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DEFENSE RESEARCH LABORATORY

THE UNIVERSITY OF TEXAS AT AUSTIN

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FINAL REPORT ON CONTRACT Nonr-3579(04)

For the Period 1 May 1964—30 April 1968

Lloyd A. Jeffress

Supported by NASA Grant R-129

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Director

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ABSTRACT

This report presents a summary of work on visual and auditory signal recognition performed under NASA Grant R-129. The visual studies included effects of chromatic adaptation on color naming, and on saturation estimates, ROC curves developed over the course of dark adaptation, and studies of the Bezold-Brücke hue shift. The studies of auditory detection included work on lateralization of sound, on masking level differences (MLDs for tone and narrow-band noise, effect of noise bandwidth on detection of a tonal signal, effect of punishment on performance in a detection task, and a series of studies of electrical and mathematical models of auditory detection.

ACKNOWLEDGMENTS

The work on the projects to be reported was supported by the National Aeronautics and Space Administration through a grant to the Defense Research Laboratory of The University of Texas at Austin (Grant R-129). The work received additional support from the Naval Ship Systems Command Contract NObsr-93124. The work on vision was conducted by Dr. Gerald J. Jacobs and his graduate students, and the work on audition by Dr. Lloyd A. Jeffress and Dr. Charles S. Watson and their graduate students. All three are, or were, members of the Psychology Department of The University of Texas at Austin.

TABLE OF CONTENTS

I. INTRODUCTION

The following is a list of problems under Contract Nonr-3579(04):

A. Detection Performance and Two Parameters of the Auditory Stimulus

B. Effects of Visual Adaptation on the Detection of a Visual Stimulus

C. Signal Detection and the Width of Critical Bands

D. Binaural Models and Psychometric Functions

E. Monaural Electrical Model

It was not possible to carry the foregoing projects through to completion because funds were not available to continue the effort past the 30 April 1968 termination date of this contract.

A summary of the work performed is given in Sections II and III. A list of publications is given in Section IV and abstracts of all publications are given in Section V.

II. VISUAL RESEARCH

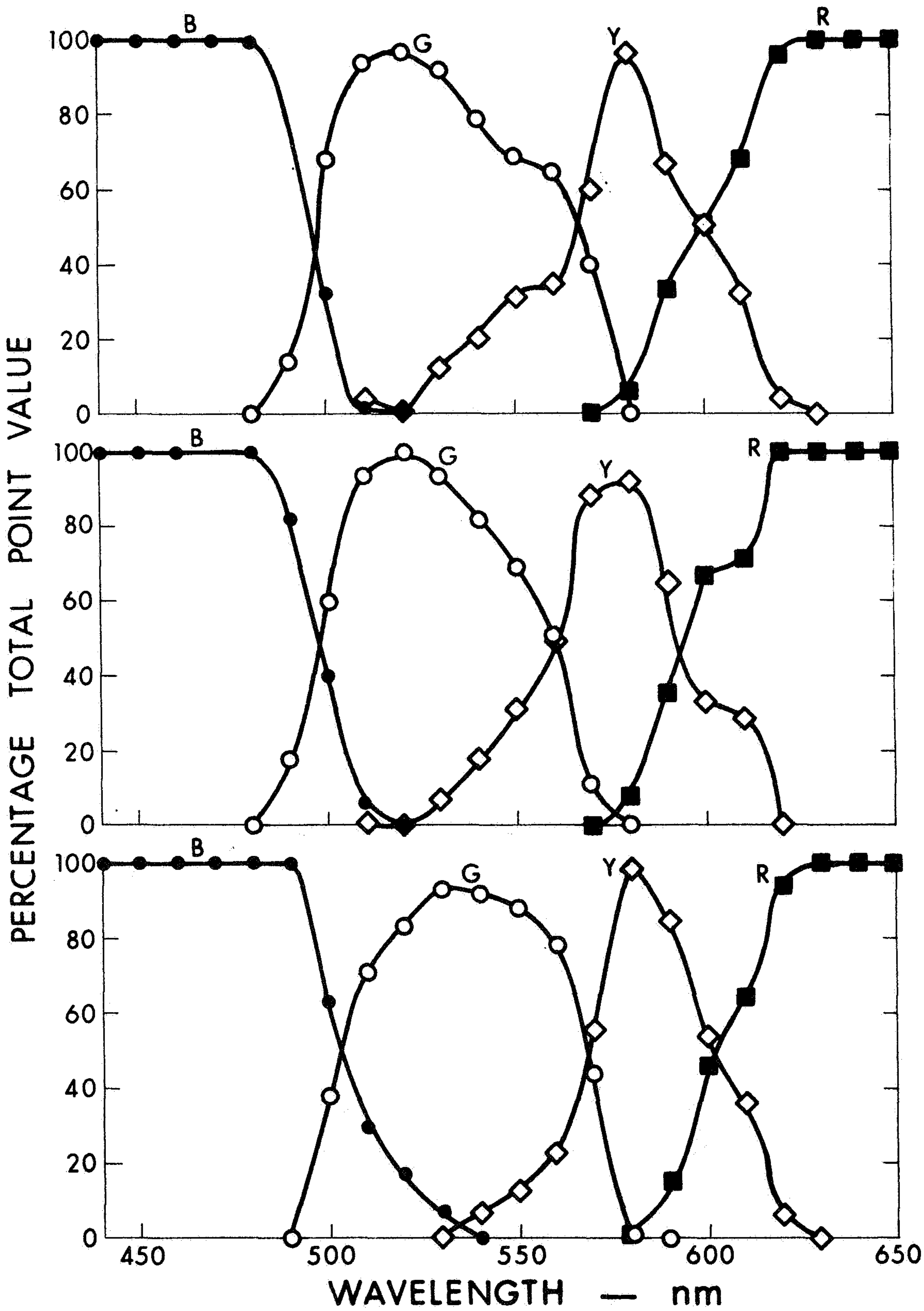
Effects of Chromatic Adaptation on Color Naming

The four color names, Blue, Green, Yellow, and Red were employed singly or in pairs by the subjects in identifying the color presented to them after a period of chromatic adaptation. The responses were scaled as follows: Blue was graded 3; Blue-Green was scaled 2 for blue and 1 for green; Green-Blue was scaled 2 for green and 1 for blue, etc. There was a possible total of 72 points for each test wavelength. The graphs show the percentage of total points assigned to each wavelength indicated on the abscissa. Drawing AS-66-739 shows the results for three subjects after 5 min of initial neutral adaptation at 195 ft L. The test stimuli were of the same luminance and were presented for 300 msec at 18 sec intervals, alternating with the adaptation light which was on between test trials. The stimuli were presented in Maxwellian view subtending 40 deg.

Drawing No. AS-66-740 shows the results after adaptation with a W 92 filter (646 nm). It will be seen that the red has almost disappeared, the yellow is shifted well toward the red, the green has been extended over a wide range of wavelengths, and the blue is virtually unaffected.

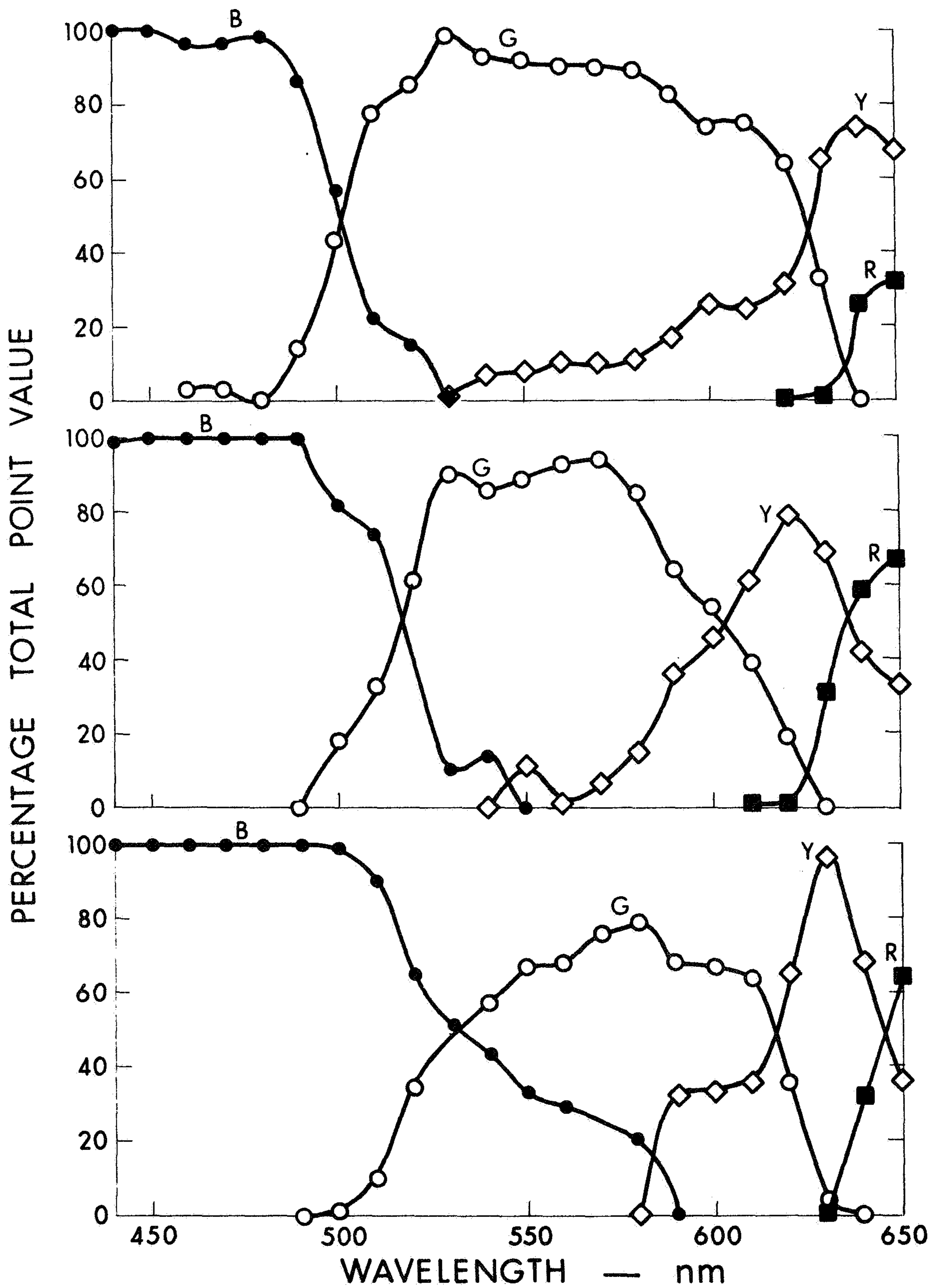
Drawing No. AS-66-741 shows the effect after adaptation with a W 98 filter (452 nm). Here the blue has been greatly restricted and moved to the left. The red has been shifted to the left and even appears in the blue region as red-blue or blue-red. The extent of the green has been greatly reduced and shifted to the left, and the area of yellow has been increased and shifted to the left.

Drawing No. AS-66-742 shows the effect of adaptation with a W 74 filter (538 nm). Here the red and blue have been expanded toward



COLOR NAMING NEUTRAL ADAPTATION

DRL - UT
DWG AS-66-739
GHJ - DCC
8 - 9 - 66



COLOR NAMING W 92 ADAPTATION

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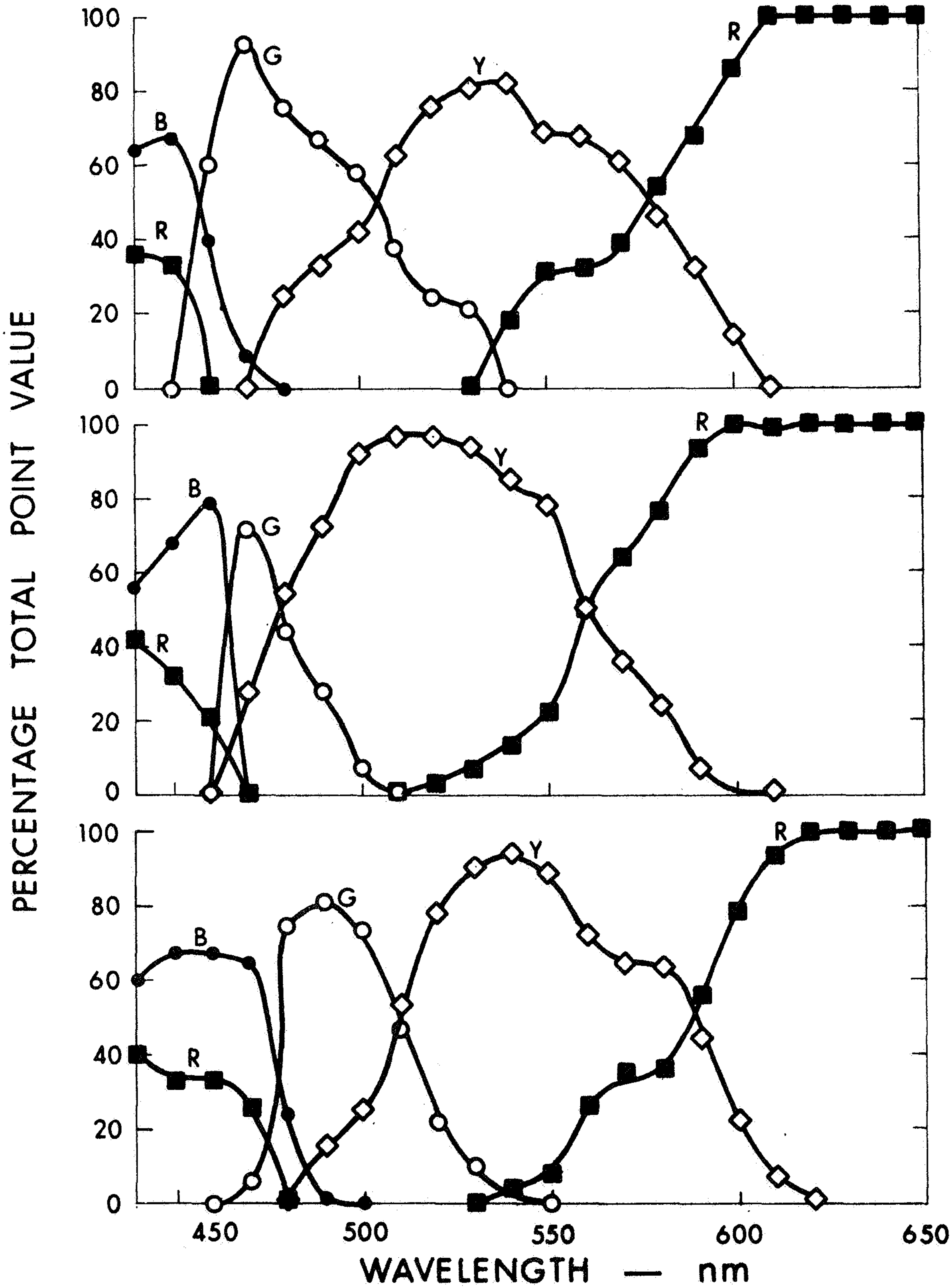
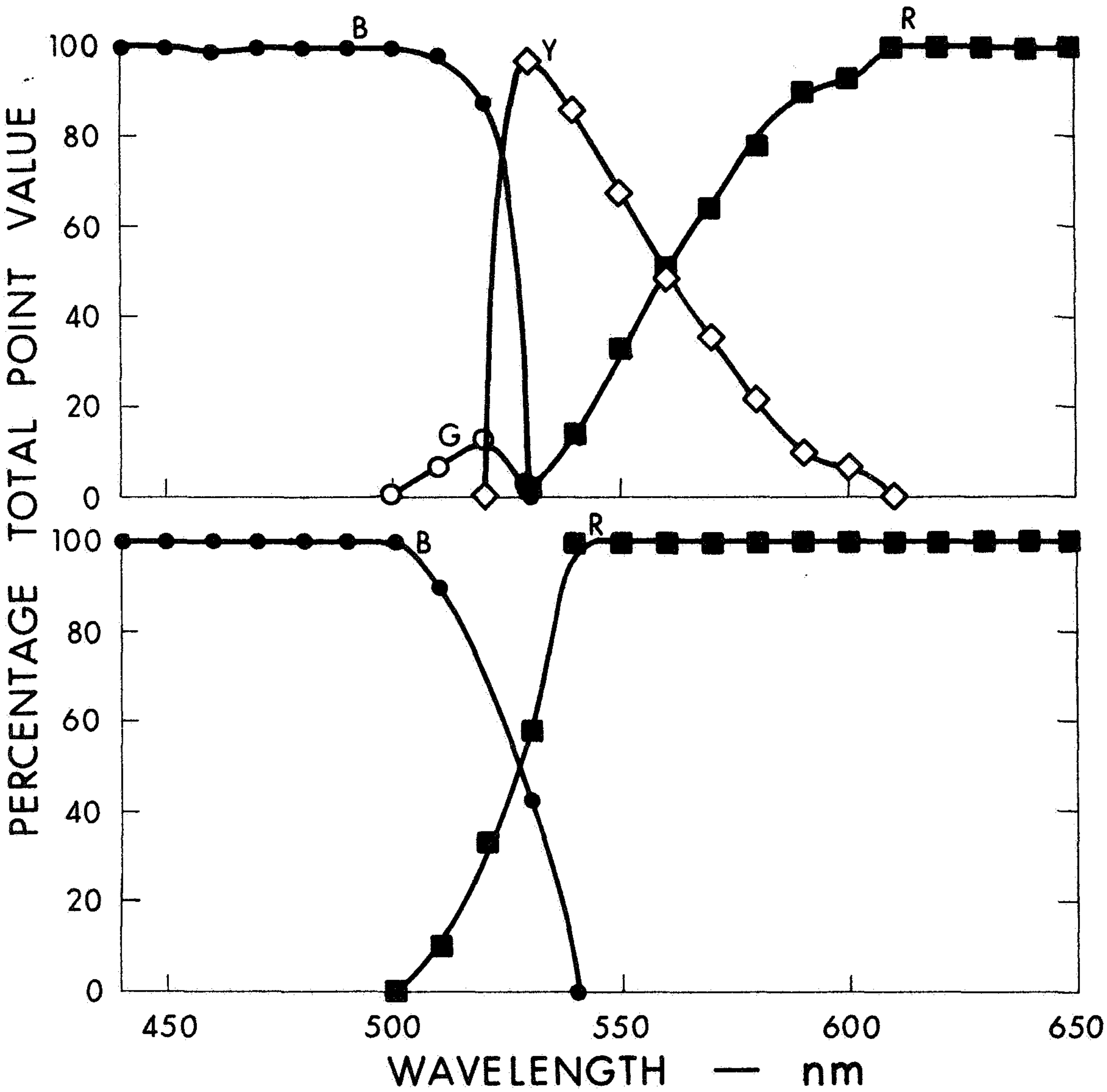
DWG AS-66-740
GHJ - DCC
8 - 10 - 66



COLOR NAMING W 98 ADAPTATION

DRL - UT
DWG AS-66-741
GHJ - DCC
8 - 11 - 66



COLOR NAMING W 74 ADAPTATION

DRL - UT
DWG AS-66-742
GHJ - DCC
8 - 11 - 66

the middle, and the green and yellow responses completely suppressed for one subject and greatly restricted for the other.

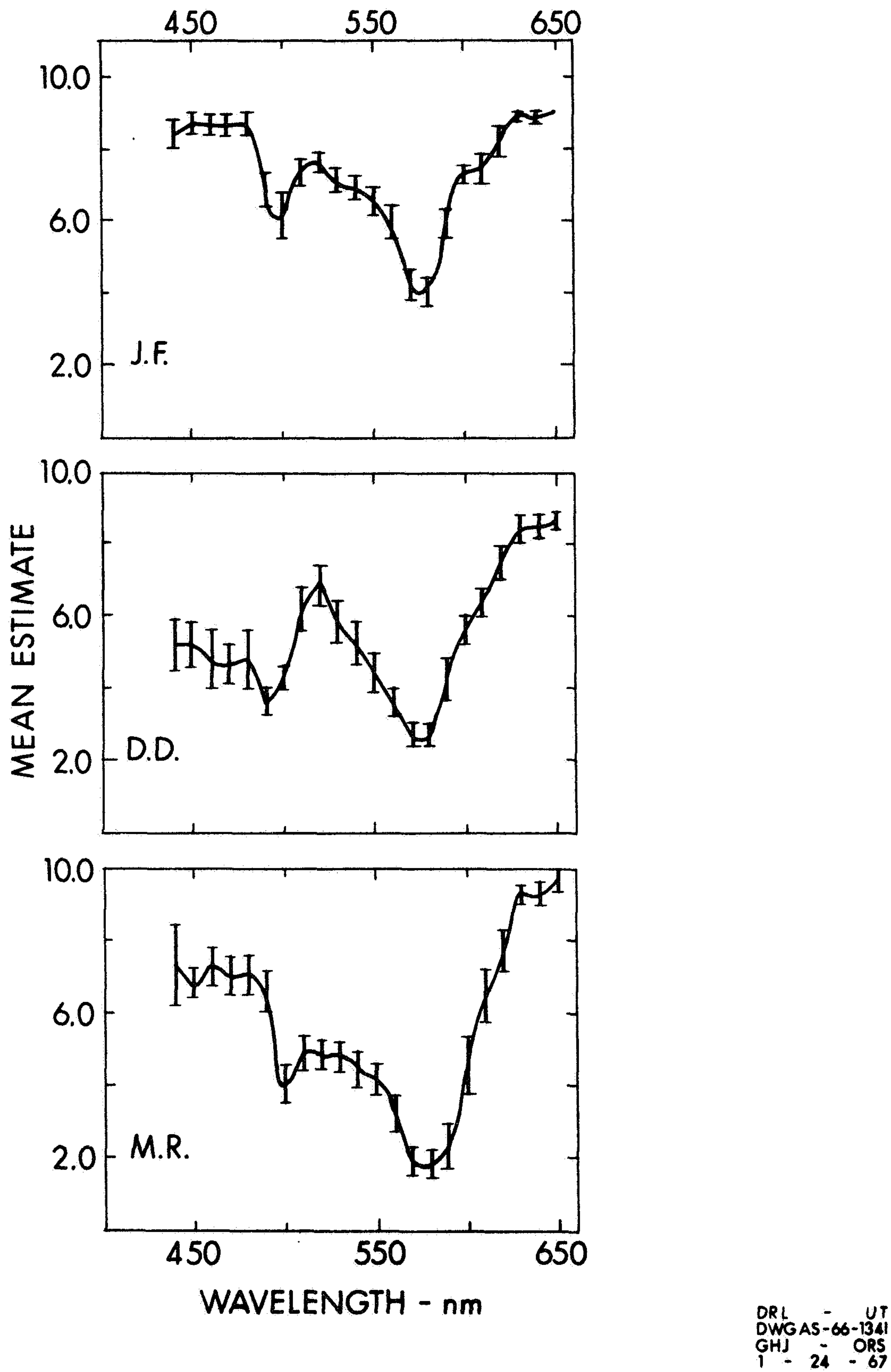
The results, in addition to indicating the effect on hue of prior adaptation, illustrate the effectiveness of color naming as a quantitative experimental research procedure. Split-half reliability correlations for the data were mostly in the high 90's, and the method is much less time consuming than matching procedures.

One practical suggestion from the results has to do with the use of colored light in the illumination of sonar and radar spaces. The red commonly employed on board ship to preserve dark adaptation is about the most inappropriate lighting for spaces where the color to be detected is the greenish yellow of many scope phosphors. Neutral light, or blue, would be much better.

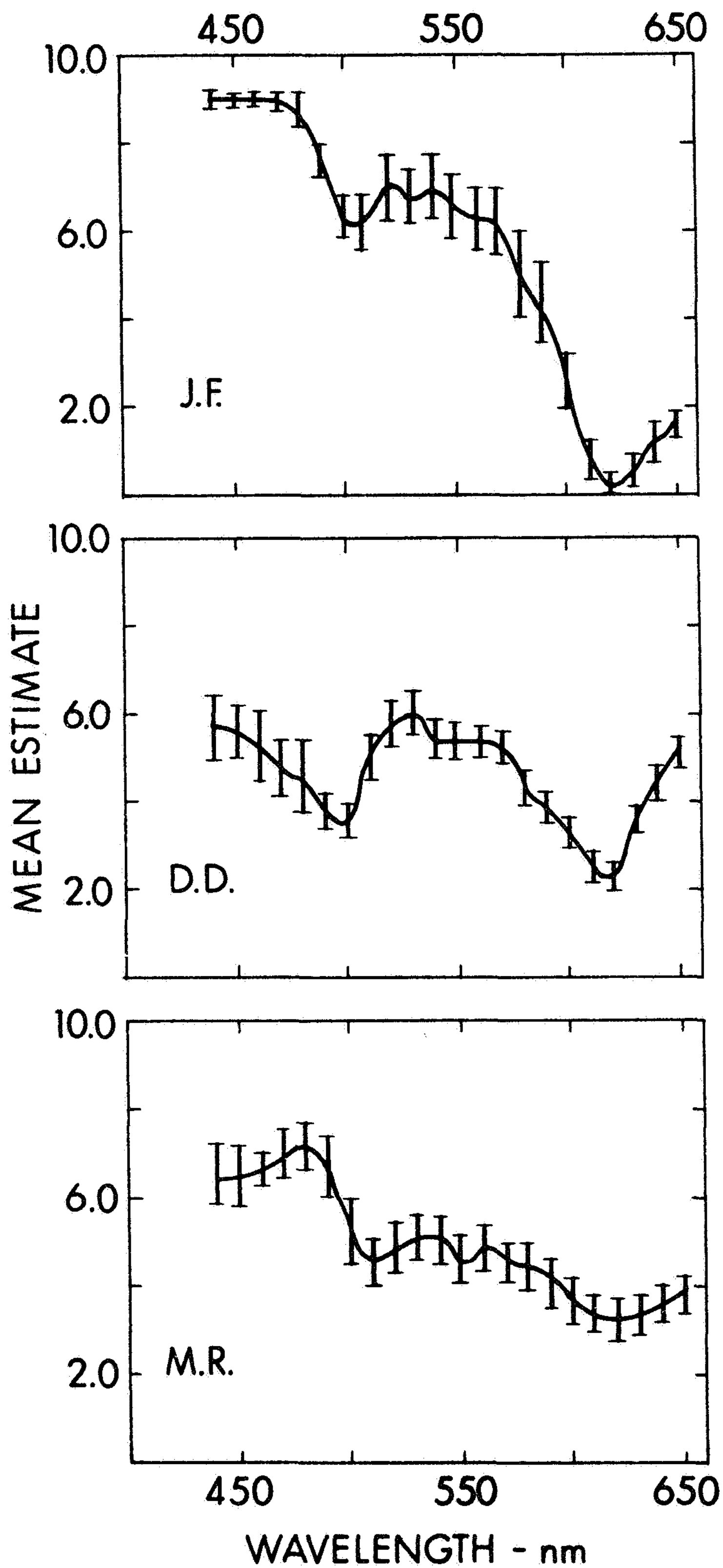
Saturation Estimates and Chromatic Adaptation

In addition to being able to assign color names reliably, subjects prove to be able to estimate the saturation of colors presented after various types of adaptation. The subjects were instructed to assign numbers ranging from zero to ten to the saturation of test colors presented after adaptation. AS-66-1341 shows data for three subjects after neutral adaptation for 5 minutes (Maxwellian view, 40 deg, same procedure as in the previous experiment). The bars indicate one standard deviation above and below the mean estimate.

Drawing No. AS-66-1342 shows the effect of adaptation to a long wavelength (W 92, 636 nm). It will be seen that saturation estimates for the long wavelengths have been greatly reduced. AS-66-1343 shows the effect of adaptation to a short wavelength (W 98, 452 nm). Here there is a marked reduction in saturation for wavelengths from medium to short, with increased saturation for wavelengths at the other end



SATURATION NEUTRAL ADAPTATION



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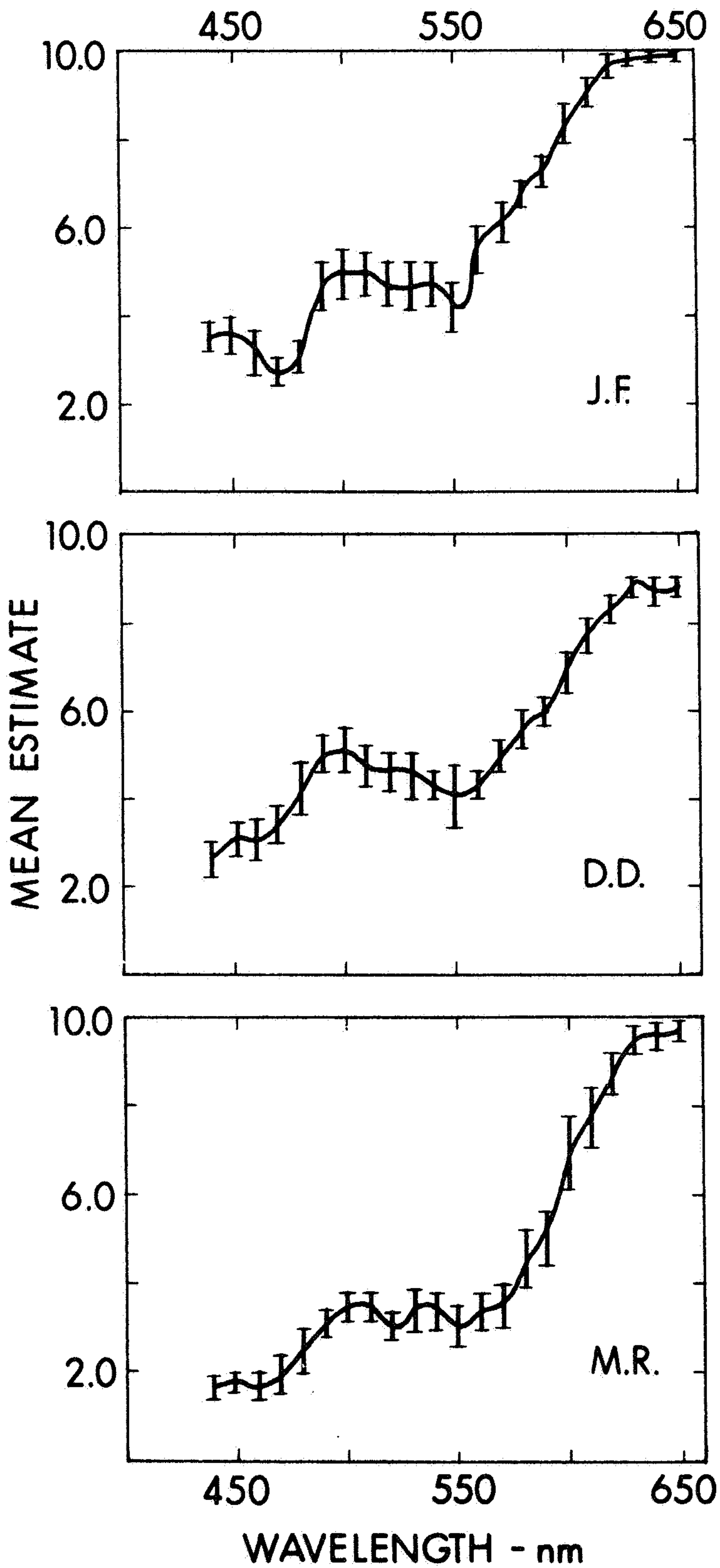
DWG AS-66-1342
GHJ - ORS
1 - 25 - 67

SATURATION W 92 ADAPTATION



SATURATION W 98 ADAPTATION

DRL - UT
DWGAS-66-1343
GHJ - ORS
1 - 26 - 67

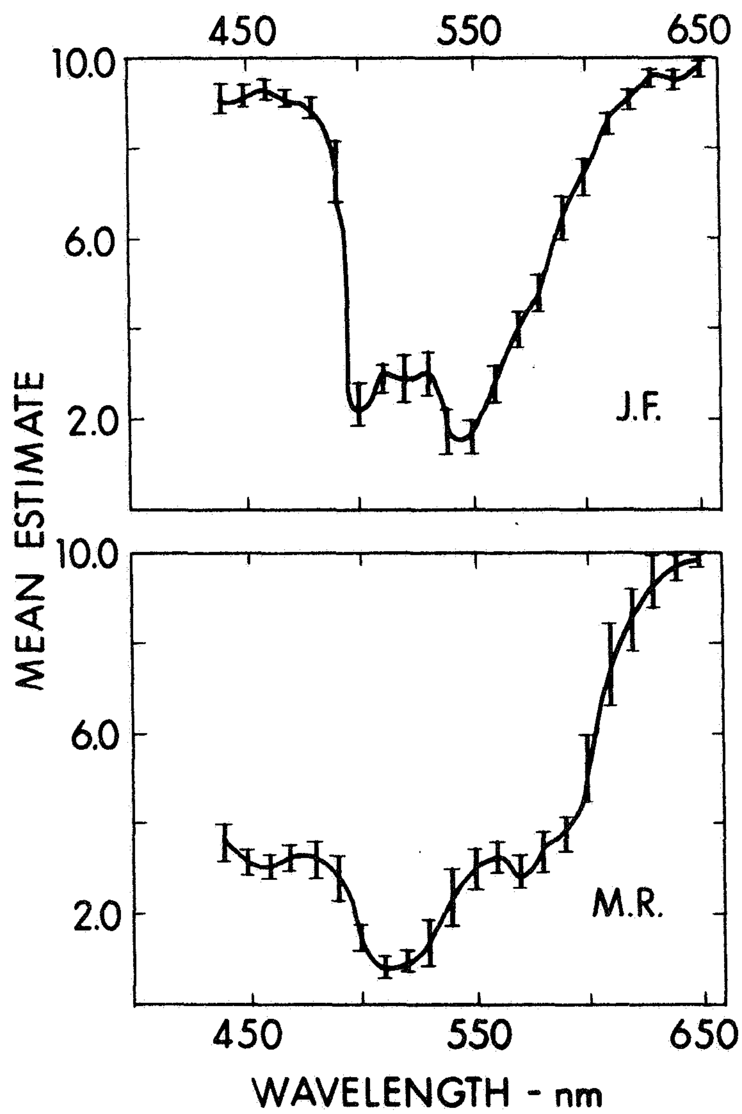
of the scale. AS-66-1344 shows the effect of adaptation for green (W 74, 532 nm). Here there is depression of the estimates in the middle, with a considerable increase in the estimates for the long wavelengths, and for one subject, for the short as well. The relatively small spread for any particular wavelength indicates that the judgments are being made with good consistency.

Effects of Adaptation on Visual Detection

It is frequently suggested in recent literature, following Barlow (1964), that the effect on the retina of exposing it to light is to make its behavior in subsequent darkness "noisy". This implies that the detection of a weak visual "signal" in the dark following a brief flash of adaptation light is essentially the detection of a signal in noise. For this, and a number of other reasons, the present experiment was undertaken as a detection task. A rating-scale procedure was employed to permit the construction of receiver operating characteristic (ROC) curves from the subjects' responses.

The adaptation light and the signal were presented in Maxwellian view. The former subtended an angle of 25 deg, and the latter, 5 deg, in the center of the adaptation field. The exposure of the adaptation light was controlled by a mechanical shutter which allowed it to be presented for 200 msec. The retinal illuminance provided by the adaptation light was 6.74 log trolands. The test light (signal) was a glow-modulator tube which was flashed electronically for 20 msec at a constant illuminance level (constant spectrum), and attenuated by a series of neutral filters 0.1 log units apart, ranging from 2.04 to 0.54 log trolands of retinal illuminance. A bite board and a dim red "grain of wheat" fixation light served to maintain the desired orientation of the eye.

After spending a minimum of ten minutes in a dimly lighted room, the subject entered the dark test booth. After 2 minutes of dark



SATURATION W 74 ADAPTATION

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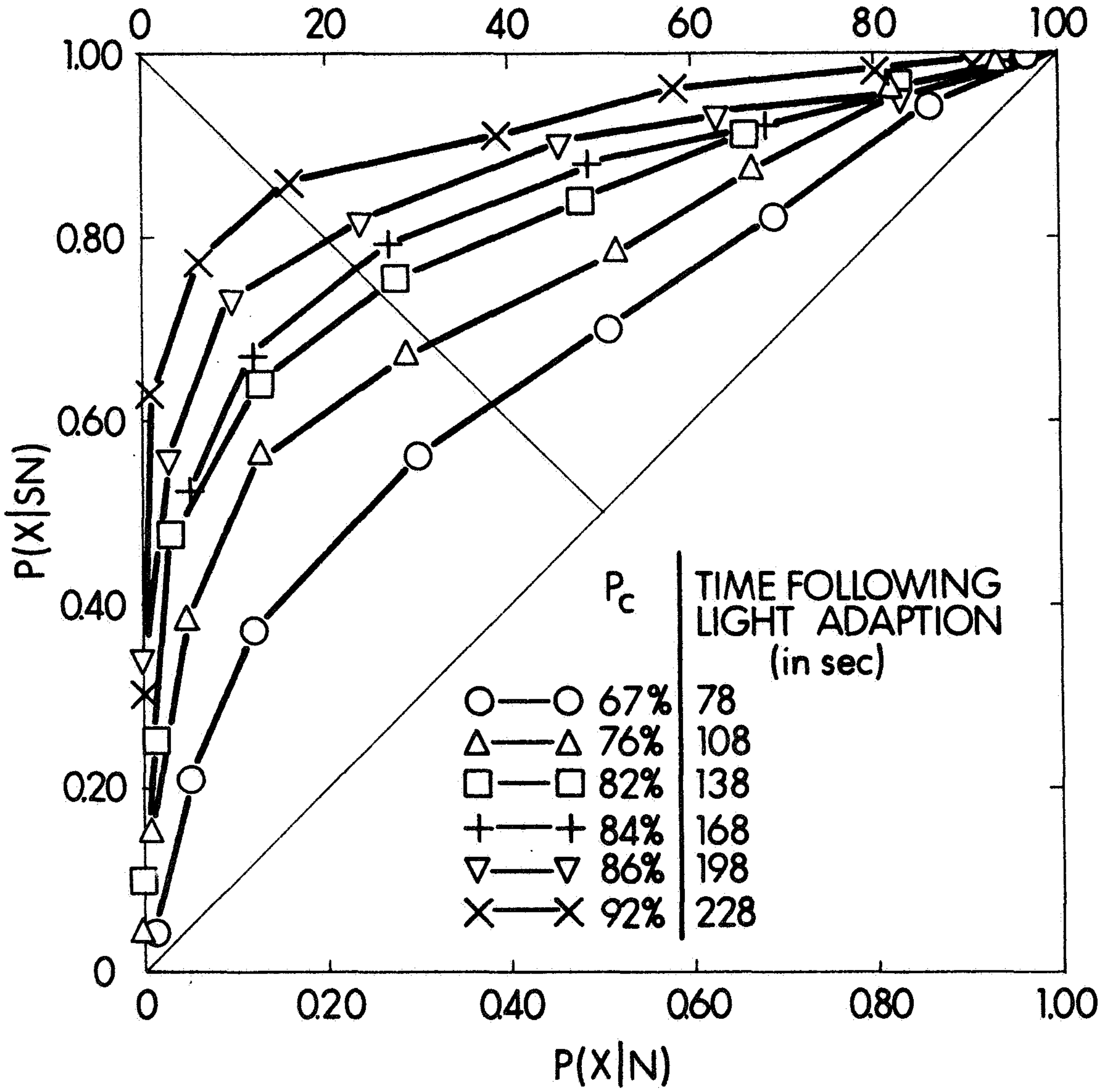
DWGAS-66-1344
GHJ - ORS
1 - 26 - 67

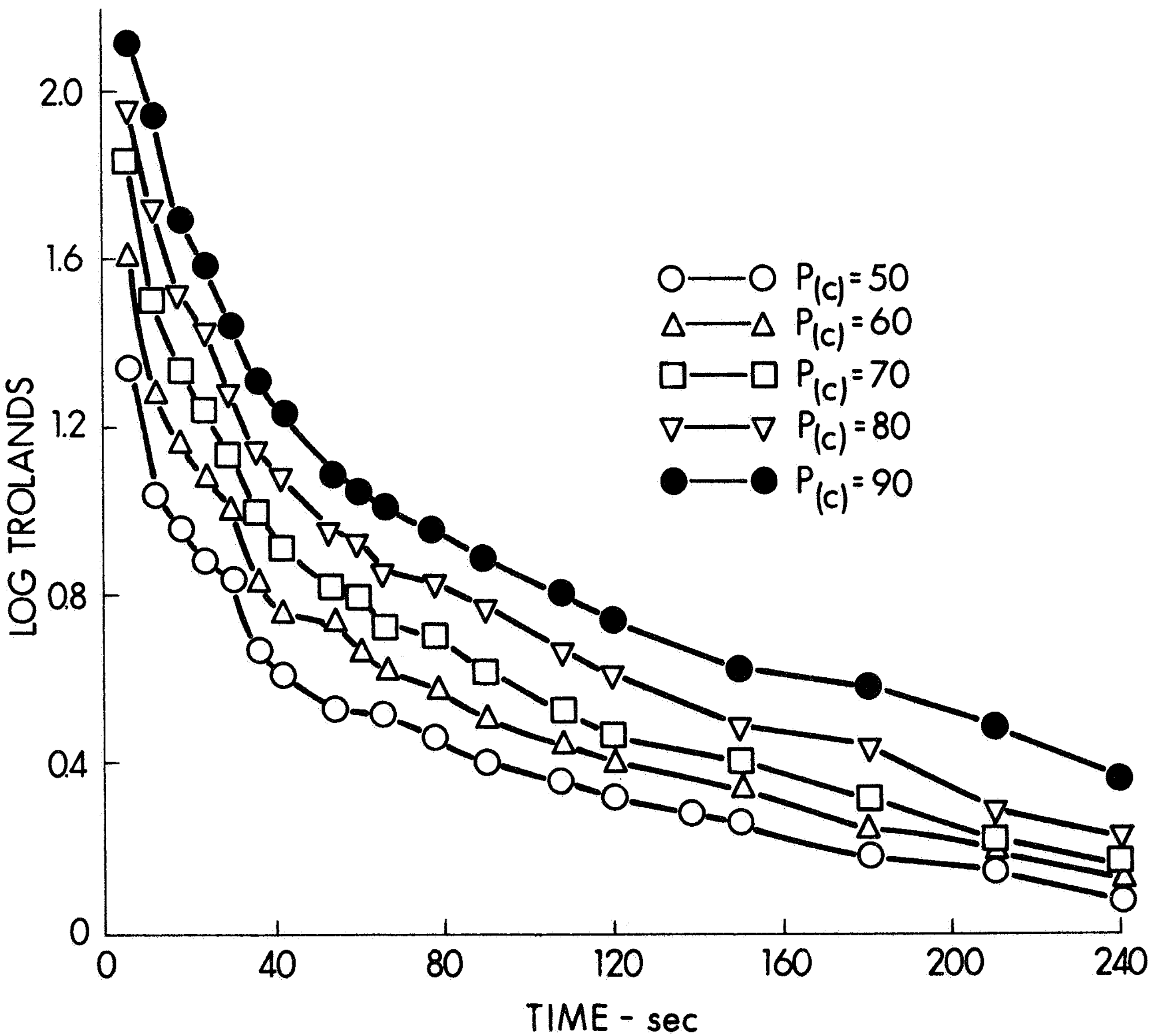
adaptation, the fixation light was turned on, and S signaled by means of a push button that he was ready. The adaptation light was then turned on for 200 msec, and every 6 seconds following the termination of the adaptation light a 1 sec warning tone was presented. At the termination of the tone, the test signal was either turned on or not (with an a priori probability of 0.5). The subject responded with an appropriate push button to indicate his assurance that a signal had or had not been presented. A response of "1" represented virtual certainty that there had been no signal, and "10", virtual certainty that there had been a signal. Forty such 6 sec periods following the adaptation flash constituted one "run", and from five to ten such runs separated by 2 minutes of dark adaptation constituted an experimental session. The luminance of the test signal was varied during the run and from one run to another according to a planned-haphazard program so that any of six or seven illuminances might occur during any trial in the run of 40. The values were chosen so that the percentage of correct responses at any period following the adaptation flash fell within a reasonable range for getting ROC curves. Some 400 ROC curves were obtained during the course of the study and the values of P(c) were determined from their area as measured by a planimeter. AS-67-1661 shows a family of ROC curves for the average of the three subjects. The data for this drawing were taken at a test light illuminance of 0.54 log trolands. The parameter of the family of curves is the time following the adaptation flash at which the data were taken.

Drawing No. AS-67-1718 shows the course of dark adaptation. The abscissa is time after the adaptation flash, and the ordinate is the illuminance needed to reach the percentage correct indicated as the parameter of the family of curves. This drawing is for a single subject. The other drawing showed similar results. The subjects were asked to report the moment when the positive after-image of the adaptation light disappeared. This occurred about



ROC CURVES FOR 0.54 LOG TROLAND "SIGNAL"

DRL - UT
AS-67-1661-S
LAJ - ORS
12 - 21 - 67



COURSE OF DARK ADAPTATION FOR ONE SUBJECT

DRL - UT
AS-67-1718-S
LAJ - ORS
12 - 21 - 67

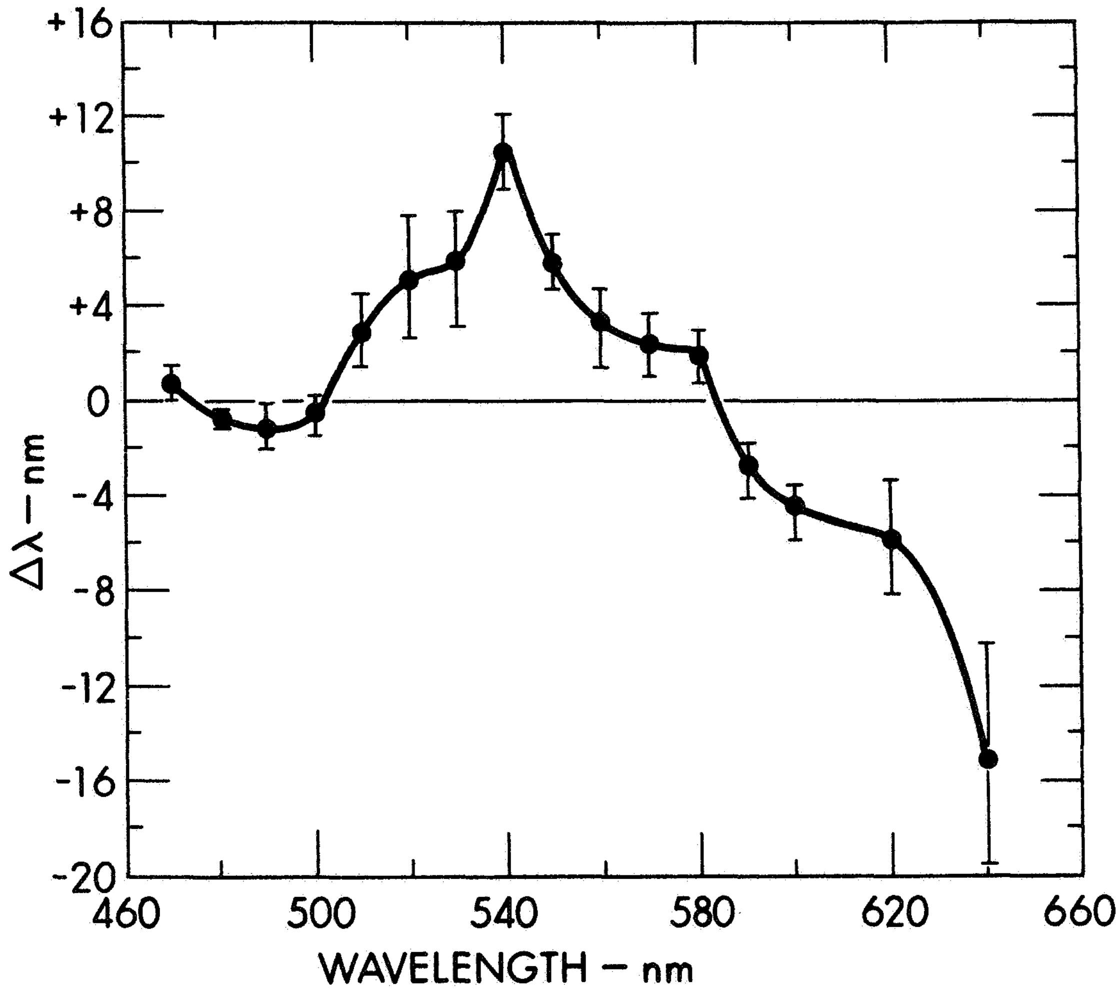
2 minutes after the exposure, but was not accompanied by any discontinuity in the recovery curve. The retinal "noise" is apparently not dependent on the presence of the positive afterimage.

This study is forming the basis for a doctoral dissertation by Mr. Heinz Gaylord.

The Bezold-Brücke Hue Shift

In spite of the importance of the Bezold-Brücke shift to theories of vision, much of our knowledge of the phenomenon is based on a single study by Purdy, made over 30 years ago and on a single subject. It therefore seemed appropriate to examine the effect with a substantial population. Seventy-two subjects, 33 females and 39 males, were employed in the present study. The color naming procedure described earlier was used. The apparatus was a two beam device with one beam providing the low level adaptation light, the other, the test wavelength. Measurements were made in the range from 470-630 nm, using a grating monochromator adjusted to yield a passband of 15 nm. Two luminance levels, 320 and 3200 trolands, were used with central fixation in Maxwellian view subtending an angle of 3 deg. Test stimuli were presented for 300 msec once every 18 sec. The adaptation light was viewed during the times between test stimuli. The order of stimulus presentation was randomized and every subject given several practice stimuli before data collection was undertaken. Each subject served for one hour and received as many stimuli as could be programmed in that time.

The color naming values were converted into nm's of shift and are presented in AS-67-416. The plotted points are the means for the sample of observers tested, and the bars represent 2 standard errors of the mean for the point. In general, the shifts shown here are smaller than those reported by Purdy, but the so-called invariant



BEZOLD-BRÜCKE HUE SHIFT

DRL - UT
DWG AS-67-416
GHJ - RFO
4 - 12 - 67

points occur at 584, 502, and 474 nm for the mean of the present sample--about the same locations as found in earlier studies.

The variability shown in the figure probably is largely the result of individual differences, since an earlier study shows that the method is capable of a high degree of reliability.

It was also possible to determine from the data the spectral location of unique yellow and unique green at the two luminances employed. The location of the unique yellow did not change systematically. The mean was 580.55 nm under the low luminance condition and 580.50 nm for the high. However, the location of the unique green showed an interesting effect. Table I shows the finding.

Table I

Unique green loci (in nm) for two classes of observers at two luminance levels. Results of statistical evaluations of row and column differences are indicated.

	N	Low luminance	High luminance	
Type I	19	513.1	509.9	$p < 0.05$
Type II	11	525.5	511.0	$p < 0.01$
		$p < 0.01$	$p > 0.05$	

It will be seen that the subjects appear to fall into two groups in their location of unique green at a low luminance level. The difference disappears at the high luminance level. Both groups show a shift in the location of the unique green at the low level, but the shift for group II is much greater than for group I.

In addition to the psychophysical work just reported, Dr. Jacobs and his students are conducting behavioral and neurophysiological studies on animals, with additional support from the National Science Foundation (Grant GB 4150 26-1007-2950). This work involves both color and spatial sensitivity of single units of the lateral geniculate. The findings of the work on color sensitivity are shown to correlate highly with the behavior of the animals in discrimination tasks.

III. AUDITORY RESEARCH

Beginning in May 1964, the National Aeronautics and Space Administration through Grant R-129 provided support for work in audition that was already receiving support from the U. S. Navy Bureau of Ships through Contract NObsr-72627. The addition allowed us to increase our effort in this field and to provide assistance for more graduate students--both experimenters working on dissertation problems and subjects who received hourly pay for their services. The grant also made it possible for us to construct considerably more flexible programming and recording equipment. At the present time most of our data are recorded on punched cards which are then analyzed by the Laboratory's CDC 3200 computer. Four subjects at a time can be run in psychophysical studies. Several signal levels can be employed in a single session and single interval, two-interval forced choice can be employed; or rating scale responses can be recorded. Serial effects can be examined where desired, and multiple observer responses as well.

Most of our recent work in audition has been concerned with detecting a signal in noise, although earlier a considerable amount of research was devoted to various problems in the localization of sound. The masking studies have fallen into two main categories, those concerned with the detection performance of the single ear, and those concerned with the binaural release from masking which can occur when stimuli to the two ears are not identical.

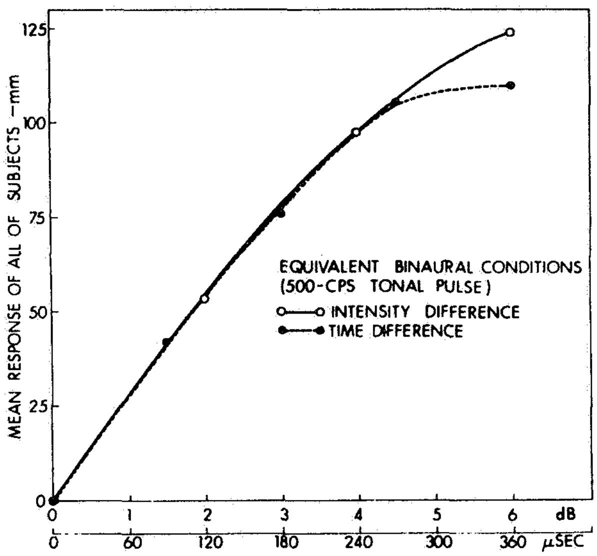
Binaural Studies

Time and Intensity Differences and Lateralization

This was a study conducted by a summer Science-Participation high school student (Brant T. Mittler) under National Science Foundation support, and supervised by Dr. Charles S. Watson. The student and his subjects were 17-year-olds. The subject's task consisted of drawing lines across a sketch of the head to indicate the range of movement of a commutated sound. The sound, a 500 Hz tone, was presented via earphones with either a level difference or a phase difference between the inputs to the phones. The inputs were commutated at half-second intervals and produced a distinct impression of movement within the head. The locations of the ends of the lines represented the point at which the subject thought movement began and ended. The data sheet was located behind a slit in a sketch of a face and was moved between trials so that each judgment could be made without reference to previous ones. The following drawing shows the mean length of line associated with the intensity difference or the time difference shown on the abscissa. It will be seen that the "trading ratio" obtained in this way is in good agreement with others in the literature: about 60 μsec per dB.

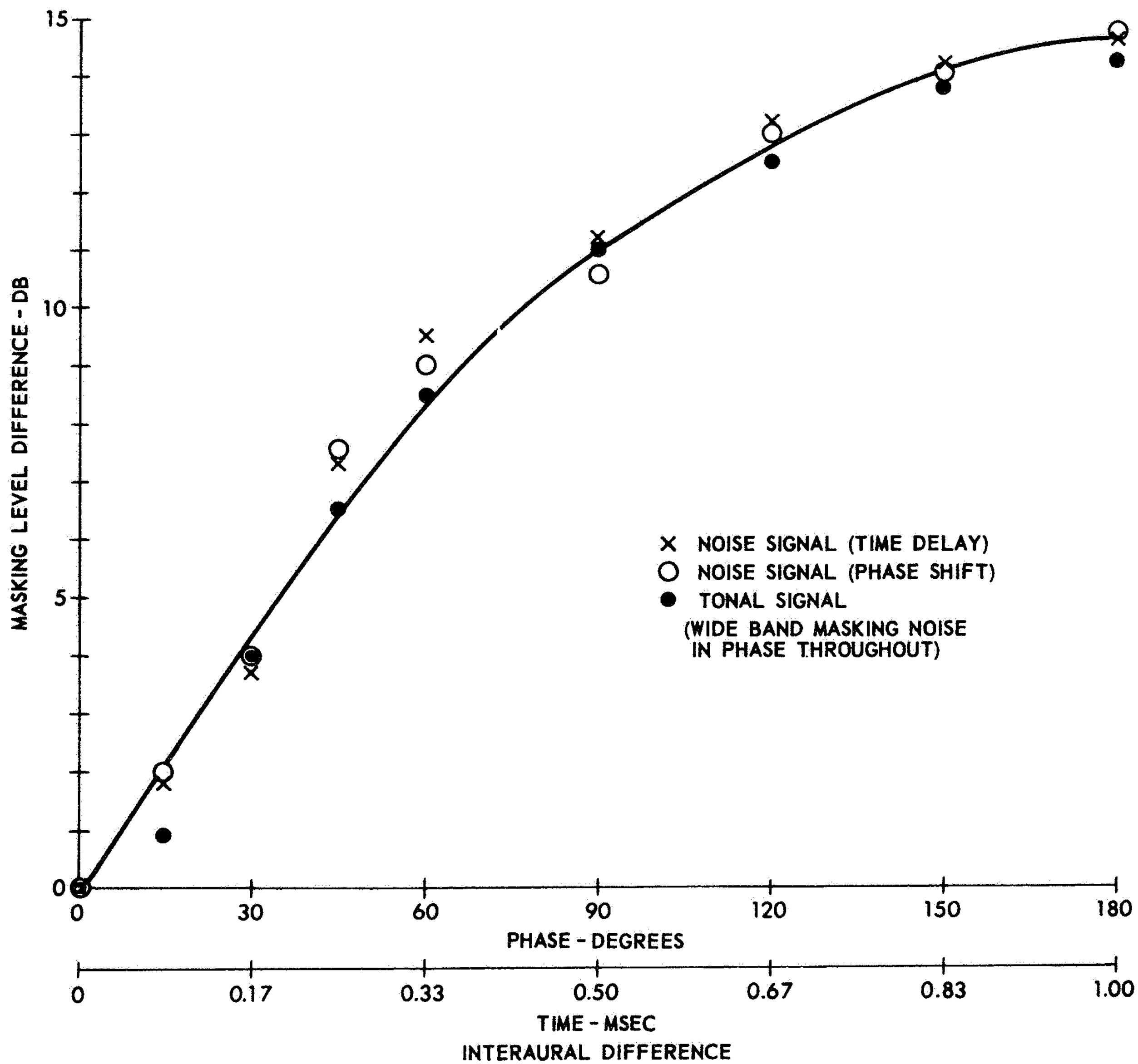
Masking Level Differences for Tone and Narrow Band Noise

A 50 Hz wide band of noise centered at 500 Hz and a 500 Hz tone were employed as signals in a binaural masking experiment. Webster and Hirsh had reported much larger masking level difference for a noise signal than for tone. The present experiment was undertaken in part to check their findings, for which no theoretical explanation was apparent. The major results are presented in AS-9174. It will



Equivalent binaural time- and intensity-differences, plotted by adjusting the abscissas to make the two functions coincident. This adjustment emphasizes the similarity in subjective effect of 60 μsec. and 1.0 db in shifting a sound image off of the median plane.

LENGTH OF LATERAL MOVEMENT OF A SOUND



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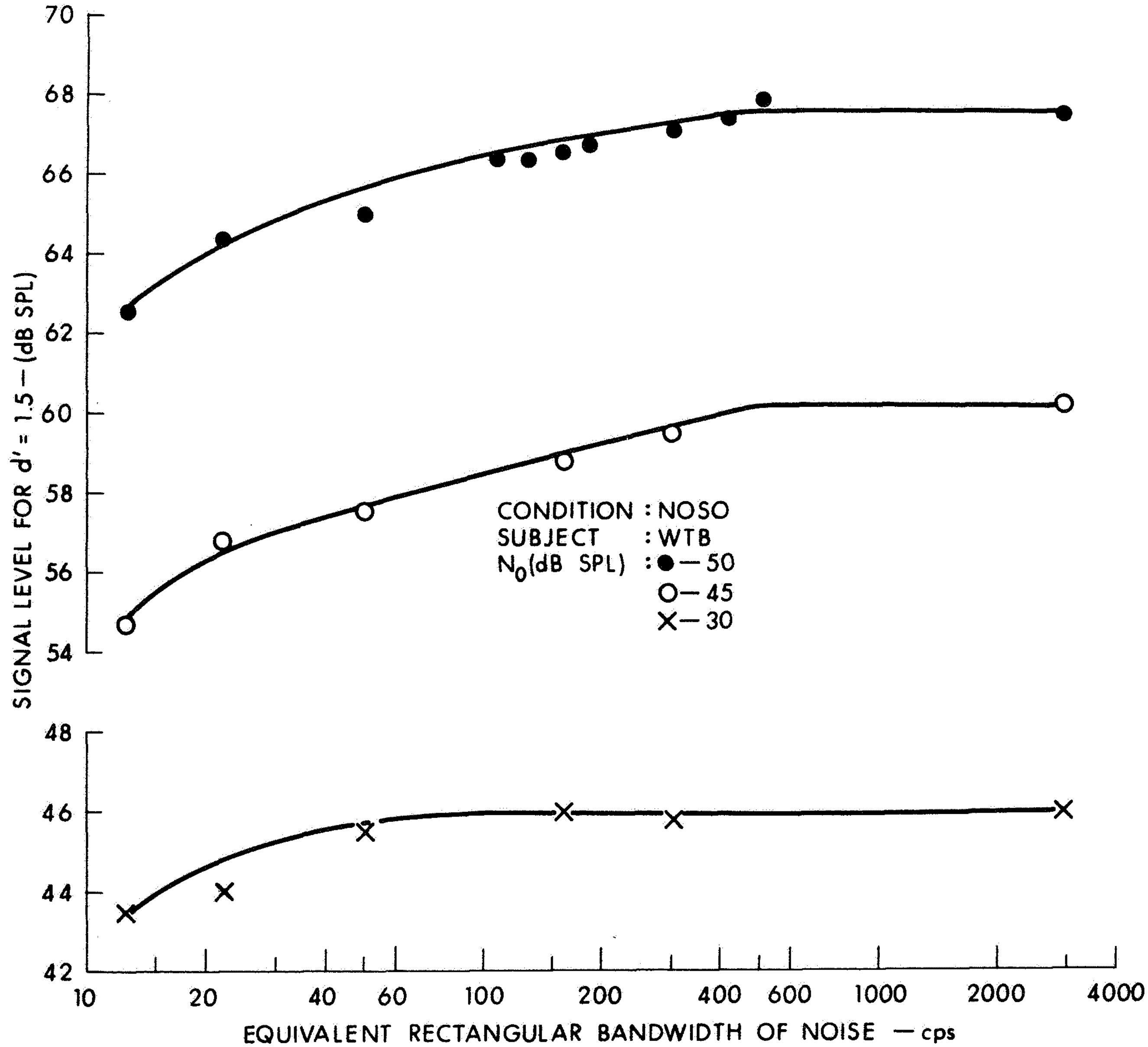
MER - EJW
4 - 24 - 64

MLDs FOR TONE AND NARROW BAND NOISE

be seen that there is no significant difference between the MLD's for noise and tone, and that it makes little difference whether the noise is shifted in time, by a delay line, or in phase by a phase shifter. A second experiment to attempt to explain the findings of Hirsh and Webster revealed that they had employed the same noise generator for their masker as for their signal. When these conditions were replicated, our findings agreed with theirs. A large MLD (18 dB) was obtained when the masker and signal were in phase opposition. It occurred, however, because of the considerable increase in the signal needed in the NO SO reference condition, not because of any great release from masking under the antiphasic condition.

Binaural Detection as a Function of the Bandwidth of the Masking Noise

Earlier work had suggested that the bandwidth involved in binaural detection is somewhat wider than that for monaural detection. The present experiment was undertaken to study this possibility. Equivalent rectangular bandwidths of 2900, 508, 422, 303, 185, 160, 130, 109, 50, 22, and 12.6 Hz were employed for the masker. The signal was a 500 Hz tone of 150 msec duration and a rise-fall time of 25 msec. Three levels of noise were employed: 50, 45, and 30 dB spectral level. A low level, wide band background noise was used to mask the second harmonic of the signal, that was about 60 dB below the fundamental. The stimuli were presented either with both noise and signal in phase at the two ears, NO SO, or with the signal reversed in interaural phase, NO Sπ. AS-65-816 shows the results for one subject for the diotic condition NO SO. It will be seen that the effect of band narrowing is not very significant until a bandwidth of about 50 Hz is reached, whereas AS-65-818 shows very substantial improvement beginning at bandwidths as wide as 200 Hz. The results



EFFECT OF BANDWIDTH ON HOMOPHASIC DETECTION

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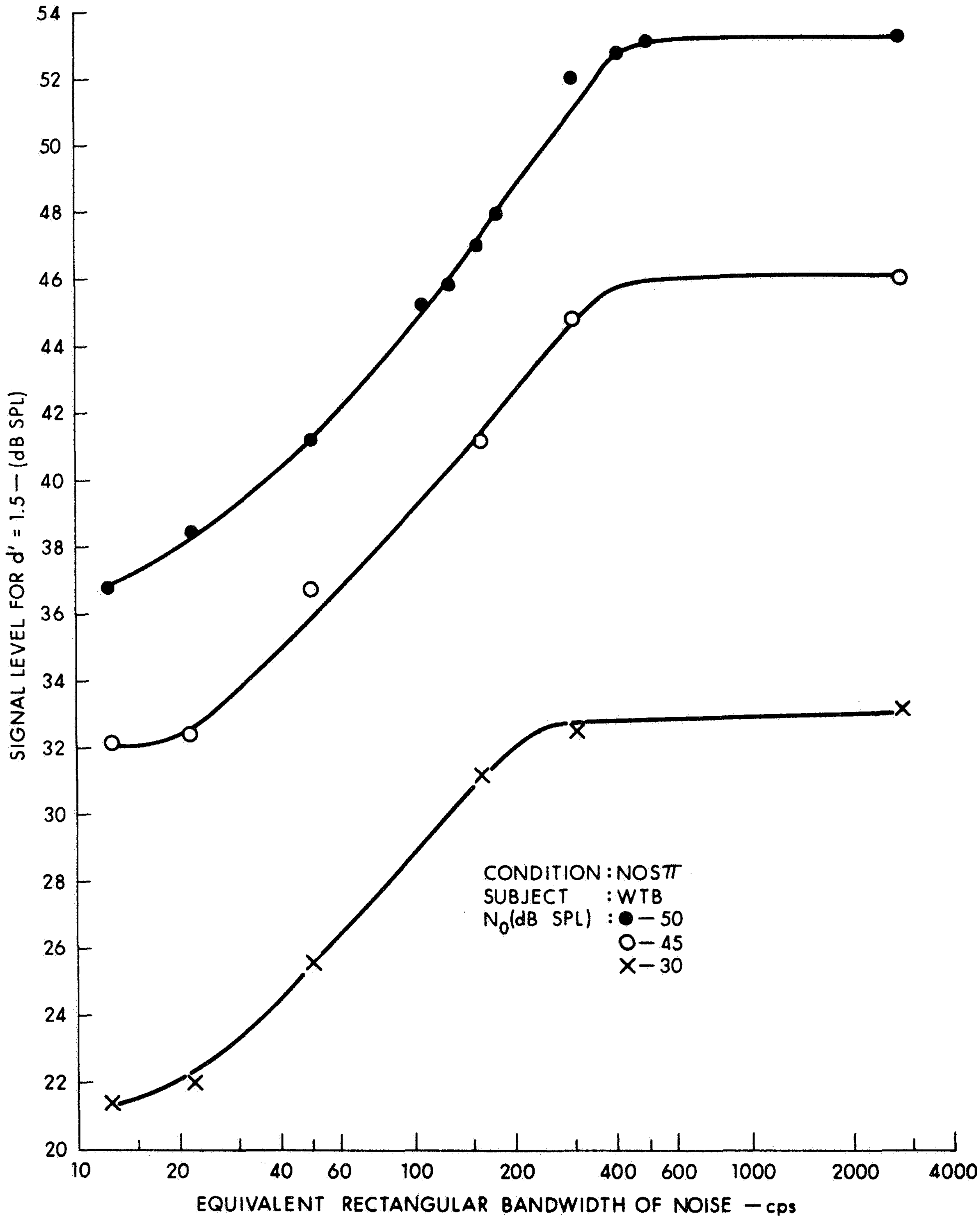
DWG AS-65-816
WTB - KLK
7 - 15 - 65



EFFECT OF BANDWIDTH ON ANTIPHASIC DETECTION

DRL - UT
DWG AS-65-818
WTB - KLK
7 - 14 - 65

strongly suggest that a much wider range of frequencies is involved in the detection of a 500 Hz tone under the NO Sπ condition than is involved in monaural or NO SO detection; this is probably not suprising, since we are presumably concerned with a population of auditory nerve cells in binaural phenomena different from these for monaural detection. Neural "funneling", as Békésy calls it, probably occurs in narrowing the bandwidth for monaural detection, whereas probably only the filtering provided by the mechanical action of the basilar membrane determines the bandwidth for binaural detection.

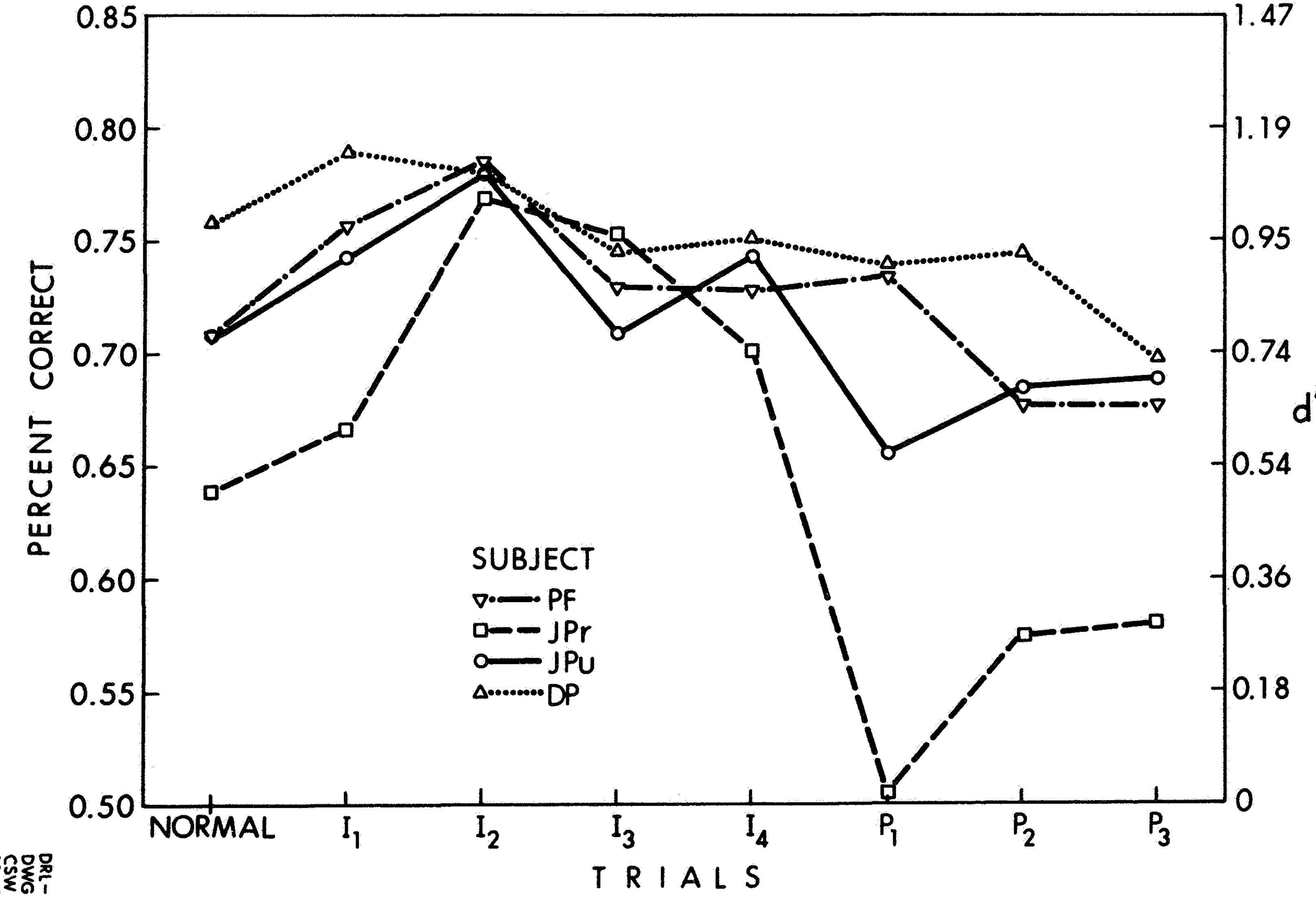
Binaural Electrical Models and Detection

Several electrical models of the binaural detection mechanism have been tested in psychophysical experiments, in an attempt to replicate human performance. Two such models have been run as subjects along with three human observers in a 2AFC experiment. The first model converts the interaural time difference produced when a signal is added antiphasically to an in-phase noise into a voltage which is averaged and sampled at the end of the observation interval. To avoid perfect performance when the noise is in phase at the two ears and the signal reversed in phase at one ear, a small amount of uncorrelated noise is introduced into one channel of the model. This simulates the "noisiness" of the subject's transduction of waveform into nerve impulses. The model yields psychometric functions which fit human functions either at high signal levels or at low, depending upon the noise correlation used. It has not been possible with this device to fit human performance over the whole range of the psychometric function. This fact may be the result of a major inadequacy of the model. It takes into account the time differences based on axis crossings, but it fails to make use of differences in level which result from adding the signal to the noise. A second model, based on Durlach's Equalization-Cancellation model, has so far failed to perform as well as the one just described. A third model employing the crosscorrelation between the two earphone channels is under consideration and will be similarly employed if some of its present weaknesses can be eliminated.

Monaural Phenomena

Effect of "Vigilance" in an Auditory Detection Experiment

Many attempts to improve detection by a manipulation of the values and costs matrix have failed to produce an appreciable improvement in detection over a block of trials. The present experiment was undertaken with the idea that enhanced vigilance is a condition which can be maintained for only a short stretch of time. Accordingly, certain trials were selected as the "important" trials and their presence was signaled to the subject by means of a light. In the first experiment, the subject was told that these were the important trials and that he must be particularly careful to respond correctly (in a 2AFC setting). This preliminary experiment failed to reveal any improvement on the "important" trials. The next experiments involved various schedules of punishment for incorrect responses on the indicated trials. The punishment was a mild shock (1.6 mA) applied to the ankle, and the experiments differed in the number of successive trials that were included in the critical block. AS-10088 shows the results of one experiment where the number of "important" trials was four. The shock for an incorrect response could occur in any of the four trials. The results show a substantial improvement by the second trial, but a falling off after that. The post-shock trials showed a considerable decrement for two of the subjects with a gradual return to a normal level of performance. The



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DWG AS 10088
CSW-CLW
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EFFECT OF PUNISHMENT ON DETECTION PERFORMANCE first points on the graph are the average for the preceding 16 days of training without the interpolated trials. The findings show that improved detection can be achieved for a very short time but is not maintained. The average for the whole block of trials was the same with and without the shock.

Width and Shape of the "Critical Band" Involved in Masking

There is considerable disparity in the estimates of the width of the "critical band" to be found in the literature. The present study was undertaken to obtain a better idea of both the width and the shape of the band of frequencies involved in masking a 500 Hz signal. It employed a set of high-pass and a set of low-pass filters in order to approach the signal frequency from one side at a time. The results, which are being prepared for publication, show that the shape of the ear's filter is distinctly unsymmetrical, having much higher skirts on the low-frequency side than on the high, and that the equivalent rectangular width is of the order of 50 to 80 Hz. One important finding appears to be that subjects differ in their bandwidths. One subject who performed more poorly than the others began to improve at considerably wider bandwidths than the others. That is, he required less narrowing of the masking noise to show improvement than did the others. Apparently in experiments where the task is the detection of a tonal signal, the Fletcher-type estimates of bandwidth are appropriate.

Models: Electrical and Mathematical

The mathematical theory of signal detectability (TSD) is based, in the usual derivations, on sampling theory--on taking a series of 2WT samples of noise (N) or noise plus signal (SN), where T is the temporal duration of the sample. There is some confusion about the meaning of W. Some writers treat it as if it were the bandwidth of the masking components of the noise (the critical bandwidth); others treat W as if it were the bandwidth measured from zero, i.e., as if it were the highest frequency present in the noise sample. In any case, N and SN are sampled in the same way and for the same duration. These assumptions immediately lead us into trouble when we attempt to apply the theory to human observers or to electrical models. The assumption that N and SN are sampled similarly means that they are sampled after being filtered, that is, that the gate follows the filter. In hearing, the filtering is presumably being done by the ear and the gating in advance of the earphone. Thus, the transient responses of the filter become involved. The mathematical theory neglects this aspect of hearing. Also, when we consider the very common experimental condition where the noise is continuous and only the signal is gated for a time, T, we are forced by the mathematical theory to assume that somehow the subject is able to gate the noise in the same way that the experimenter gates the signal--a not very realistic assumption. The question of when and how long to sample becomes one of major concern when dealing with a physical model of the auditory system.

The Role of Signal Duration

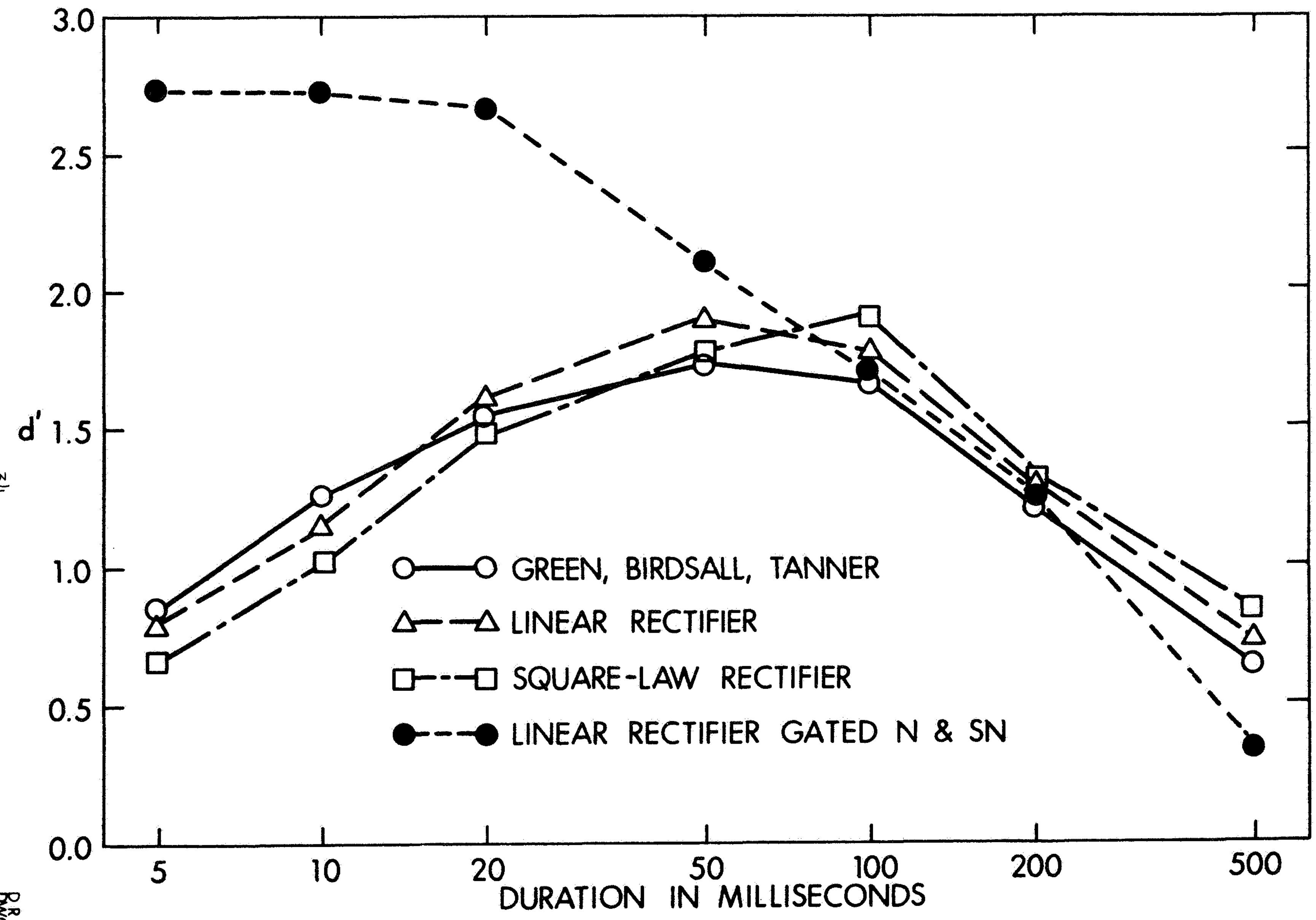
The classic study of the role of duration in the detection of a gated signal in a continuous noise background was made by Green, Birdsall, and Tanner (1957). They employed a constant-energy signal of various durations and used a four-interval forced choice procedure for determining the observers' d's. Their basic finding was that observers did best over a range of durations from about 20 msec to about 200 msec, and fell off rather sharply for durations much longer or shorter than these.

We attempted to replicate the results on signal duration by means of an electrical model which consisted of a narrow filter, a half-wave rectifier, and a post detection (envelope) filter. When the post detection filter had the short time-constant needed to obtain a close-fitting envelope, the data failed to resemble those of the experiment by Green et al. Instead of being reasonably flat across a range of durations, the data showed a decided peak at a duration that was the reciprocal of the filter bandwidth. It was only when we increased the time-constant of the post detection filter to 50 or 100 msec that we succeeded in replicating the psychophysical data. This time constant is of the same magnitude as that arrived at by Zwislocki from a very different set of experiments.

Drawing AS-66-368-S shows the results of the final series of experiments. The circles show the averages for the subjects of the experiment by Green, Birdsall, and Tanner; the triangles, the data obtained with the model using a half-wave rectifier; and the squares show the effect of employing a square-law (energy) detector instead of the half wave. When the tenets of TSD are more nearly observed, by gating both the masking noise and the signal in the same way, the solid circles were obtained. This suggests that if subjects are presented with gated noise and signal they should perform better, for a constant-energy signal, when both the noise and signal are gated than when the noise is continuous and only the signal is gated.

Gated Noise and Signal

Following the lead suggested by the previous drawing, we undertook an experiment in which subjects were presented signals of various duration but of constant-energy both with continuous noise and with noise gated for the same duration as the signal. AS-66-1036-S shows the averages for three subjects. It will be seen that the subjects did perform better with gated noise than with continuous. They did not show, however, as the model did, continued improvement for gated noise and signal at the short durations.



EFFECT OF SIGNAL DURATION ON DETECTION

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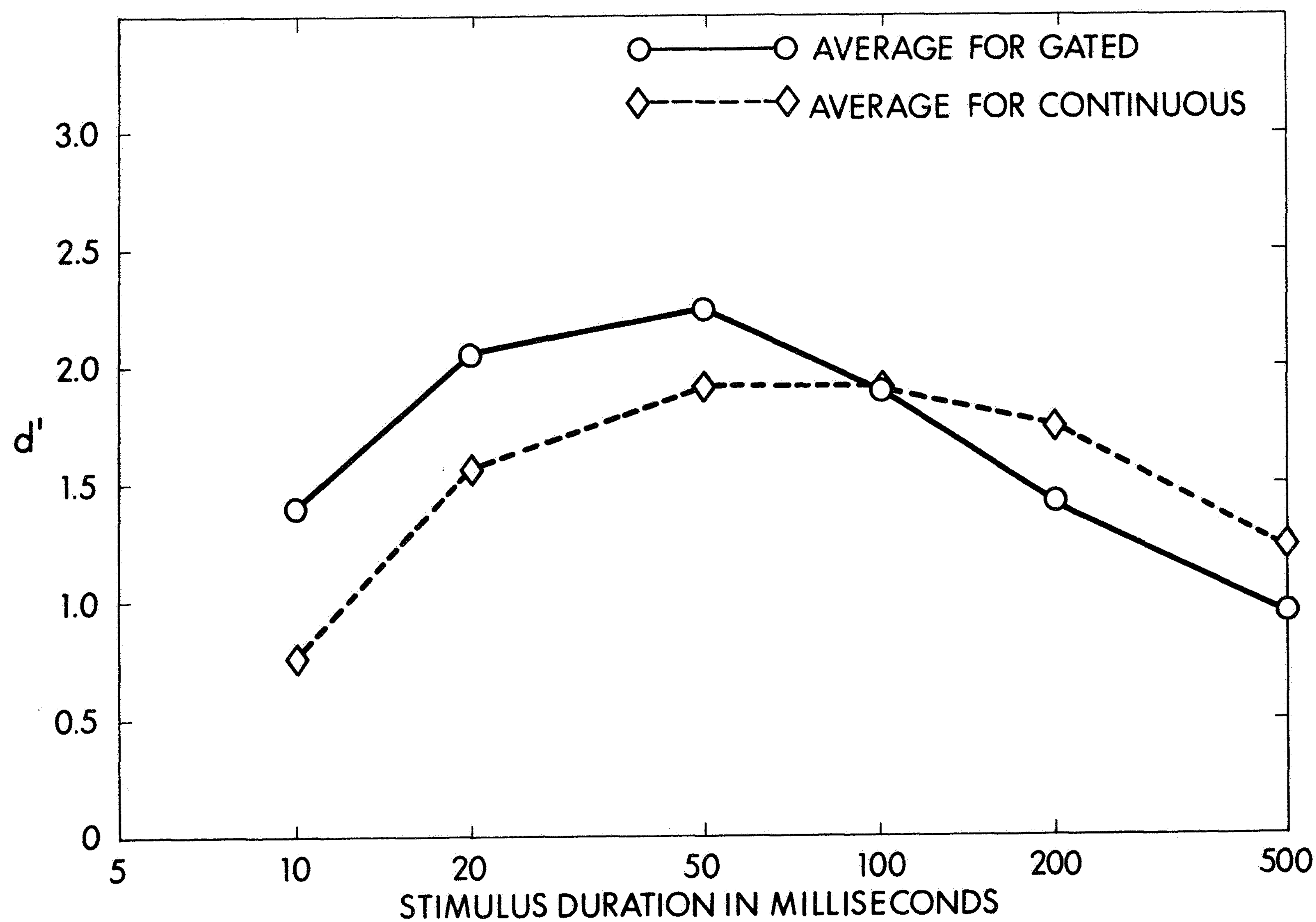

DETECTION FOR CONTINUOUS AND GATED NOISE

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Dr. John Whitmore (a postdoctoral student here) suggested that detection of a signal in a brief gated noise is a very difficult judgment, and that possibly our findings would be different with highly trained subjects. The experiment was therefore repeated using trained observers, with the result that the predicted improvement in performance as the signal was shortened was actually observed. The subjects did better at 5 msec than at 10 and better at 10 than at 20 or 50. The results are being prepared for publication.

Electrical Model as a Predictor of Observers' Responses

Since the electrical model appeared to simulate human performance in several important respects, it was employed as a subject along with human observers in several psychophysical experiments. In the first experiment (by Thomas L. Nichols) it was run as a subject with a human observer in a yes-no experiment (four subjects were tested in this way). It proved to predict the subjects' responses better than whether the signal was present or not. It also proved to be a better predictor than another electrical measure of the stimulus. This was a peak device that recorded the largest envelope peak that occurred during the 250 msec observation interval. Both noise and signal were gated for 250 msec. The two electrical measures showed a correlation of 0.5 to 0.6 for the 250 msec duration. Shorter durations increased the correlation to near unity for very short durations. The 250 duration was chosen to permit the two electrical measures to be reasonably independent with the possibility that they would respond to different aspects of the stimulus and would predict the subjects' responses better than either measure alone. Actually, the peak detector added only about one percent to the predictions of the other electrical model.

A second experiment with the model was carried out--this time employing it with three human observers in a 2AFC experiment using seven levels of signal, and with some trial on which noise alone was presented in both intervals. Table II shows the results.

Table II

E/N_o	$P(C)_m$	$P(C)_{\bar{o}}$	$P(A)_{\bar{o},m}$	$P(A)_{\bar{o},\bar{o}}$	$P(C)_{3\bar{o}}$	$P(A)_{m,3\bar{o}}$
12.8	98.8	92.6	92.4	88.9	99.4	99.1
7.6	91.3	80.4	80.8	76.6	94.1	94.4
5.7	87.3	76.2	77.6	75.2	91.1	93.2
4.8	85.4	72.8	73.6	70.3	87.4	89.8
4.0	79.3	67.2	71.8	70.1	78.7	86.4
3.1	77.0	65.9	72.0	66.5	78.6	88.3
2.5	71.3	60.1	66.1	60.7	68.9	81.7
0.0	50.0	50.0	65.0	63.0	50.0	81.9

The first column is the signal employed, ranging from an E/N_o of 12.8 to zero--noise alone presented in both intervals. The second column is the percentage correct for the model, and the third is the average percentage correct for the three subjects. It will be seen that the model yields superior detection throughout the range of stimuli. Recent work has shown that we could have obtained a more nearly human fallibility from the model by employing a shorter time constant in the post detection filter.

The fourth column is the percentage of agreement between the model and the average of the three observers. It will be seen that the model's prediction of the subjects' responses is better than their percent correct. That is to say: the model is predicting their response better than the presence of the signal does. When no signal occurs in either interval, the model predicts their responses 65% of the time.

The fifth column is the average percentage of agreement between one observer and the other two. Comparing this column with column five shows that the model predicts the responses of the human subjects better than they predict each other.

The sixth column is the percentage of correct responses made by the subjects to the stimuli on which all three agreed, whether right or wrong. The column shows that the percentage correct for the stimuli on which the three observers agree is considerably higher than their percentage correct for all of the stimuli. This is of course to be expected--the multiple observer is better than the single observer. The last column shows the agreement of the model with the subjects on those stimuli where the subjects all agree. Again the percentages are higher. Even when no signal is present, the model agrees with the three subjects on more than 80% of the trials.

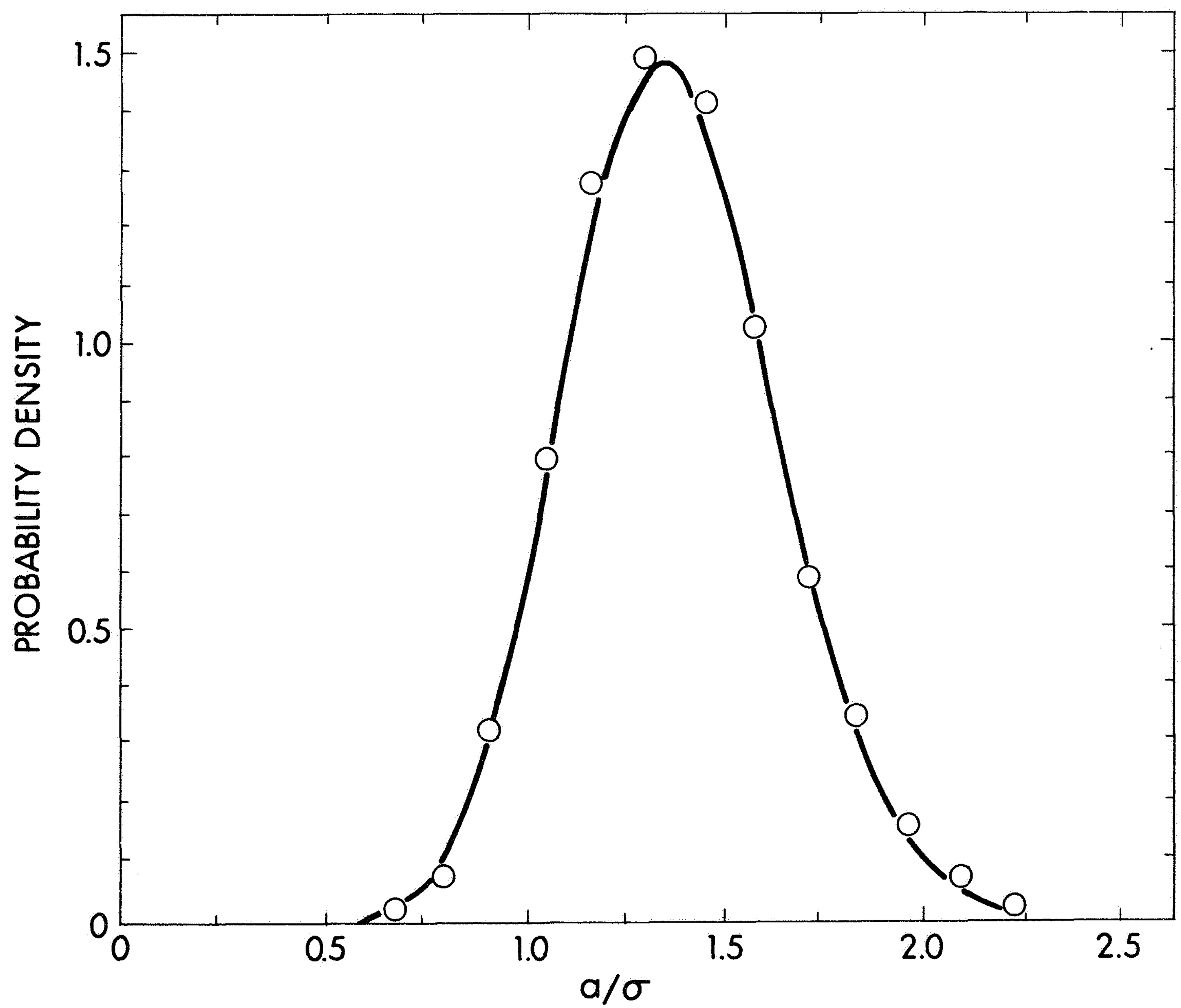
We may conclude that the model is apparently responding to the aspect of the stimulus most important in human signal detection, a considerably smoothed representation of the stimulus envelope.

A Mathematical Model of Monaural Detection

In a recent, brilliant paper, McGill (1967) has shown that the results of an early experiment by Marill (1964) can be explained in terms of an energy detector model. Marill had employed an envelope detector in his derivations and had arrived at a formula for predicting the percentage of correct responses in a two-alternative, forced-choice experiment. McGill arrives at the same formula by way of an energy detector. He assumes that a narrow band of noise, or noise plus signal, is gated for a time T, the resulting voltage is squared and then integrated. The integrator is discharged between observations. From the statistics of this device he derives Marill's equation. He then goes on to show that the bandwidth assumptions made by Marill in fitting his theoretical function to human observers are inappropriate, and that a better adjustment can be made by assuming a different number of degrees of freedom in the probability functions. He shows that the Rayleigh-Rice statistics employed by Marill can be replaced, and more generality achieved, by employing the noncentral chi-square distribution.

The electrical model we have been discussing is capable not only of voting in a 2AFC experiment but, by recording samples of its output, of generating the distribution functions of its underlying statistics. We find that if we sample the noise distributions measured at the output of the post detection filter, we obtain an probability density function which resembles, but differs from, the Rayleigh distribution. It is less skewed, but still has considerable skewness. It does not resemble any chi-square distribution. The resemblance to the Rayleigh distribution suggests that the appropriate function would be a Rayleigh-like distribution with more degrees of freedom, and this proves to be a special case of the chi density function. AS-67-1551 shows a chi distribution with 14 deg of freedom. The points represent 10,000 samples of the output of the post-detection filter.

Since the chi distribution fits the data for noise alone, the next question is whether the noncentral chi distribution with the same number of degrees of freedom will fit the data for noise plus signal. AS-67-1552 shows the resulting "psychometric" function. The abscissa is signal-to-noise ratio and the ordinate is the difference of means divided by the standard deviation of the



CHI DISTRIBUTION $\nu = 7$ AND DATA FROM ELECTRICAL MODEL

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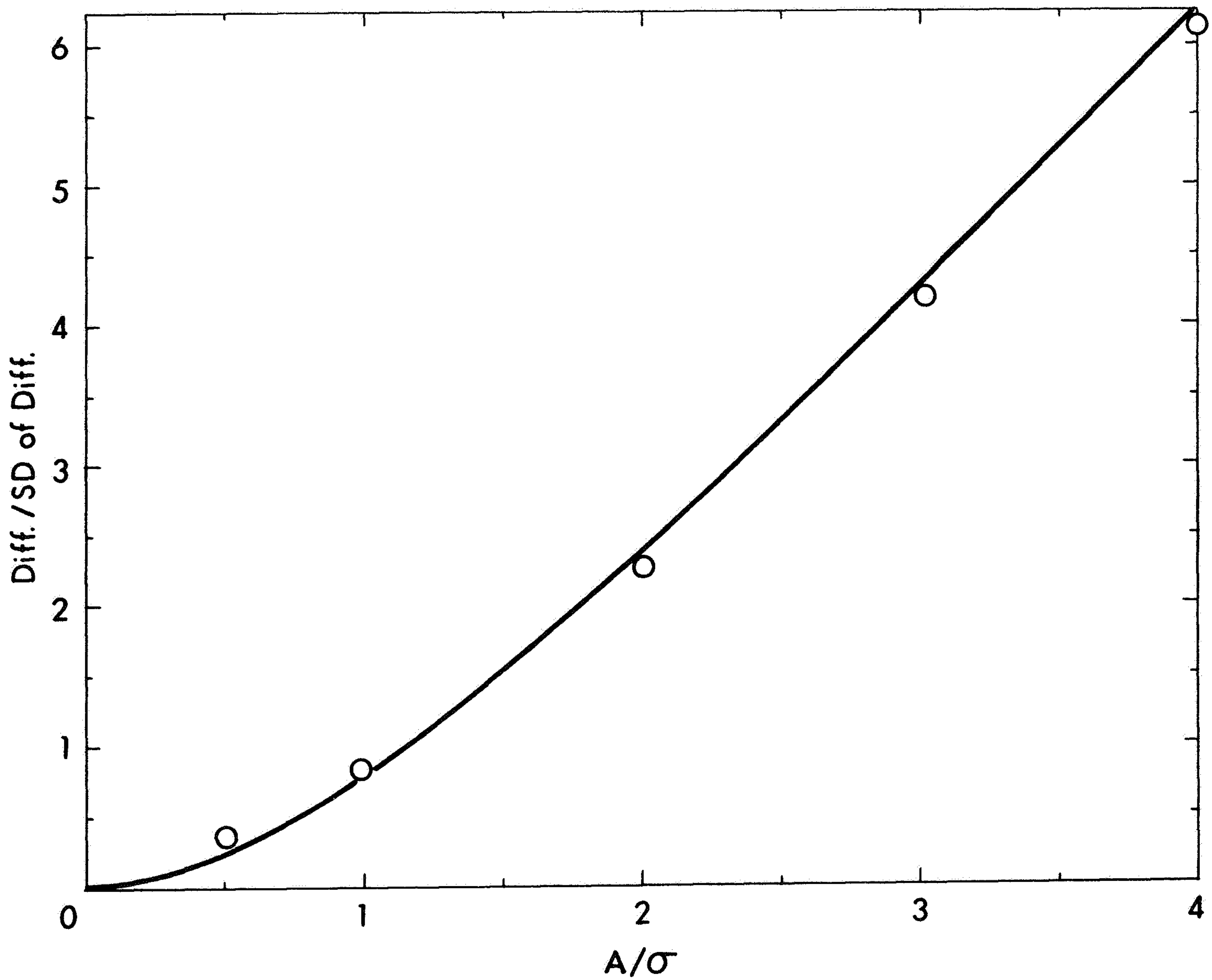

NONCENTRAL <u>CHI</u> DISTRIBUTION AND DATA FROM ELECTRICAL MODEL

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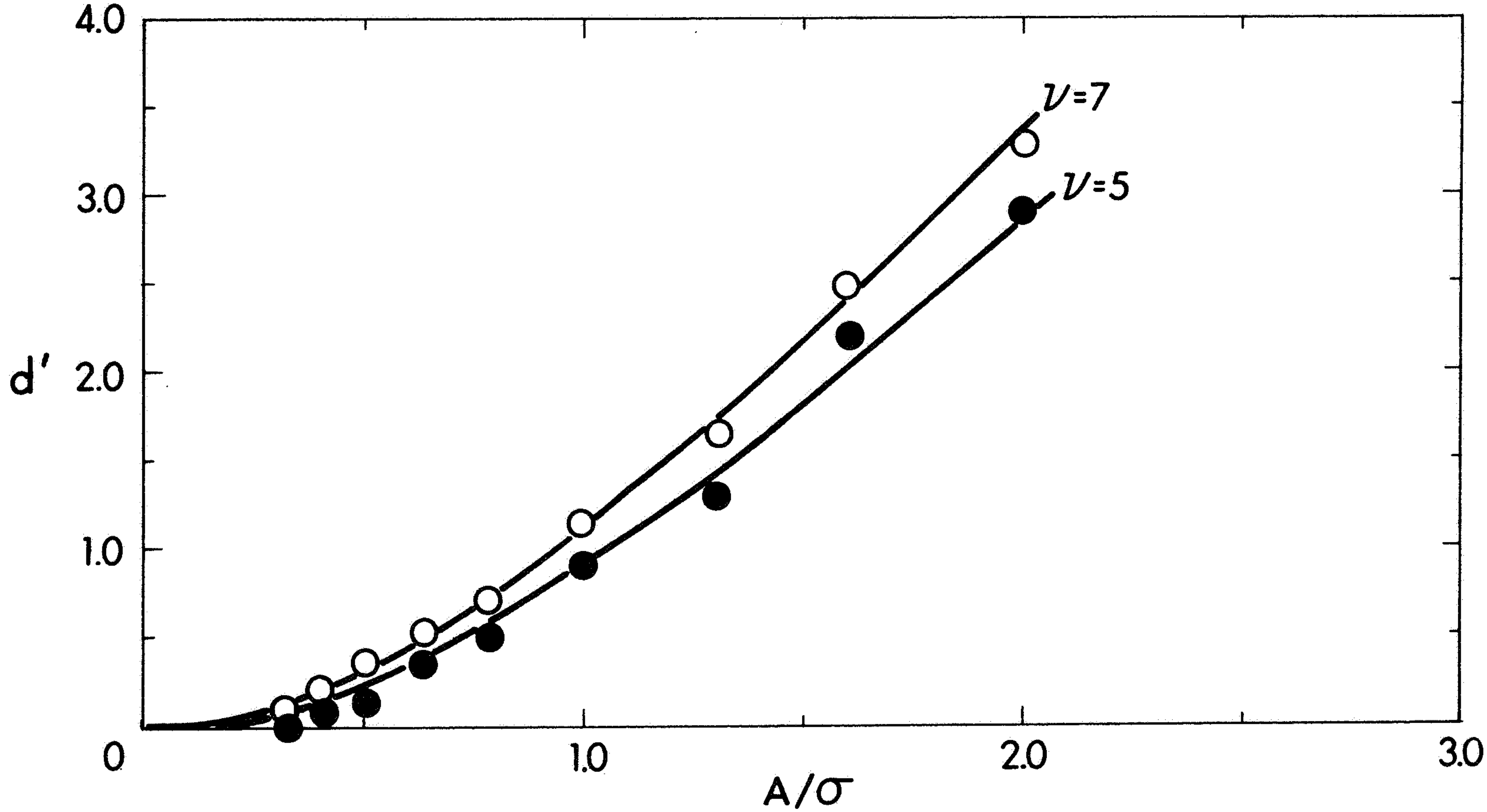
difference. The fit appears to justify the assumption about the appropriateness of the distribution functions.

Noncentral Chi Distribution and Psychometric Data

Drawing No. AS-67-1553 shows the same chi distribution and another with 10 deg of freedom along with data for Marill's two subjects. It will be seen that one of the subjects fits the curve for $v = 7$ (14 deg of freedom) very well. The other subject apparently requires fewer degrees of freedom and even then yields a rather ragged fit. Apparently the parameters chosen for the electrical model (50 Hz bandwidth and a time constant for the post detection filter of 50 msec) correspond reasonably well with the parameters employed by the first subject. The data for the second subject requires the assumption that he employs either a wider filter (Marill's conclusion) or that his integration time is shorter. At the present state of our knowledge of individual differences it is not possible to decide which (or both). The raggedness of the second subject's fit also suggests that nonstimulus factors are influencing his behavior, attention lapses, indecision about which button to press, etc.

The rather surprising agreement between the data for the model and for one of Marill's subjects suggests that this subject, like the model, is governed in his responses almost wholly by the statistics of the stimulus. The parameters chosen for the distribution employed are well within the range of values estimated for detection experiments--a "critical" bandwidth of 50 Hz and a time constant of 50 msec. The latter is the figure recently reported by Zwislocki for the auditory system.

The studies with the model and the mathematical developments were published in the Journal of the Acoustical Society of America for July 1968.



NONCENTRAL CHI DISTRIBUTION AND PSYCHOMETRIC DATA

DRL - UT
AS-67-1553
LAJ - ORS
12 - 6 - 67

IV. LIST OF PUBLICATIONS

C. S. Watson, M. E. Rilling, and W. T. Bourbon, "Receiver-Operating Characteristics Determined by a Mechanical Analog to the Rating Scale," J. Acoust. Soc. Am. 36, 283-288 (1964).

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E. R. Hafter, W. T. Bourbon, Anne S. Blocker, and Ann Tucker, "Detection of Lateral Movement under Antiphasic Masking Conditions," J. Acoust. Soc. Am. 36, 1991-1992(A) (1964).

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C. S. Watson, "Response Latency as a Criterion-Dependent Measure," J. Acoust. Soc. Am. 37, 1193(A) (1965).

L. A. Jeffress, "Masking and Binaural Phenomena," Defense Research Laboratory Acoustical Report No. 245, 14 June 1965. Note: This report consists of Chapters 13 and 15 to appear in Foundations of Modern Auditory Theory. J. V. Tobias and E. D. Schubert (Eds.) Academic Press: New York.

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V. ABSTRACTS

Receiver-Operating Characteristics Determined by a Mechanical Analog to the Rating Scale. Charles S. Watson, Mark E. Rilling, and Walter T. Bourbon.--In one portion of a fixed-interval-observation experiment, observers indicated their certainty that a 500-cps signal had been presented in a thermal-noise background by positioning a slider after each interval. In a second portion of this experiment, the observers responded by making binary decisions. Slider positions were treated as typical confidence ratings; the conditional probability of a given rating or of one indicating greater confidence, given signal plus noise, was plotted against the probability of these ratings, given noise alone. Functions produced in this manner, for a rating scale divided into thirty-six positions, were fit closely by the receiver-operating characteristics (ROC's) of the theory of signal detectability. A psychophysical model using two straight-line segments did not provide a good approximation to these data. Values of d' were generally lower for the rating procedure than for the binary-decision procedure. The use of a large number of rating categories did not result in large increases in information transmitted by the observers, but it did provide the desired fine resolution of the ROC's.

Stimulus-Oriented Approach to Detection. Lloyd A. Jeffress. Distribution curves for amplitude (envelope), drawn for noise and for noise plus signal, provide the basis for determining the proportion of area (probabilities) lying above various "criterion" levels. Probability pairs $P(y|n)$ and $P(y|sn)$ for various criterion levels furnish the coordinates of points generating ROC curves, which, because of the skewness of the distributions, show a slight curvature when plotted on normal-normal paper. This curvature (concave downward) provides a better fit to detection data obtained from rating-scale experiments than do the straight lines obtained from normal curves. The ROC curves belong to a family derived through the theory of signal detectability for the ideal observer in the case where signal phase is unspecified. The fact that the distribution for noise-plus-signal amplitudes has, in general, a larger variance than that for noise alone explains why many experiments find the ratio of σ_{sn} to σ_n to be greater than unity. A detection measure d_s derived from the two distribution curves, when plotted against signal amplitude is a straight line over most of its course but bends in to the origin for weak signals. Its failure to touch the positive abscissa supports the TSD argument against the threshold hypothesis. A second curve, derived from this one, provides a convenient way of determining the signal required to yield a particular value of d_s, when the signal that yields some other value of d_s is known. Finally, the concept of "effective bandwidth" is developed, and provides a single parameter for use in fitting detection data. Data give some support for the notion that the auditory system adjusts its bandwidth in accordance with the duration of the signal.

Effect of Phase Difference between Signal and Masker on Detection of a Narrow-Band Noise Signal. Mark E. Rilling and Lloyd A. Jeffress. In a comparison of tonal and narrow-band signals, reported by the authors in 1964, the masking level differences (MLD's) for the two signals were the same for corresponding phase shifts. Earlier, Hirsh and Webster reported differences for similar conditions. In the authors' experiment, there was a random phase difference between the signal and masker since separate noise generators provided the signal and noise, while Hirsh and Webster's single noise generator gave a fixed phase difference between the signal and masker. In the present experiment, a single noise generator was used and the phase difference between the signal and masker was shifted in phase by 30° steps between 0° and 180°. For each signal masker phase difference, the signal was presented in phase at the ears and reversed in phase at one ear. Data are presented as MLD's relative to the signal-in-phase condition for each signal masker phase difference. The MLD's increase monotonically from 13 dB at 0° to 18.5 dB at 180°.

Theoretical and Obtained ROC Curves for Antiphasic Stimulation. Lloyd A. Jeffress, Charles S. Watson, Mark E. Rilling, and Walter T. Bourbon.--The ROC curves of the paper [Watson, Rilling, and Bourbon, "Receiver-Operating Characteristics by Rating Scale for Antiphasic Stimulation,"] for the diotic stimulus condition can be fitted closely by theoretical curves derived from amplitude distributions for noise and noise plus signal. The ROC curves for the antiphasic condition $N0\ S\pi$ cannot; nor can they be fitted by theoretical curves derived from normal distributions. They can, however, be fitted reasonably well by theoretical curves based on the idea that the stimulus, now, is interaural time difference, that the noise is neural "noise" resulting from time uncertainty of neural firing, and that the signal is the interaural time difference that results from adding the tonal signal antiphasically to narrow-band, acoustic noise.

Receiver-Operating Characteristics by Rating Scale for Antiphasic Stimulation. Charles S. Watson, Mark E. Rilling, and Walter T. Bourbon. This paper describes the replication by the same authors of an experiment that was reported earlier [J. Acoust. Soc. Am. 36, 283-288 (1964)]. The replication differs from the original experiment in employing an antiphasic stimulus condition NO Sπ. The equipment, a mechanical, rating-scale device, was the same as used formerly, and with the same procedure. The new ROC curves are strikingly different from those obtained earlier for the same subjects under the diotic stimulus condition NO SO, and imply substantially different noise and noise-plus-signal distributions. The rating-scale procedure appears to be a useful tool in discovering the nature of the underlying distributions for noise and noise plus signal.

Detection of Lateral Movement under Antiphasic Masking Conditions. Ervin R. Hafter, Walter T. Bourbon, Anne S. Blocker, and Ann Tucker. In a discussion of Binaural Phenomena of Masking, Jeffress, Blodgett, Sandel, and Wood [J. Acoust. Soc. Am. 28, 416 (1956)] suggested that detection under the antiphasic condition, NO Sπ, results because the noise plus signal moves from the median plane previously occupied by the noise. The direction of the movement is random, but the amount of movement depends upon the amplitude of the signal relative to the noise. In the present study, listeners were presented with gated, 500 cps tones, 180° out of phase at the ears, in the presence of a continuous diotic noise, and asked to indicate the lateral displacement of the resulting stimulus. Distributions of their lateralization responses were obtained for several signal levels and showed reasonably good agreement with prediction.

Auditory Sensitization and the Method of Interpolated Trials. Charles S. Watson and Ben M. Clopton.--Recent neurophysiological evidence suggests that the sensitivity of receptors may be varied through efferent control. A psychophysical method, a "method of interpolated trials," has been devised for the study of such changes in sensitivity. The method is intended to measure short-term changes (in the order of seconds, rather than minutes or hours) in a listener's ability to detect signals in a noisy background, where the heightened sensitivity is elicited on demand by the experimenter. Observed effects, which are consistent with the hypothesis of efferent controls, are found to be generally small, less than might be caused by a 2- or 3-dB increment in the level of a tonal signal.

Short-Term Changes in Auditory Sensitivity for Human Observers. Ben M. Clopton.--Short-term increments in auditory sensitivity equivalent to signal increments of about 2 dB were found. The promise of monetary reward was ineffective in producing the increments, but the immediate threat of shock produced them in nine observers. The Method of Interpolated Trials was introduced as a means of measuring the transient changes in sensitivity. Neurophysiological evidence was partially responsible for initiating the investigations, and latencies as short as one second indicate that the behavioral findings do have neural correlates. The results suggest an upper limit on observer performance, and the theoretical significance of this predicted limit is discussed.

Time-Intensity Equivalence in Auditory Lateralization: A Graphical Method. Charles S. Watson and Brant T. Mittler.--A graphical response was used to establish equivalent binaural time- and intensity-differences in auditory lateralization. For intensity differences less than about 4.5 dB a constant equivalence of approximately 60 μsec per dB is found, for 500 cps tonal pulses. For larger intensity differences more time per dB is required.

The Use of Multiple Signal Levels in a Study of the Relationship between Signal Level and the Detectability Index, d'. Anne S. Blosser. A psychoacoustical procedure employing multiple signal levels was utilized in an attempt to 1) clarify the relationship between d' and signal voltage and 2) provide a method of converting a signal (dB SPL) and its obtained detectability to a signal which would have yielded a d' of some fixed value. Results obtained from the use of multiple signal levels were considerably more variable than results obtained using single signal levels. Effects of bias, time, adaptation-level, context, sequence, practice, and motivation are investigated to account for this variability. Implications for detection theory are discussed.

Lateral Geniculate Responses to Shifts in Light Intensity: Adaptation Effects. Gerald H. Jacobs.--Single units in the lateral geniculate nucleus of the monkey which transmit information about the brightness of a stimulus light are of two types; some show an increase in firing rate to all spectral stimuli (broad-band on cells), others respond with a decrease in firing rate (broad-band inhibitors). The behavior of these two classes of cells in response to stepped shifts in light intensity, both increments and decrements, from a given adaptation intensity has been examined. The on cells respond with an increase in firing rate to increments in stimulus intensity; they respond with a decrease in firing rate to decrements in stimulus intensity. Inhibitory cells behave in the opposite manner. The response to a specific stimulus intensity is dependent on the intensity of the adaptation light. The relationship between firing rate and the size of the stimulus shift shows characteristic changes as a function of the adaptation intensity. The total range of shift intensities over which any cell shows good differentiation is usually not more than ±1 log unit around the adaptation intensity. An index of the discriminatory ability of these cells has been derived, based on the differences between the inhibitory and excitatory responses for any given stimulus shift.

Effect of Bandwidth of Masking Noise on Detection of Homophasic and Antiphasic Tonal Signals. Walter T. Bourbon and Lloyd A. Jeffress. Langford and Jeffress [J. Acoust. Soc. Am. 36, 1455-1458 (1964)] report evidence that the bandwidth involved in masking an antiphasic signal, NO $S\pi$, is considerably wider than that involved in monaural or homophasic masking. The present paper describes a study of the effect of narrowing the noise band used for masking a 500-cps tonal signal from 100-3000 cps to about 10 cps in width. The same band of noise was employed for both the diotic conditions NO SO and the antiphasic NO $S\pi$. In the former case, no improvement in detection occurred until the bandwidth was less than about 150 cps, but in the latter substantially increased MOD's were found for bandwidths as great as 300 cps. The rate of improvement of detection under the antiphasic condition was much more rapid as the bandwidth was narrowed than was the case for the diotic condition. The findings support von Békésy's idea that some kind of neural "funneling" assists in narrowing the band of frequencies involved in monaural detection. In antiphasic detection, the bandwidth may depend solely on the mechanical filtering provided by the cochlea without assistance from neural funneling.

Response Latency as a Criterion-Dependent Measure. Charles S. Watson.--The latency of responses to auditory stimuli is proposed to be a joint function of the time required to process sensory (auditory) information and of a criterion adopted by the listener. This criterion appears to represent a compromise between accuracy and a speed of responding that is adjusted to meet the demands of a particular listening situation. Evidence is presented that listeners can vary their accuracy in a binary-decision, single-interval detection task between nearly perfect and nearly chance performance, as instructions emphasize the relative desirability of accuracy or speed, with correspondingly large changes in response latencies. The "latency criterion" is discussed in relation to (1) latency as a measure of detectability, (2) latency in complex reactions (those requiring decisions about the stimulus), and (3) latency in simple reactions (those requiring no differential responses).

Masking and Binaural Phenomena. Lloyd A. Jeffress.--The two chapters comprised in this report were written for publication in a book, Foundations of Modern Auditory Theory, to be edited by J. V. Tobias and E. D. Schubert, and published by the Academic Press.

The first chapter summarizes recent work on the subject of masking, particularly the masking of tonal signals by Gaussian noise. It discusses various theories of masking and of auditory function with considerable emphasis on the theory of signal detectability (TSD).

The second chapter presents the vector theory of binaural unmasking, with some discussion of the possible underlying neurophysiological machinery.

Narrow-Band Noise and Tones as Signals in Binaural Detection. Mark E. Rilling and Lloyd A. Jeffress.--Two experiments compare the effect of fixed and random phase relations between masker and signal in binaural masking. In Experiment 1, a comparison is made between interaural time delay and phase shift of a narrow-band-noise signal where the phase relations between the signal and the masker are random. The signal is Gaussian noise passed through a 50-cps filter centered at 500 cps. The masker is broad-band noise from a second noise generator. The conditions using noise as the signal are compared with the same conditions in which a 500-cps tone is the signal. A two-interval, forced-choice procedure was used to obtain MLD's (masking-level differences). The MLD increases rapidly as the interaural phase shift or interaural time delay increases. The MLD's for corresponding phase-shift and time-delay conditions are approximately the same for tonal and noise signals. In Experiment 2, a single noise generator is used and a comparison is made between NO SO and NO $S\pi$ for various phase relations between the narrow-band-noise signal and the masker. The noise signal has the same bandwidth as in Experiment 1. The results show a substantial dependence of the MLD's on the signal-noise phase relation.

Rating Scales and Two-State Threshold Models. Charles S. Watson and Walter T. Bourbon.--The use of rating-scale isosensitivity data for testing discrete, two-state detection models is admitted to be inappropriate, unless additional assumptions are made. It is suggested that simple assumptions may, in fact, be made by which this model may maintain its basic description of sensory processes and yet make predictions about rating results. The predictions are shown to produce the same isosensitivity curves (ROC curves) as did the original, two-choice version of the model. These functions do not describe the results of rating experiments.

Effects of Adaptation on the Lateral Geniculate Response to Light Increment and Decrement. Gerald H. Jacobs.--Response characteristics of two types of cells in the lateral geniculate nucleus of the squirrel monkey have been examined in experiments in which the luminance of a stimulus is shifted in stepped increments and decrements from an adaptation luminance. These two types of cells are found to show opposite changes in discharge frequency in response to shifts in stimulus luminance: some respond with an increase in firing rate to increases in luminance and show a decrease in response rate when luminance is decreased; others behave in the opposite fashion. The magnitude of change of the response is graded according to the amount of change of the stimulus. For any cell, the direction of change of the response for a given change of stimulus is dependent on the adaptation luminance. The total range of change of luminance over which any cell shows a good differentiation is usually not more than ±1 log unit around the adaptation luminance. An analysis of the discriminatory ability of these units as a function of adaptation luminance and the amount of change of the stimulus is presented.

Statistics of Interaural Time Differences under Antiphasic Stimulus Conditions. Lloyd A. Jeffress and Audley D. Gaston, Jr.—At the Austin meeting of the Society, Watson, Rilling, and Bourbon [J. Acoust. Soc. Am. 36, 1991(A) (1964)] presented ROC curves obtained from subjects' responses under one antiphasic condition $NOS\pi$. An attempt was made to fit their data from theoretically derived probability densities for noise and signal. The signal distribution was obtained by a rather tedious numerical computation. The present paper shows examples of the interaural time differences arising under various antiphasic stimulus conditions. The distribution for dichotically presented noise $N\pi$ is distinctly platkurtic. The distribution obtained by adding a signal $N\pi SO$ is bimodal with greater separation of the modes as the signal is increased. The distribution for $NOS\pi$ has a density function that resembles the Rayleigh distribution and has zero frequency of occurrence of zero interaural time differences.

ROC Curves from an Ear Model. Lloyd A. Jeffress and Audley D. Gaston, Jr.—Many investigations have likened the ear in its ability to detect a tonal signal in noise to a narrow filter followed by a detector mechanism. The present paper describes the performance of such a device, consisting of a 50-cps filter centered at 500 cps followed by an envelope filter. The latter is a half-wave rectifier, and RC integrator, and a low-pass filter. Gated noise or noise plus signal is presented to the device and its output is sampled at each presentation. For a stimulus duration equal to the reciprocal of the bandwidth of the filter, the efficiency measure η is near to unity. At longer and shorter durations, the efficiency decreases. The ROC curves yielded by the device resemble those obtained with human subjects, and are shaped like those for the ideal detector of a signal of unknown phase.

Distributions of Silent Periods in Speech: Stutterers versus non-Stutterers. Charles S. Watson and Laura R. Love.—The distribution of silent periods in speech (frequency of occurrence of silent periods as a function of their duration) has been shown by other investigators to be a stable characteristic of the individual speaker, but these distributions differ considerably among speakers. Data are presented that extend this finding, previously established for silent periods ranging from 0.5 to 10.0 sec, to intervals as brief as 0.1 sec. Silent periods between 0.1 and 0.5 sec in the present data are found to be even more effective than the longer periods in distinguishing between speakers. Comparison between average distributions for normal speakers and stutterers shows unusually high numbers of brief silent periods for the stutterers, which could not be attributed to overt stuttering.

Effects of Bandwidth and Level of Masking Noise on Detection of Homophasic and Antiphasic Tonal Signals. Walter T. Bourbon, Jr.--The mechanisms of auditory frequency analysis and masking have been examined in many ways. A large body of that research centers about the concept of the critical band. The purpose of this study was to investigate the ears' bandwidths for homophasic and antiphasic detection at different stimulus intensities.

The signal used was a 500 cps tone with a duration of 150 msec, gated with a rise-fall time of 25 msec. The signal had a phase difference of 0° or 180° at the two ears. The masker was thermal noise with spectral levels of 50, 45, and 30 dB. The bandwidth of the masker was varied from 2900 cps to 12.6 cps. Eleven bandwidths were used at the 50-dB spectral level, and six at 45 and 30 dB. In all conditions run in the study, a wide noise band with its spectral level 40 dB down from that of the narrow-band masker was used to mask the harmonics of the signal.

A two-interval forced-choice procedure was used. In order to obtain MLD's, the signal level necessary to produce a d' of 1.5[P(c) = 85%] was determined for the diotic and dichotic conditions at each bandwidth.

For the antiphasic condition, detection improved when the noise was narrowed to 400 cps. The rate and range of improvement in detection with further narrowing of the noise was greater at higher noise levels.

The bandwidth of the ear for homophasic signals was narrower for the lowest noise level, where it was 50 cps. The bandwidth for higher noise levels was 400 cps.

For narrow widths of the masker, the rate of improvement for NOSO increased, while that for NOSπ decreased. The possible shapes of filters which could produce the data of this study were discussed.

The MLD's obtained in this study supported the work of Langford and Jeffress with two noise bandwidths and one spectral level. The present data also supported their contention and that of Jeffress, Blodgett, Sandel, and Wood, and Blodgett, Jeffress, and Taylor, that the ears' bandwidth for NOSπ must be wider than that for NOSO. Possible sources of discrepencies between the present data and that of other studies of critical bandwidth were discussed.

Responses of the Lateral Geniculate Nucleus to Light Increments and Decrements and the Encoding of Brightness. Gerald H. Jacobs.--Two types of cells in the lateral geniculate nucleus of the monkey which transmit information signalling stimulus brightness show opposite changes in firing rate when the luminance of a stimulus light is shifted up or down. The observation suggests that, in the situation where the stimulus is rapidly changed in luminance, it is more likely the difference in firing rate between these two types of units than the total activity that is utilized to code brightness. A similar mechanism may operate to characterize the response to steady-state stimulation.

Effect of Signal Duration on Detection for an Electrical Model. Lloyd A. Jeffress and Audley D. Gaston, Jr.--At the November 1965 meeting of the Society [J. Acoust. Soc. Am. 38, 928(A) (1965)], we presented the results of a series of unsuccessful attempts to replicate the findings of Green, Birdsall, and Tanner [J. Acoust. Soc. Am. 29, 523-531 (1957)] on detection versus duration. Since then, still using a fixed-bandwidth filter, but by changing the time constants of the detector, we have come much closer. Like them, we have employed a continuous masker and a constant value of E/N_o and our new data yield a close fit to theirs. The filter is followed by a linear (half-wave) detector and by an integrator with a decay time of 100 msec. A replication of the experiment, this time employing a square-law rectifier (energy detector), but using the same integration time constants, yielded reasonable similar results.

Replication and Revisions of Egan's Method of Free Response. Charles S. Watson and Thomas L. Nichols.--Listener performance was measured under several conditions similar to that described by Egan as the "Method of Free Response" [J. Acoust. Soc. Am. 33, 993-1007 (1961)]. In addition to randomly spacing 10 signals of low detectability, 150 msec in duration, 500 Hz, within each 5-min listening period, 10 "noise-alone intervals" were also defined in each period. The latencies of first responses were measured, timed from the onset of each observation interval. Distributions of these response latencies were separately constructed for signal-plus noise and for noise-alone intervals. Indices of detectability calculated from these distributions support Egan's conclusions that (a) signal strength must be increased by approximately 2 dB when observation intervals are not defined for the listener, if he is to maintain his performance at the level achieved with defined intervals, and (b) this decrement in performance is largely a function of uncertainty about the exact instant of signal occurrence and not of the sparcity of signals.

Psychometric Functions for the Antiphasic Binaural Conditions $NOS\pi$ and $N\pi SO$. Rand B. Evans, Ann Tucker, and Lloyd A. Jeffress.--Psychometric functions for $NOS\pi$ and $N\pi SO$ were determined, using a 2AFC procedure. The signal was a 500-Hz, 150 msec tone, and the masker, a continuous wideband noise (100-3000 Hz). The function for $N\pi SO$ showed the bend at high levels reported earlier

[L. A. Jeffress and A. D. Gaston, Jr., J. Acoust. Soc. Am. 38, 929(A) (1965)] for measured interaural time differences. The function for NOSπ was similar to that described by Green [J. Acoust. Soc. Am. (to be published)].

Effect of Duration upon Detection with Gated Noise and Signal. Ann Tucker, Rand B. Evans, and Lloyd A. Jeffress.--A 2AFC procedure was used to study the effect of duration on signal detectability, with noise and signal detectability, with noise and signal gated simultaneously. Durations employed were 10, 20, 50, 100, 200, and 500 msec. The data do not show the near constancy of detection with duration for constant signal energy over the range found by Green, Birdsall, and Tanner. [J. Acoust. Soc. Am. 29, 523-531 (1957)] for gated signal and continuous noise. Instead, for constant signal energy, they indicate a tendency to peak at about 20 msec (reciprocal of the critical bandwidth?).

Detection Performance and Two Parameters of the Auditory Stimulus. Thomas L. Nichols.--Four subjects were run in a conventional yes-no psychophysical experiment in auditory masking. The stimulus consisted of a 250 msec burst of band limited white noise. On 50% of the trials, a 500 Hz sinusoidal signal was added to the noise burst. On each trial, a record was made of the nature of the stimulus (i.e., either signal-plus-noise, or noise alone), the subject's response latency, the nature of his response (i.e., "yes", or "no"), and two physical measures of the stimulus waveform. The two physical measurements were made using an electronic ear model consisting of a narrow band filter (simulating the subject's critical band) followed by a rectifier and two measurement devices. One of these devices measured the magnitude of the largest peak voltage occurring during the stimulus interval, and the other measured the average voltage of the stimulus envelope.

A series of multiple linear regression models were constructed to determine the independent contribution of each of these electrical measurements to prediction of the nature of the stimulus event, and the nature of the subject's response. The average energy of the stimulus envelope was found to be the more efficient predictor of both of these criteria, and also the more important in determining the subject's response. The maximum peak amplitude was a poor predictor of both criteria, and added little predictive efficiency of a model which already contained the average energy predictor. The Theory of Signal Detectability states that an observer uses a large number of stimulus dimensions in reaching a decision about the nature of the source of a stimulus. This research indicates that the average energy of the input is a dimension of great importance in the decision process, and that the maximum peak value is a relevant, but far less important dimension.

Response distributions were constructed by plotting all "yes", and all "no" responses separately against the value of the average stimulus energy associated with each response. The index of detectability, d', computed from these distributions was in good agreement with the d' values computed from the conventional theoretical distributions of TSD.

The probability of a "yes" response, the probability of a correct response, and the response latency of all responses were also plotted as a function of stimulus level (expressed as average energy level). The probability of a "yes" response was found to increase with the average energy of the stimulus (even though the overall signal to noise ratio, E/N_o, was constant), and the probability of a correct response was found to be highest for low and high values of the average energy. Response latency was greatest for middle values of average energy.

These results indicate that gradations in stimulus level, whether a signal is present or not, produce gradations in response probability and latency in a continuous fashion. These results are in opposition to classical threshold theory, and support the formulations of the Theory of Signal Detectability.

Stimulus-Oriented Approach to Detection Re-examined. Lloyd A. Jeffress.--The present paper is a re-examination of some of the conclusions of an earlier one. It is motivated by some new insights resulting from attempts to replicate experiments with human observers through the use of an electrical model of the auditory system. It is concerned primarily with the effect of signal duration on detection in the presence of a continuous masking noise. The model, of those tried, that best fits human performance consisted of a bandpass filter obtained by subtracting the output of a 500 Hz sharp-cutoff, low-pass filter from another having a cutoff of 525 Hz. The filter was followed by a linear half-wave rectifier, and it in turn by an integrator having a 100 msec decay time. The integrator can be thought of as a device which takes a running average of its input.

The probability density distributions for N and SN yielded by the model lie between the Rayleigh-Rice distributions on the one hand and a pair of normal distributions of unequal variance on the other. The exact shape of the two distributions depends upon both the bandwidth of the filter employed and the time constant of the averager.

The Effect of Duration Upon Detection for Both Gated and Continuous Noise and Signal. Ann Tucker.--A two-alternative forced-choice procedure was used to study the effect of duration on auditory signal detectability under two conditions; gated noise and gated signal. The durations employed were 10, 20, 50, 100, 200, and 500 milliseconds, with $\sqrt{2E/N_o}$ held constant. The signal was a 500 Hz sinusoid with rise and decay times of 0.5 milliseconds each. Band-limited (100-3000 Hz) Gaussian noise with a spectral level of approximately 48 dB re 0.0002 μbar was used as the masker.

In Experiment I, each of three naive observers performed under the gated noise and signal condition, at the six durations and for at least 1800 trials per duration. A constant value for $\sqrt{2E/N_0}$ was maintained at 4.0. The detection measure, d', was higher for all observers at short signal durations than at long. One observer showed best detection at 20 milliseconds, another at 50, and the third at 100. All three observers were also given at least 1800 trials using a continuous noise with the 100 milliseconds gated signal. All did substantially worse under this condition.

Three new observers were used in Experiment 2. These, also naive, performed under both the gated and continuous conditions, at the same six signal durations. The $\sqrt{2E/N_0}$ employed in this experiment was 4.5. For short durations gated noise and signal yielded better detection than continuous noise and gated signal. At the longer durations, however, detection was slightly poorer for the gated noise than for continuous.

The Theory of Signal Detectability assumes that the observer samples the noise and the signal-plus-noise distributions in a similar manner. However, the psychophysical procedure most often used involves gating the signal, but not the noise. The observer is therefore asked, in effect, to turn his detection mechanism on and off in agreement with the experimenter's signaling of the intervals. The present study has shown the effect of gating both the noise and the signal, and how this gating relates to signal duration and influences signal detection.

<u>ROC Curves for Multiple-Signal Levels in a Detection Task</u>. Ann Tucker, Rand B. Evans, and Lloyd A. Jeffress.--Seven signal levels were presented to four observers in a pseudorandom fashion. A 500-Hz tone was used, and the signal duration was maintained at 100 msec with a rise-decay time of 10 msec. Wide-band (100-3000 Hz) continuous noise was used as the masker. The listening interval was indicated by a light, and observers were instructed to clarify or rate the loudness of the masked signal by using one of 10 ordered push buttons. On some trials noise alone was present; on the remaining trials $(2E/N_0)^{1/2}$ ranged from 2.0 to 5.0. ROC curves were plotted for each signal level, and a remarkably small number of trials was needed to yield satisfactory curves. The multiple-level rating procedure yields smooth curves for seven signal levels in about the same time previously needed for only one level. The observer's task, to rate the loudness of the stimulus, appeared to be simpler than that of earlier studies, in which he was asked to rate his "certainty" that a signal was present.

An Electrical Model for Binaural Detection. Lloyd A. Jeffress and Audley D. Gaston, Jr.--An electrical model that takes a running average of interaural time differences yields results similar to human performance under several binaural conditions, NOSπ, NπSO, and NOSm: with continuous noise and gated signal. It shows a response to signal duration similar to that given by people. Previous models, such as the theta model and the E-C model, have no provision for handling the case of the continuous noise and gated signal, and leave the effect of signal duration under these conditions unaccounted for. The device achieves its measurement of time difference by amplifying and clipping the inputs from the two channels, subtracting one from the other, and discarding differences of one sign while averaging those of the other. The voltage being averaged can be expressed by the following equation:

$$E = E_i \frac{e^{t/RC} - 1}{e^{T/RC} - 1},$$ where t is the time that, say, the left ear leads the right, T is the period of the center frequency of the narrow-band noise, and E_i is the magnitude of the rectangular input voltage.

Bezold-Brücke Hue Shift: Measurements on Untrained Observers. Gerald H. Jacobs.--Despite the prominence of the effect, only a relatively small number of individuals are represented in the published measurements of the Bezold-Brücke hue shift and most of those measurements were made under rather permissive experimental conditions. In the experiment reported here, the Bezold-Brücke effect was assessed for a large number of previously untrained, color-normal observers using a limited-category forced-choice color naming procedure. Measurements are presented on the magnitude and direction of the hue shift in this group of subjects. An indication of the variability of the shift across observers is given and these measurements are compared to those presented elsewhere. Some comments on the spectral locations of the unique points and their relationship to luminance level are also made.

Effects of Chromatic Adaptation on Color Naming. Gerald H. Jacobs and Heinz A. Gaylord.--Some effects of chromatic adaptation have been evaluated in the context of a color-naming task. Color-naming responses were obtained from three observers under both neutral and chromatic-adaptation conditions and those data were used to generate indices of the magnitude of change in spectral appearance under various adaptation conditions. A few general comments on the use of color-naming procedures are made.

Saturation Estimates and Chromatic Adaptation. Gerald H. Jacobs.--Category estimates of spectral saturation were obtained from three observers under neutral adaptation and under three conditions of chromatic adaptation. The data so obtained show that chromatic adaptation causes a shift in the location of minimal spectral saturation toward the spectral locus of the adapting light. The existence of secondary minima and enhancement effects in spectral saturation are also noted.

Agreement in Detection: Observers and Electrical Model. Paul I. Williams and Lloyd A. Jeffress.--At the Los Angeles meeting, Nichols reported that an electrical model (narrow filter-rectifier-envelope filter) predicted the responses of four observers in a single-interval detection experiment better than either a different electrical device (envelope-maximum detector) or the presence or absence of the signal. He suggested the desirability of employing multiple signal levels and a two-alternative, forced-choice method with a similar detector. The present paper reports such an experiment, with the first electrical model and three observers responding to the same stimuli. Seven signal levels were employed, and on some trials, noise alone occurred in both intervals. P(C) ranged from about .99 to chance (for noise-alone trials). The data show that the model predicts observers' behavior better than the presence or absence of the signal does, and better than one observer predicts another. When the three observers agreed in their responses (whether right or wrong) the model agreed with them on more than 81% of the trials. The weaker the signal the greater was the superiority of the model over the signal as predictor. (Noise: 100-3000 Hz, 50 dB Spectral level. Signal: 500 Hz, 0.25 sec.)

MLDs and the Phase Angle, Alpha. Lloyd A. Jeffress and Dennis McFadden.--This Letter describes two experiments designed to discover the effect of the phase angle, α, (the angle between a narrow-band masker and a tonal signal) on binaural detection; and offers an explanation of why they failed to reveal any effect.

Mathematical and Electrical Models of Auditory Detection. Lloyd A. Jeffress.--McGill's generalization of Marill's formula for the probability of a correct response in a two-alternative, forced-choice experiment is obtained from a special case of the noncentral chi-square distribution. The present paper shows that a special case of the noncentral chi distribution is more appropriate than the noncentral chi square for monaural detection of a tonal signal in a continuous background of Gaussian noise. The special noncentral chi function fits distributions obtained from an electrical model, and yields psychometric functions appropriate both to it and to human observers. Estimates of bandwidth and of integration time derived from the distribution functions lie within the range of values often assumed from human subjects.

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13. ABSTRACT

This report presents a summary of work on visual and auditory signal recognition performed under NASA Grant R-129. The visual studies included effects of chromatic adaptation on color naming, and on saturation estimates, ROC curves developed over the course of dark adaptation, and studies of the Bezold-Brücke hue shift. The studies of auditory detection included work on lateralization of sound, on masking level differences (MLDs for tone and narrow-band noise, effect of noise bandwidth on detection of a tonal signal, effect of punishment on performance in a detection task, and a series of studies of electrical and mathematical models of auditory detection.

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