outside the nominal signal passband; performance is therefore governed by the energy statistics of the "ideal" models (W_s-model, W_n-model).

Although the mode of the masker has little influence on the bandwidth effect for the homogeneous conditions, with heterogeneous stimuli reciprocity-factors are greater when gated maskers are employed then when continuous maskers are used (see Table 3-6; Figures 3-3, 3-4, and 3-5). Our analysis of the W_n-model indicated that reciprocity-factors between -5 and -10 result from widening the input filter beyond the nominal signal passband. In some unknown manner (perhaps by supplying information about the center frequency of the stimulus), the presence of the continuous masker may alert the subject to the portion of the auditory spectrum needing maximum attention. If auditory memory is poor, such cues may not be available with gated stimulus presentations. Unfortunately, the coarse spacing of the data in Figures 3-3, 3-4, and 3-5, precludes our validating this hypothesis.

Under the homogeneous conditions the observer listens "wide-band" at all times. Little advantage is realized by knowing the center frequency of the stimulus spectrum. This is reflected in the similar reciprocity-factors found with continuous and gated maskers, when signal and masker passbands are identical.

There are two difficulties with our explanation for the relatively large intensity-bandwidth reciprocities found in the heterogeneous conditions. First, we have not accounted for the effects of biological noise. As noted previously, Raab and Goldberg, (1975) demonstrated that an energy-detection model which incorporates additive internal noise exhibits "shallower" reciprocities than purely stimulus-oriented theories. Whether such a mechanism operates to dilute intensity-bandwidth reciprocities in the heterogeneous conditions is unclear. It is possible that the auditory filter is consistently set wider than the nominal signal passband. This would tend to bring reciprocity-factors closer to -10. On the other hand, internal variance would pull reciprocity-factors in the opposite direction (see page 145). The resulting reciprocity-factors might very well be in reasonable agreement with the values determined from the experimental data. As before, the continuous maskers could supply information useful for matching the auditory filter to the signal passband. Thus, smaller reciprocity-factors would be expected with continuous maskers than with gated maskers.

A second problem arises when we consider the experiment of Moore and Raab (1975). These investigators studied intensity-discrimination for noise bursts in the presence of a continuous, bandstop-filtered background, whose spectrum-level in the passband was 10 dB above that of the standard burst (see their Figure 1, p. 401). They found that performance improved with increasing width of the bandstop. However the average reciprocity-factor of -2.5 was about half the magnitude of the intensity-bandwidth reciprocity observed in our heterogeneous conditions.

It is reasonable to assume that the continuous, bandstop background supplied precise information about the band-limits of the gated stimuli; the subject had no ambiguity about the location of the signal passband, as in our heterogeneous conditions, where at best, the center frequency of the stimulus was conveyed by the continuous masker. By assuming additive internal noise, we may then account for the reduced bandwidth effect observed in the Moore and Raab (1975) study, as compared to the square-root reciprocity given by the W_s-model.

In summary: (1) Changing the ERB of the noise stimuli in the homogeneous conditions by approximately two-decades had little effect on intensity-discrimination thresholds, with either continuous or gated maskers. For these noise-bands, important stimulus components were shown to exist outside the ERB of the noise-signal. Inclusion of such components, after whitening, in the noise sample fed to the energy-detector effectively makes the homogeneous stimuli more alike with respect to their bandwidths. Hence, the change in threshold 10 log S_O/N_O brought about by switching stimulus-filters is minimal. Additive internal noise serves further to reduce the degree of intensity-bandwidth reciprocity. (2) For the heterogeneous conditions, optimal stimulus processing necessitates matching the auditory filter to the nominal passband of the signal. Failure to do so results in both decreased sensitivity and reciprocity-factors between -5 and -10. Our results provide some evidence that subjects do indeed maintain input passbands that are wider than the ERB's of the noise-signals. Internal noise probably forces the reciprocity-factors to cluster around a value of -5.

3. Intensity-Discrimination Functions

A "near-miss" to Weber's Law was found for the narrowband stimuli under the homogeneous conditions, for both modes of masker (see Tables 3-7 and 3-8). As the bandwidth of the noise was increased, slopes of intensity discrimination functions approached or exceeded unity with the continuous maskers, while with the gated maskers slopes close to unity were obtained only for the widest passband employed (10,000 Hz). These findings may be better understood if we consider the availability of noise components outside the nominal passband of the stimulus, as a function of masker spectrum-level.

Recall that in the homogeneous conditions, prewhitening of the stimulus within its effective passband results in a significant improvement in differential sensitivity. As masker level is increased, more and more stimulus components outside the nominal signal passband become audible, that is, their levels are raised above the levels of both system and biological noises. Essentially, the effective bandwidth of the stimulus grows with increasing masker spectrum-level, at least until very high stimulus intensities are reached.

The change in effective bandwidth with masker spectrum-level is less for the stimuli generated by the "wide-band" filters than for the stimuli generated by the more "narrow-band" filters. Even at high masker levels, the ratio of audible stimulus components outside the signal passband, to stimulus components within the nominal passband, is smaller for a "wide-band" stimulus than for a "narrow-band' stimulus. Thus a "near-miss" to Weber's Law is predicted for narrow, homogeneous bands of noise, while slopes of intensity-discrimination functions tend toward unity as stimulus bandwidth is broadened. Why mode of masker affects the slope of intensity-discrimination functions in the homogeneous conditions remains unexplained.

In the heterogeneous conditions, the decision strategy serves to limit the power spectrum of the noise-input to the nominal passband of the signal. Therefore, increasing the level of the masker does not result in any "new" components being added to the noise sample passed to the energy detector. Even if the input filter is not set precisely to the passband of the signal, the broadband masker ($W_n > W_s$) "swamps" signal components at remote frequency regions, as we have shown before. Thus, Weber's Law is expected and obtained with both masker-modes for all the heterogeneous stimuli employed in the experiment save one, viz., the combination of the 100-Hz signal and 316-Hz masker.

Slopes of intensity-discrimination functions for this particular stimulus indicate that Weber fractions (S_o/N_o) rapidly diminish with increasing masker spectrum-level. This observation is readily explained. We have seen that information-processing of this stimulus (100-Hz signal, 316-Hz masker) best proceeds by positioning the auditory filter at a region outside the nominal signal passband, where signal-to-masker ratios are high. When the spectrum-level of the masker is raised, the location of the auditory filter is shifted to newly audible regions where even larger signal-to-masker ratios are to be found.

C. Concluding Remarks

Our investigation has shown that the simple energy-detector (W_S-model) fails to describe the effect of noise bandwidth on intensity discrimination for homogeneous bands of tinted noise. Furthermore, the model does not accurately predict the slopes of intensity-discrimination functions for these stimuli.

We have developed a version of an energy detection scheme which will account for significant features of the obtained data. Specifically, the model incorporates mechanisms for utilizing information from noise components outside the nominal stimulus passband whenever possible, a source of information ignored by the W_s-model. These mechanisms reduce differences in stimulus variability and lessen the effect of changing bandwidth on intensity discrimination thresholds in the homogeneous conditions. In the heterogeneous conditions, the subject is assumed to adopt an information-processing strategy similar to that of the receiver of the W_s-model. As a result, reciprocity factors are fairly "steep." Additive internal noise serves to reduce the trade of signal power with signal bandwidth from the predictions of the purely stimulus-oriented models, under both bandwidth conditions.

Most models of intensity-discrimination do not distinguish between continuous and gated maskers, although real subjects often do. While we have offered a tentative explanation for the effect of masker-mode on intensity-bandwidth reciprocity, we have shed no light on why the mode of the masker influences the slope of intensity-discrimination functions in the homogeneous conditions, and why it has little effect in the heterogeneous conditions. Theories which explicitly model the response of the auditory nervous system to stimulus onset and termination may be more fruitful in describing performance differences as a function of masker mode.

Appendix

THE MASKER BANDWIDTH MODEL

Raab (unpublished) has extended the energy detector model for noise-intensity discrimination (W_s-model) to include those experimental conditions where the noise-signal bandwidth is smaller than the noise-masker bandwidth (W_n-model). Consider the means and variances of the masker alone and signal-plus-masker energy distributions. For those trials where the masker is presented alone, the mean stimulus energy is

$$N_o W_n T.$$

The variance of this distribution is

$$N_o^2 W_n T.$$

Likewise, the mean of the signal-plus-masker energy distribution is

$$(N_o + S_o)W_s T + N_o(W_n - W_s)T,$$

where the quantity $(W_n - W_s)$ represents that portion of the stimulus outside the signal passband. The variance of this distribution is

$$(N_o + S_o)^2 W_s T + N_o^2 (W_n - W_s)T.$$

Note that since the masker alone and signal-plus-masker noise samples are derived independently, the variance of the difference distribution is simply the sum of the variances of the two energy distributions.

Thus, the normalized mean of the difference distribution, "M," is

$$M = \frac{(N_o + S_o)W_s T + N_o(W_n - W_s)T - N_o W_n T}{\left[N_o^2 W_n T + (N_o + S_o)^2 W_s T + N_o (W_n - W_s)T\right]^{1/2}}.$$

Expanding terms and performing the indicated algebra,

$$M = \frac{S_o W_s T}{\left[2N_o^2 W_n T + 2N_o S_o W_s T + S_o^2 W_s T\right]^{1/2}},$$

$$M = \frac{S_o}{N_o} \cdot \frac{\sqrt{W_s T}}{\sqrt{2}} \frac{1}{\left[1/2(S_o/N_o)^2 + (S_o/N_o) + W_n/W_s\right]^{1/2}}$$

When signal and masker bandwidths are the same, $W_n/W_s = 1$, and the above equation becomes identical to Equation 1-1 of the W_S-model.

BIBLIOGRAPHY

Bendat, J.S., & Piersol, A.G. Random data: Analysis and measurement procedures. New York: Wiley, 1971.

Beranek, L.L. Acoustic Measurements. New York: Wiley, 1949.

Blackman, R.B., & Tukey, J.W. The measurement of power spectra. New York: Dover, 1958.

de Boer, E. Detection function for noise bursts. Paper F26 presented at 5th International Congress on Acoustics, Liege, 1965.

de Boer, E. Intensity discrimination of fluctuating signals. Journal of the Acoustical Society of America 1966, 40, 552-560.

Bos, C.E., & de Boer, E. Masking and discrimination. Journal of the Acoustical Society of America, 1966, 39, 708-715.

Campbell, R.A. Detection of a noise signal of varying duration. Journal of the Acoustical Society of America, 1963, 35, 1732-1737.

Campbell, R.A. Masker level and noise-signal detection. Journal of the Acoustical Society of America, 1964, 36, 570-575.

Campbell R.A. Auditory intensity perception and neural coding. Journal of the Acoustical Society of America 1966, 39, 1030-1033.

Campbell, R.A., & Lasky, E.Z. Adaptive threshold procedures: BUDTIF. Journal of the Acoustical Society of America, 1968, 44, 537-541.

Dimmick, F.L., & Olson, R.M. The intensive difference limen in audition. Journal of the Acoustical Society of America, 1941, 12, 517-525.

Fechner, G. [Elements of psychophysics (Vol. 1)] (H.E. Adler, trans.). New York: Holt, Rhinehart, & Winston, 1860/1966.

Fletcher, H. Auditory patterns. Reviews of Modern Physics, 1940, 12, 47-65.

Green, D.M. Auditory detection of a noise signal. Journal of the Acoustical Society of America, 1960, 32, 121-131.

Green, D.M. Consistency of auditory detection judgement. Psychological Review, 1964, 71, 392-407.

Green, D.M. Additivity of masking. Journal of the Acoustical Society of America, 1967, 41, 1517-.

Green, D.M. Masking with continuous and pulsed sinusoids. Journal of the Acoustical Society of America, 1969, 46, 939-946.

Green, D.M., & Sewall, S.T. Effects of background noise on auditory detection of noise bursts. Journal of the Acoustical Society of America, 1962, 34, 1207-1216.

Green, D.M., & Swets, J.A. Signal detection theory and psychophysics. New York: Wiley, 1966.

Harris, J.D. The effect of inter-stimulus interval on intensity discrimination for white noise. American Journal of Psychology, 1949, 62, 202-214.

Harris, J.D. The effect of sensation-levels on intensive discrimination of noise. American Journal of Psychology, 1950, 63, 409-421.

Harris, J.D. Loudness discrimination. The Journal of Speech and Hearing Disorders, 1963, (Monograph Supplement Number 11).

Henning, G.B. Model for auditory discrimination and detection. Journal of the Acoustical Society of America, 1967, 42, 1325-1334.

Hind, J.E., Anderson, D.J., Brugge, J.F., & Rose, J.E. Coding of information pertaining to paired low-frequency tones in single auditory nerve fibers of the squirrel monkey. Journal of Neurophysiology, 1967, 30, 794-816.

Kiang, N.Y-S., Discharge patterns of single fibers in the cat's auditory nerve. Research Monograph Number 35. Cambridge, Mass.: MIT Press, 1965.

Leshowitz, B.F., & Cudahy, E. Masking patterns for continuous and gated sinusoids. Journal of the Acoustical Society of America, 1975, 58, 235-242.

Leshowitz, B., & Wightman, F.L. On frequency masking with continuous sinusoids. *Journal of the Acoustical Society of America*, 1971, *49*, 1180-1189.

Luce, R.D., & Green, D.M. A neural timing theory for response times and the psychophysics of intensity. *Psychological Review*, 1972, *79*, 14-57.

Macmillan, N.A. Detection and recognition of intensity changes in tone and noise: The detection-recognition disparity. *Perception and Psychophysics*, 1973, *13*, 65-75.

Maiwald, D. Die berechungen von modulationsschwellen mit hife eines funktionsschemas. *Acustica*, 1967, *18*, 193-207.

Mathews, M.V., & Pfafflin, S.M. Effect of filter type on energy-detection models for auditory signal detection, *Journal of the Acoustical Society of America*, 1965, *38*, 1055-1056.

McGill, W.J. Neural counting mechanisms and energy detection in audition. *Journal of Mathematical Psychology*, 1967, *4*, 351-376.

McGill, W.J., & Goldberg, J.P. Pure-tone intensity discrimination and energy detection. *Journal of the Acoustical Society of America*, 1968a, *44*, 576-581.

McGill, W.J., & Goldberg, J.P. A study of the near-miss involving Weber's law and pure-tone intensity discrimination. *Perception and Psychophysics*, 1968b, *4*, 105-109.

Miller, G.A. Sensitivity to changes in the intensity of white noise and its relation to masking and loudness. *Journal of the Acoustical Society of America*, 1947, *19*, 609-619.

Moore, B.C.J. Mechanisms of masking. *Journal of the Acoustical Society of America*, 1975, 57, 391-399.

Moore, B.C.J., & Raab, D.H. Intensity discrimination for noise bursts in the presence of a continuous, bandstop background: Effects of level, width of the bandstop, and duration. *Journal of the Acoustical Society of America*, 1975, *57*, 400-405.

Olson, W., & Carhart, R. Integration of acoustic power at threshold by normal hearers. *Journal of the Acoustical Society of America*, 1966, *40*, 591-599.

Penner, M.J. Neural or energy-summation in a Poisson counting model. *Journal of Mathematical Psychology*, 1972, *9*, 286-293.

Penner, M.J., Leshowitz, B., Cudahy, E., & Ricard, G. Intensity discrimination for pulsed sinusoids of various frequencies. *Perception and Psychophysics*, 1974, *15*, 568-570.

Peterson, W.W., Birdsall, T.G., & Fox, W.C. The theory of signal detectability. *Transactions of the IRE Professional Group on Information Theory*. PGIT-4, 171-212.

Pfafflin, S.m., and Mathews, M.V. Energy-detection model for monaural auditory detection. *Journal of the Acoustical Society of America*, 1962, 1842-1843.

Pollack, I. Sensitivity to differences in intensity between repeated bursts of noise. *Journal of the Acoustical Society of America*, 1951, *23*, 650-653.

Postman, L. The time-error in auditory perception. *American Journal of Psychology*, 1946, 59, 193-219.

Raab, D.H., & Goldberg, I.A. Auditory intensity discrimination with bursts or reproducible noise. *Journal of the Acoustical Society of America*, 1975, *57*, 437-447.

Raab, D.H., Osman, E., & Rich, E. Effects of waveform correlation and signal duration on detection of noise bursts in continuous noise. *Journal of the Acoustical Society of America*, 1963, *35*, 1942-1946.

Raab, D.H., & Schacknow, P.N. Adapting the Grason-Stadler 829 electronic switch for use with solid state programming equipment. *Behavior Research Methods and Instrumentation*, 1973, *5*, 444.

Rochester, S. Detection and duration discrimination of noise increments. *Journal of the Acoustical Society of America*, 1971, *49*, 1783-1789.

Rodenburg, M. *Sensitivity of the auditory system to differences in intensity.* Unpublished doctoral dissertation, Medical Faculty Rotterdam, The Netherlands, 1972.

Scharf, B. Critical bands. In J.V. Tobias (Ed.), *Foundations of Modern Auditory Theory* (Vol. 1). New York: Academic, 1970.

Schacknow, P.N., & Raab, D.H. Intensity discrimination of tone bursts and the form of the Weber function. *Perception and Psychophysics*, 1973, *14*, 449-450.

Shannon, C.E., & Weaver, W. *The mathematical theory of communication.* Urbana, Illinois: University of Illinois Press, 1949.

Siebert, W.M. Some implications of the stochastic behavior of primary auditory neurons. *Kybernetik*, 1965, *2*, 206-215.

Siebert, W.M. Stimulus transformations in the peripheral auditory system. In P.A. Kolers & M. Eden (Eds.), *Recognizing Patterns.* Cambridge, Mass.: MIT Press, 1968.

Small, A.M., Jr., Bacon, W.E., & Fozard, J.L. Intensive differential thresholds for octave-band noise. *Journal of the Acoustical Society of America*, 1959, *31*, 508-510.

Swets, J.A. Central factors in auditory frequency selectivity. *Psychological Bulletin*, 1963, *60*, 429-440.

Viemeister, N.F. Intensity discrimination of pulsed sinusoids: The effects of filtered noise. *Journal of the Acoustical Society of America*, 1972, *51*, 1265-1269.

Viemeister, N.F. Intensity discrimination of noise in the presence of band reject noise. *Journal of the Acoustical Society of America*, 1974, *56*, 1594-1600.

Whitfield, I.C. *The auditory pathway*. London: Arnold, 1967.

Zwicker, E. Die elementaren grundlagen zur bestimmung der Informationskapazitat des gehors. *Acustica*, 1956, *6*, 365-381.

Zwicker, E., & Fastl, M. On the development of the critical band, *Journal of the Acoustical Society of America*, 1972, *52*, 699-702.

Zwicker, E., & Feldtkeller, R. *Das ohr als nachrichtenempfanger*. Stuttgart: Hirzel Verlag, 1967.

Zwislocki, J.J. *Frequency analysis in hearing*. (Special Report #LSC-S-4.) Syracuse: Syracuse University, Laboratory of Sensory Communication, October 1968.