INFORMATION TO USERS

This was produced from a copy of a document sent to us for microfilming. While the most advanced technological means to photograph and reproduce this document have been used, the quality is heavily dependent upon the quality of the material submitted.

The following explanation of techniques is provided to help you understand markings or notations which may appear on this reproduction.

1. The sign or "target" for pages apparently lacking from the document photographed is "Missing Page(s)". If it was possible to obtain the missing page(s) or section, they are spliced into the film along with adjacent pages. This may have necessitated cutting through an image and duplicating adjacent pages to assure you of complete continuity.
2. When an image on the film is obliterated with a round black mark it is an indication that the film inspector noticed either blurred copy because of movement during exposure, or duplicate copy. Unless we meant to delete copyrighted materials that should not have been filmed, you will find a good image of the page in the adjacent frame.
3. When a map, drawing or chart, etc., is part of the material being photographed the photographer has followed a definite method in "sectioning" the material. It is customary to begin filming at the upper left hand corner of a large sheet and to continue from left to right in equal sections with small overlaps. If necessary, sectioning is continued again—beginning below the first row and continuing on until complete.
4. For any illustrations that cannot be reproduced satisfactorily by xerography, photographic prints can be purchased at additional cost and tipped into your xerographic copy. Requests can be made to our Dissertations Customer Services Department.
5. Some pages in any document may have indistinct print. In all cases we have filmed the best available copy.

University
Microfilms
International

300 N. ZEEB ROAD, ANN ARBOR, MI 48106
18 BEDFORD ROW, LONDON WC1R 4EJ, ENGLAND

TWO-PULSE MEASURES OF VISUAL TEMPORAL INTEGRATION IN THE FOVEA AND AT 7° ECCENTRICITY

by

MICHAEL DEBS GOTTLIEB

A dissertation submitted to the
Graduate Faculty in Psychology
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy, The City
University of New York.

1979

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.

Date

Mitchell L Kietzman

Chairman of Examining Committee

5/24/79

Date

Martin L. Hoffman

Executive Officer

Supervisory Committee

The City University of New York

Abstract

TWO-PULSE MEASURES OF VISUAL TEMPORAL INTEGRATION IN THE FOVEA AND AT 7° ECCENTRICITY

by

MICHAEL DEBS GOTTLIEB

Advisor: Professor Mitchell L. Kietzman

The temporal integrative capacity of the human visual system was investigated in the fovea and at 7° eccentricity (along the horizontal meridian in the right visual field) in the dark adapted eye. The stimuli consisted of two, equal luminance, 1-msec light pulses, separated by various intervals of darkness (from 1 to 400 msec). Some experiments also used a 1-msec single-pulse reference stimulus. A glow modulator tube was used to present a 22' diameter, white-appearing, square-wave stimulus in a free-viewing situation. A total of eight observers, with normal vision, participated in three experiments. Within each session retinal locus was counterbalanced in an ABBABAAB design.

Experiment 1 used a yes-no signal detection rating scale procedure to obtain measures of frequency-of-seeing and signal detectability (via ROC curves and P(A) estimates) for equal-energy double-pulse stimuli of different total stimulus durations (i. e., the time from the onset of the first pulse to the offset of the second pulse). In this experiment, the stimuli were randomized within each block along with approximately

25% blanks. The data of three observers indicated that: (a) Bloch's law of intensity-time reciprocity held out to longer total stimulus durations in the periphery at 7° than in the fovea --- i. e., equal-energy double-pulse stimuli produced a constant visual effect out to longer total stimulus durations at 7° than in the fovea, (b) the observer's response criterion (measured via the number of false alarms committed) differed idiosyncratically across the two retinal loci, (c) the signal detection measure, P(A), yielded the same results as the more classical psychophysical measure of frequency-of-seeing, and (d) the false alarm rate appeared to be unrelated to the time course of temporal integration.

Experiments 2 and 3 used a three-interval temporal forced-choice procedure to measure the luminance necessary for 67% correct responding at each of a number of dark intervals, i. e., total stimulus durations. In Experiment 1, the observer's response criterion was monitored, and a measure of signal detectability was extracted from the data which is purported to be independent of criterion. In Experiments 2 and 3, the forced-choice procedure was used to control for possible response criterion differences across retinal loci. The data of eight observers indicated that: (a) the period of complete integration was longer in the periphery at 7° than in the fovea and (b) the longer duration double-pulse stimuli in the periphery were evidencing probability summation while in the

fovea the longer duration stimuli were evidencing either no integration or inhibition.

The loci differences in temporal integration found in the present study are supported by electrophysiological evidence --- the fact that rod and cone receptor potentials differ in their time course of recovery from stimulation.

In summary, the present study is perhaps the only two-pulse investigation to show that :(a) complete integration occurs out to longer stimulus durations in the periphery at 7° than in the fovea, (b) this difference is independent of the specific experimental paradigm used (i. e., equal-energy vs. equal-performance), (c) the observer's response criterion could not have caused this difference in integration, and (d) the longer duration stimuli in the fovea were evidencing either no integration or inhibition while in the periphery at 7° these stimuli were evidencing probability summation.

ACKNOWLEDGMENTS

I thank the members of my dissertation committee (Drs. W. S. Battersby, W. C. Clark, D. C. Hood, M. L. Kietzman, and P. Pasik) for their advice and constructive criticism.

I also thank my colleagues and friends at Biometrics Research and the Psychiatric Institute, Ira J. Berenhaus, Barbara Bienstock, Gerard E. Bruder, Salvatore Mannuzza, and Eleanor Shapiro, for their friendship, understanding, and support.

Thanks also to Ray Simon for building and maintaining the equipment.

I especially thank Dr. M. L. Kietzman. He provided the apparatus, funding, humor, and exhortations necessary for a successful dissertation.

Finally, I thank my girlfriend, subject, wife, and mascot, Diane Goldman Gottlieb. Only she knows what the completion of this dissertation means to me.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure Page

CHAPTER I

INTRODUCTION

In visual psychophysics, Bloch's law of visual temporal integration describes the fact that a constant amount of luminous energy will produce a constant visual effect (e. g., 50% frequency-of-seeing) regardless of how that luminous energy is distributed over time (Graham, 1965). Intensity (I) and time (T) are interchangeable and reciprocally related such that for rectangular light pulses I x T = K for a constant visual effect. Traditionally, Bloch's law has been demonstrated by determining the threshold luminance for stimuli of various durations. The longest duration at which reciprocity is found is known as the critical duration. Psychophysical studies using threshold measures have also demonstrated that for durations longer than the critical duration, there may be a region of partial integration where luminance-duration reciprocity is incomplete, yet increases in stimulus duration are still effective in modifying the response (Barlow, 1958; Sperling & Jolliffe, 1965). The longest duration showing partial integration has been referred to as utilization time (Kietzman & Gillam, 1972; Pieron, 1952). Finally, beyond utilization time, there may be a period of no integration and/or probability summation (Clark & Blackwell, 1959).

Numerous stimulus conditions, a variety of response measures, several experimental paradigms, and a diversity of observers have been used in psychophysical investigations of visual temporal integration. These studies have shown that many factors affect the magnitude of the critical duration and utilization time: target size (e. g., Graham & Margaria, 1935), number of light pulses (e. g., Herrick, 1973a), response criterion (e. g., Levine & Kietzman, 1972), state of adaptation (e. g., Barlow, 1958), data analysis procedures (e. g., Kietzman, 1968), stimulus wavelength (e. g., Sperling & Jolliffe, 1965), spatial frequency (e. g., Legge, 1978), response measure or task (e. g., Bruder & Kietzman, 1973), as well as organismic variables such as age (Eriksen, Hamlin, & Breitmeyer, 1970).

The temporal integration of luminous energy has also been studied electrophysiologically (Adrian & Mathews, 1927; Alpern & Faris, 1956; Baker, Sanseverino, Lamarre, & Poggio, 1969; Bartley, 1934; Biersdorf, 1958; Hartline, 1934; Hood & Grover, 1974; Johnson & Bartlett, 1956; Levick & Zacks, 1970; Wasserman & Kong, 1975; Wicke, Donchin, & Lindsley, 1964; Zacks, 1967) using a variety of recording techniques (e. g., single-cell, evoked potentials, and electroretinograms) in a number of different organisms (e. g., human beings, monkeys, cats, goldfish, and conger eel) in several different structures (e. g., visual cortex, lateral geniculate nucleus, retinal ganglion cells, and photoreceptors). Interestingly, these electrophysiological investigations have yielded temporal integration functions that are highly similar to those obtained in human psychophysical studies, and thereby furnish a physiological substratum for the psychophysical data.

Few psychophysical studies have investigated the influence of retinal locus on the time course of temporal integration, and the conclusions drawn from the results of these studies are contradictory. This dissertation seeks to determine whether there are or are not differences in visual temporal integration as a function of retinal locus. In order to achieve this end, the limitations of past investigations had to be overcome. For example, prior studies manipulating retinal locus used the classical psychophysical methods of limits and/or constant stimuli, which have been criticized for possibly confounding nonsensory (i. e., criterion) and sensory measures (Swets, 1961). This study seeks to overcome such a limitation by using signal detection procedures which control for criterion effects (Blackwell, 1951; Swets, 1964). Furthermore, this research will investigate whether the criterion that an observer adopts has an effect upon the time course of integration. More specifically, do signal detectability measures which are purported to be independent of the observer's response criterion (Green & Swets, 1966) yield different estimates of temporal integration from the frequency-of-seeing measures obtained with the more classical psychophysical methods?

Moreover, previous investigators used either an equal-energy or an equal-performance stimulus paradigm to generate temporal integration functions, and therefore,it is possible that contradictory results were due to this difference. The present study will use both procedures, enabling a comparison between the two to be made.

Finally, although no electrophysiological studies have been uncovered by the author to have specifically investigated visual temporal integration as a function of retinal locus, electrophysiological evidence will be brought to bear on the findings of this work.

The following two sections provide the reader with: (a) a general overview of the literature relevant to threshold studies of visual temporal integration, and (b) a review of the literature specific to the present study.

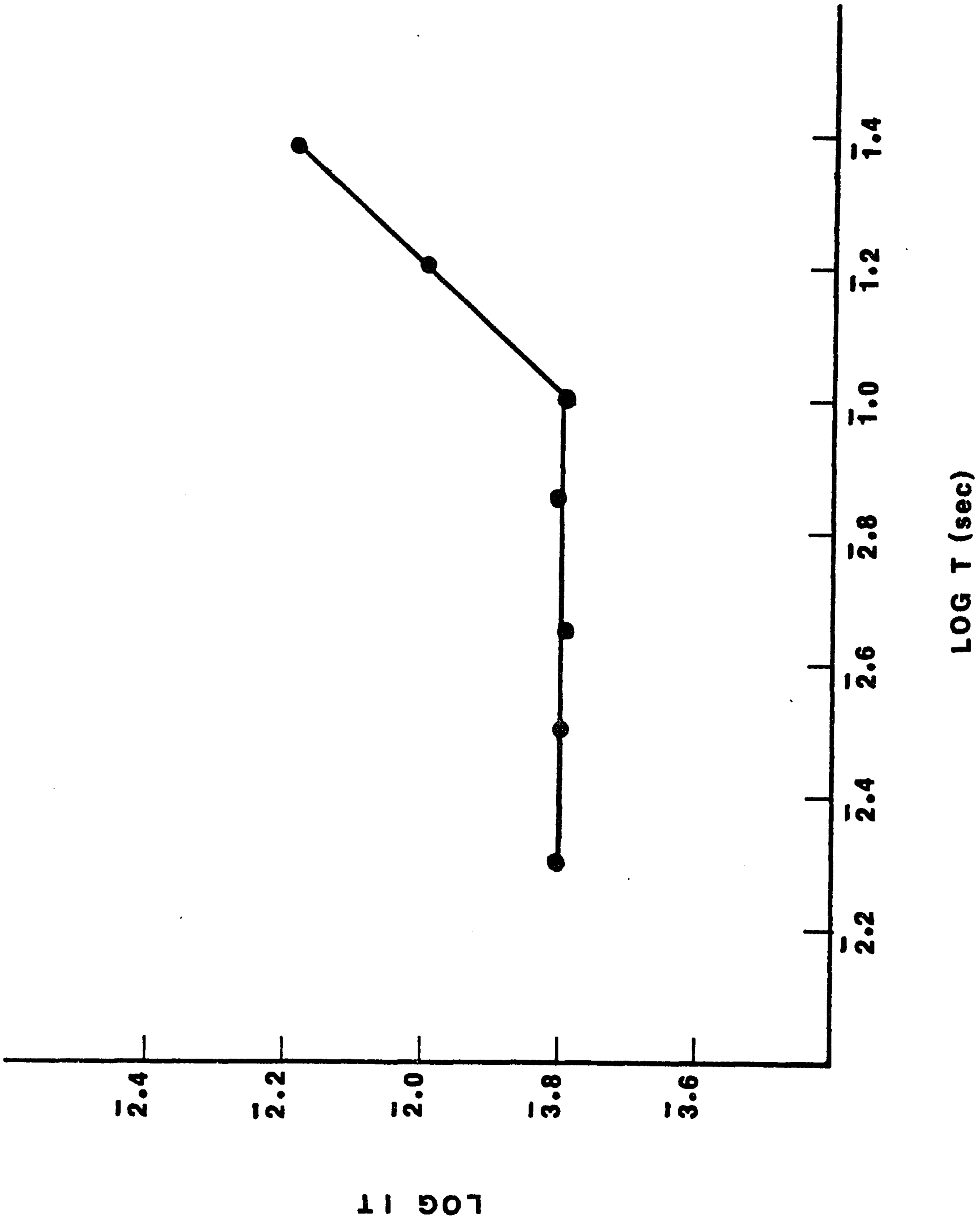
CHAPTER II

GENERAL OVERVIEW OF THE LITERATURE

Single-Pulse Studies of Visual Temporal Integration

The temporal integrative capacity of the human visual system has traditionally been investigated by measuring the luminance (I) necessary to obtain a constant threshold response (e. g., 50% frequency-of-seeing) at each of a number of stimulus durations (T). The results of these studies are usually displayed in a figure showing the log luminous energy (IT) at threshold as a function of the log stimulus duration (T). Figure 1 shows the log IT vs. log T function obtained by Long (1951), who investigated visual temporal integration using square-wave, white flashes, 2' in diameter presented 15° from fixation to the dark adapted eye. The form of this function is representative of that obtained in most threshold studies of visual temporal integration. At the shorter stimulus durations, the data points fall along a straight line of zero slope indicating that the IT product at threshold was constant ($I \times T = K$) for a constant visual effect (50% frequency-of-seeing). Thus, as the duration of a visual stimulus was increased, the corresponding intensity necessary to reach threshold decreased in a reciprocal fashion. In visual psychophysics, Bloch's law describes the phenomenon whereby light pulses less than some critical duration are equally detectable when their total energies are equal. For rectangular pulses, $I \times T = K$.

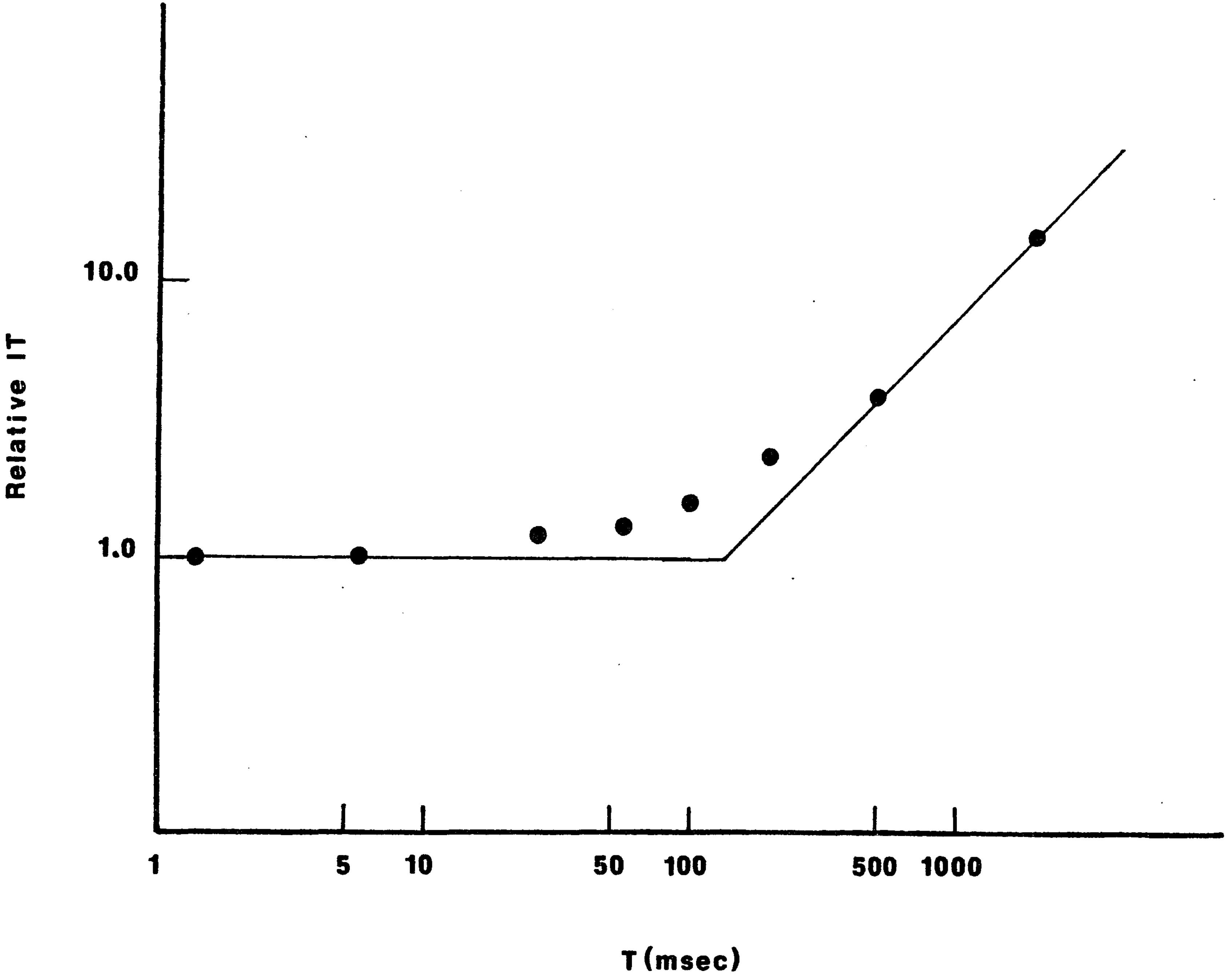
Figure 1. The intensity-time curve obtained by Long (1951) showing the logarithm of the product of intensity and duration (IT) required for threshold as a function of the logarithm of the duration (T) of the stimulus.


$\bar{2}.4$
$\bar{2}.2$
$\bar{2}.0$
$\bar{3}.8$
$\bar{3}.6$
LOG IT
$\bar{2}.2$
$\bar{2}.4$
$\bar{2}.6$
$\bar{2}.8$
$\bar{1}.0$
$\bar{1}.2$
$\bar{1}.4$
LOG T (sec)

Intensity (I) and duration (T) can be traded, on a one-to-one basis to keep detectability constant. Such a reciprocity between luminance and duration has been interpreted to mean that all of the luminance is being integrated over the duration of the stimulus. The presence of complete integration of luminance over time indicates that it is the summated luminous energy that determines the response.

At the longer stimulus durations, the data points fall along a line of unit slope indicating that luminance alone determined the threshold (I = C). This can be seen much more clearly in a log I vs. log T plot (see Barlow, 1958). Increases in stimulus duration no longer have an effect upon the luminance necessary to reach threshold. The latter part of the curve in Figure 1 indicates a region of no integration. Although there may be a fairly abrupt transition from complete integration to no integration in some studies (e. g., Karn, 1936; Long, 1951), a more gradual transition from complete integration to no integration is evident in the functions obtained in other investigations (e. g., Blondel & Rey, 1911, Clark & Blackwell, 1959). The duration at which the first deviation from intensity-time reciprocity occurs is known as the critical duration. Beyond the critical duration, there may exist a partial reciprocity between luminance and duration for some range of stimulus durations. Figure 2 shows the log IT vs. log T function obtained by Sperling and Jolliffe (1965) using 580 nm (orange) square-

Figure 2. The log IT vs. log T function from Sperling and Jolliffe (1965).


Relative IT
10.0
1.0
1
5
10
50
100
500
1000
T (msec)

wave light pulses 45' in diameter, presented to the dark adapted fovea. In their study, the duration at which the first deviation from reciprocity occurs (i. e., the critical duration) is followed by a period of partial intensity-time reciprocity or partial integration. In such cases, as the duration of the stimulus is increased, the luminance can be decreased but not to the same extent as the duration increment, in order to maintain a constant response. Consequently, partial integration is said to exist when increasingly more luminance is required to maintain the same response level as duration is lengthened. Partial integration, if present at all, extends only for a limited range of stimulus durations. The duration at which the function adopts a unit slope (the endpoint of partial integration) is referred to as utilization time (after Pieron, 1952). For stimulus durations equal to or greater than utilization time or beyond the critical duration if there is no partial integration, there is an absence of any reciprocity --- i. e., increasing the duration of the stimulus has no effect upon the level of response. Interestingly, Clark and Blackwell (1959) found that even beyond a period of no integration, luminance could still be decreased as the duration was increased to maintain a constant response. They interpreted this phenomenon as a form of probability summation.

Some investigators have used the intersection of the lines of zero slope (I x T = K) and unit slope (I = C) as an estimate of the critical duration (e. g., Biersdorf, 1955; Nolan, 1957; Ronchi, 1971, 1974). This procedure ignores the period of partial integration. When there is a period of partial integration, the intersection of the lines of zero slope and unit slope comes at a considerably longer duration than the point of initial deviation from complete integration. An example of this can be seen in Figure 2.

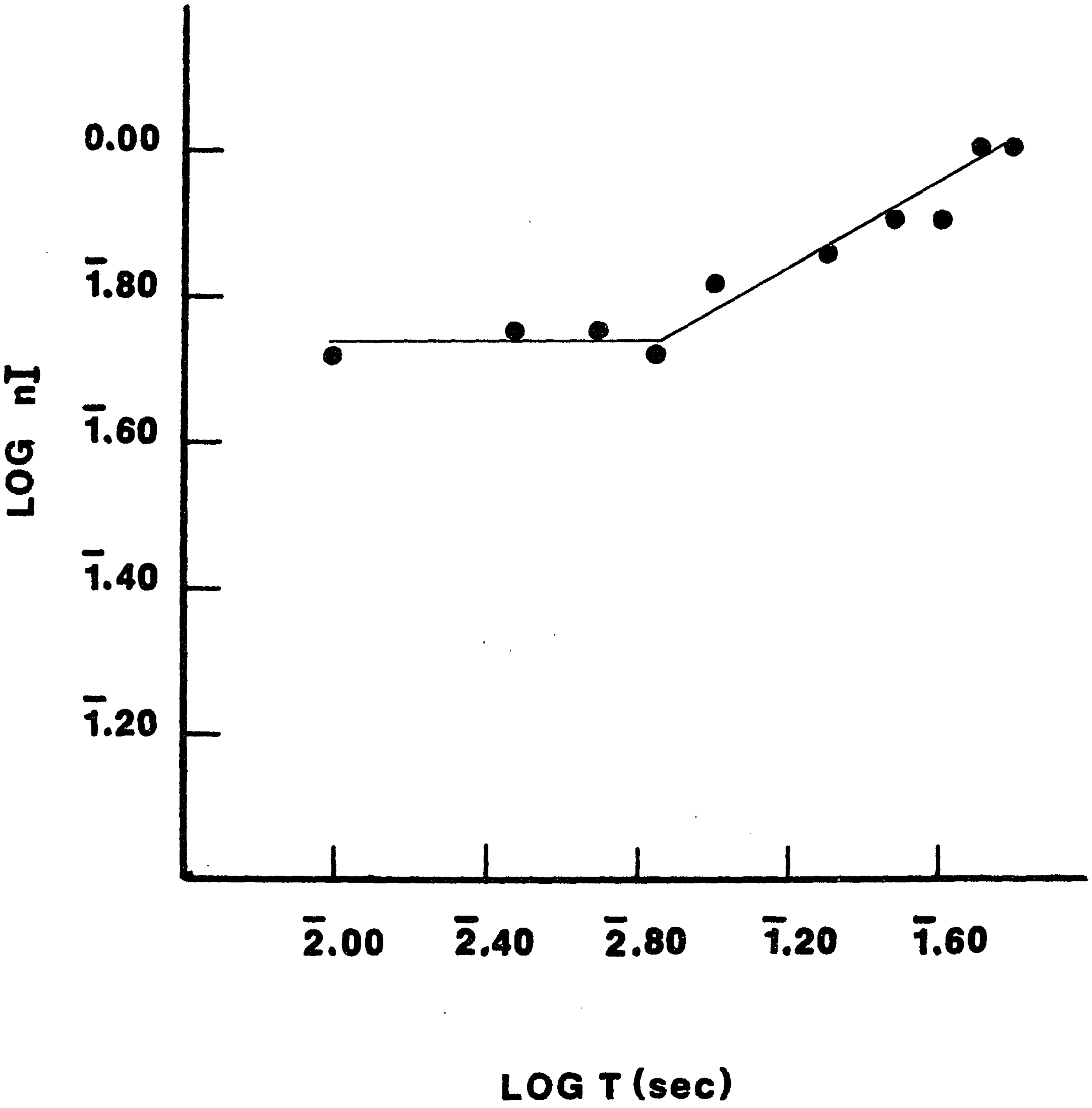
In summary, there are five characteristics of visual temporal integration which may be observed in the log IT vs. log T functions of most threshold studies of temporal integration using single-pulse stimuli: (a) complete integration or intensity-time reciprocity, (b) a critical duration, (c) partial integration or partial intensity-time reciprocity, (d) a utilization time, and (e) no integration or an absence of any intensity-time reicprocity.

Two-Pulse (Double-Pulse) Studies of Visual Temporal Integration

Traditionally, single-pulse stimuli have been used to study visual temporal integration; however, researchers have also used multiple pulse stimuli (e. g., two-pulse or double-pulse stimuli) to investigate temporal processing in the human visual system. In two-pulse studies, the duration of the double-pulse stimulus is varied by changing the length of the dark interval between two equal luminance light pulses. The results of these studies are usually displayed in a figure showing the log luminance (I) at threshold as a function of the log total stimulus duration (T). Since light time is always equal to the combined durations of the two pulses, changes in summated luminous energy and changes in luminance parallel one another, and are equally as often presented on figure ordinates. The independent variable is the dark time, and this can be specified in terms of the total stimulus duration (the time from the onset of the first pulse to the offset of the second pulse).

The five characteristics of integration observed in single-pulse log IT vs. log T functions may also be seen in the log I vs. log T functions obtained using double-pulse stimuli. Figure 3 shows the log nI (total summated luminous energy) vs. log T function obtained by Davy (1952) using white-appearing double-pulse stimuli, 2' in diameter, presented to the dark adapted eye 15° from the center of fixation. The stimuli consisted of two, equal luminance, 10-msec light pulses separated by intervals of darkness which ranged from 10 to 600 msec. At the shorter total stimulus durations, the data points tend to fall on a straight line of zero slope indicating that the summated luminous energy required to yield a constant threshold-level of responding remained relatively constant regardless of the distribution of that luminous energy in time; this is the period of complete integration. The point where the slope of zero first changes

Figure 3. Log summated luminous energy (nI) required for threshold as a function of the logarithm of the time (T) between the two light pulses for O:RW (from Davy, 1952). The lines were drawn by eye.


0.00
$\bar{1}.80$
$\bar{1}.60$
$\bar{1}.40$
$\bar{1}.20$
LOG nI
$\bar{2}.00$
$\bar{2}.40$
$\bar{2}.80$
$\bar{1}.20$
$\bar{1}.60$
LOG T (sec)

to a positive value provides an estimate of the critical duration. As the total stimulus duration is gradually increased, the luminance (and therefore total summated luminous energy) necessary to maintain a constant level of responding also gradually increased. The line segment with the positive slope greater than zero represents the region of partial integration. Double-pulse stimuli in this region need more luminous energy than the shorter completely integrated stimuli but less luminance than a single, 10-msec stimulus (not shown). Finally, at the longer stimulus durations, the total summated luminous energy needed for a constant response becomes twice (i. e., + .3 log units) that originally required for a single-pulse (10-msec) light pulse. This suggests that after a certain separation, the human visual system responds as if only one pulse were present. At the longest stimulus durations, the line of positive slope (i. e., partial integration) is replaced by a line segment with a zero slope (not shown in Figure 3). This transition point gives an estimate of utilization time. Thus, the five characteristics of visual temporal integration can be obtained in both single-pulse and double-pulse studies.

Probability Summation

In Davy's (1952) study, both subjects reported seeing two flashes for the two longest interpulse intervals. Under these circumstances, one might expect probability summation.

Probability summation refers to the fact that when two light pulses are presented, the chance of detecting either of them is greater than the chance of detecting only one of them, even when there is no physiological integration whatsoever (see Battersby & Defabaugh, 1969; Blake & Fox, 1973; Clark & Blackwell, 1959; Cohn & Lasley, 1976; Eriksen, 1966; Pirenne, 1967; Thorn & Boynton, 1974). In effect, the observer gets "two chances" to see a pulse. Pirenne (1943) showed mathematically that if the two pulses of a double-pulse stimulus act upon the visual system independently, the probability of a "yes" response could be predicted by the following equation:

$$Px = P_1 + P_2 - (P_1)(P_2)$$

where Px is the probability of detecting at least one of the pulses, and P_1 and P_2 are the probabilities of detecting each pulse separately. This implies that a luminance level which results in a single-pulse being detected 29% of the time would provide a detection level of 50% if an observer had "two chances" to see it, as in a long duration double-pulse stimulus. If probability summation occurs for long duration double-pulse stimuli, the threshold luminous energy (i. e., total summated luminous energy) for such a pair of pulses would not be twice that for a single-pulse stimulus, but would differ from it by an amount corresponding to the difference between 29% and 50% frequency-of-seeing for a single-pulse stimulus, even if there is no physiological integration.

The frequency-of-seeing curves obtained by Clark and Blackwell (1959) suggest that for foveal stimuli this "savings" due to probability summation should be approximately 0.1 log units.

In Davy's (1952) study, the threshold luminous energy (i. e., that which yielded 50% detection) for the longer duration double-pulse stimuli was twice that necessary for a single-pulse (10-msec) stimulus. If operative, probability summation would have lowered the threshold luminous energy below this amount by approximately 0.1 log units, dependent upon the slope of the subject's psychophysical function (see Clark & Blackwell, 1959; Herrick, 1972, 1973a, 1973b, 1974; Ikeda, 1965; Tittarelli & Marriott, 1970).

The fact that a double-pulse stimulus was no more detectable than a single-pulse stimulus at the longer stimulus durations may be indicative of some form of neural inhibition (Ikeda, 1965; Meijer, Van der Wildt, & Van den Brink, 1978; Rashbass, 1970). The first pulse might be inhibiting the second pulse; the second pulse might be inhibiting the first pulse; or both pulses might be inhibiting each other. On the other hand, physiological integration may very well continue until the probability of seeing the double-pulse stimulus decreases to that for the single-pulse stimulus. In this case, at the longer stimulus durations, the luminous energy from one of the two pulses might not be contributing to the response at all. This is the "ignoring hypothesis" of Clark and

Blackwell. This hypothesis states that as the dark interval between the two pulses of a double-pulse stimulus increases, the second pulse contributes less and less to the response until, at the longest stimulus durations, the double-pulse stimulus results in the same behavioral response as a single-pulse stimulus.

The Equal-Performance Stimulus Paradigm

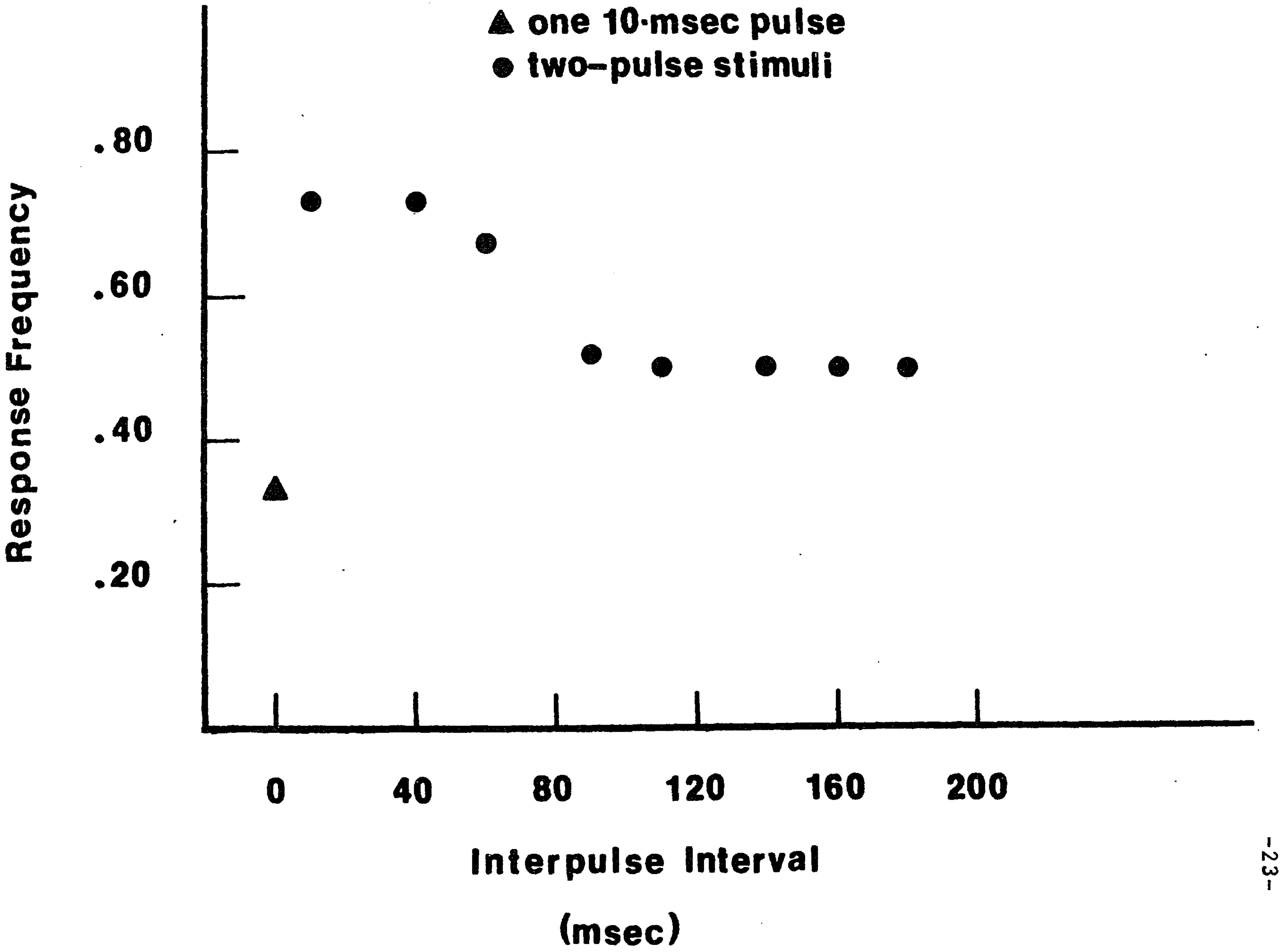
In the studies described above, visual temporal integration was investigated by measuring the summated luminance necessary to reach threshold at each of a number of stimulus durations. The experimental paradigm used in these studies is known as an equal-performance paradigm because a criterion value of performance is chosen (e. g., the absolute threshold, defined as detection of the stimulus 50% of the time), and conditions of duration and luminance are sought which yield this level of performance. As described above, both single-pulse and double-pulse stimuli can be used in conjunction with an equal-performance stimulus paradigm to obtain five measures of visual temporal integration.

The Equal-Energy Stimulus Paradigm

An equal-energy stimulus paradigm can also be used to investigate visual temporal integration. In this procedure, using single-pulse stimuli, the independent variable consists of different stimulus packages, all containing the same amount of summated luminous energy ($I \times T = K$), but composed of various combinations of luminance and duration. The dependent variable is the level of performance (e. g., frequency-of-seeing). In an equal-energy experiment, using double-pulse stimuli, the distribution of total luminous energy over time is changed by varying the dark interval between the two light pulses. Thus, the independent variable is the magnitude of the dark time and is presented in terms of interpulse interval (IPI --- the time from the offset of the first pulse to the onset of the second pulse), interonset interval or interonset asynchrony (IOI or IOA --- the time between the onsets of the two pulses), or total stimulus duration (T or TSD --- the time from the onset of the first pulse to the offset of the second pulse). In this paper, only T or TSD, the total stimulus duration will be used. Since the stimulus luminance in an equal-energy stimulus paradigm is not changed, and the light time of the two pulses remains constant, the total luminous energy of the two pulse package remains constant. Systematic changes in performance have been shown to result from changes in the total duration of such equal-energy stimuli (Bouman & Van den Brink, 1952; Grossberg, 1970; Herrick, 1974; Kietzman & Gillam, 1972; Meijer, Van der Wildt, & Van den Brink, 1978; Van den Brink & Bouman, 1954). A limiting case of the two-pulse situation occurs as the luminous energy of one of the pulses approaches zero. The single pulse that remains is often used as a reference condition against which the various double-pulse stimuli can be compared. As will be seen, the inclusion of a single-pulse (i. e., the first pulse of a double-pulse stimulus) within the equal-energy stimulus paradigm will permit the five characteristics of temporal integration to be derived as in the equal-performance studies. A period of complete, partial, and no integration --- each of which refers to the amount of integration of the luminous energy of the second pulse of a double-pulse stimulus --- can be shown to exist.

Figure 4 shows an integration function obtained by Bouman and Van den Brink (1952) using two-pulse stimuli in an equal-energy stimulus paradigm. Bouman and Van den Brink measured the frequency of seeing double-pulse stimuli, 2.3' in diameter, presented 11°20' from the center of fixation to the dark adapted eye. Their stimuli consisted of two, 10-msec red, green, or red and green light pulses

Figure 4. The chance of observation (%) as a function of the time (T) between two stimuli projected 11°20' temporal from the fovea for green flashes (from Bouman & Van den Brink, 1952).



▲ one 10-msec pulse
● two-pulse stimuli
Response Frequency
.80
.60
.40
.20
0
40
80
120
160
200
Interpulse Interval
(msec)

separated by intervals of darkness which ranged from 10 to 210 msec. The luminance of the pulses was set such that the chance of seeing one, 10-msec pulse was between 20 and 40%. At the shorter total stimulus durations, the data points fall on a straight line of zero slope indicating a constant level of performance for equal-energy (i. e., the total summated luminous energy was equal) packages of different durations, i. e., complete integration. The shortest duration of the stimulus associated with a decrement in performance provides an estimate of the critical duration (the endpoint of complete integration). As the total stimulus duration is further increased, the response level continues to decrease indicating partial integration. Stimuli in this region are considered partially integrated with less and less integration occurring as the stimulus duration increases. Partial integration continues as long as some of the luminous energy of the second pulse continues to affect the response. This is indicated by a higher level of performance with regards to the double-pulse stimulus in the region of partial integration than to a half-energy stimulus. The response level does not continue to change indefinitely; instead, the response may finally reach the same level as that obtained for the half-energy stimulus, which contains the same amount of luminous energy as the first pulse of a double-pulse stimulus. Thus, the response level for the half-energy stimulus is a baseline value against which the changing response to the double-pulse stimulus can be measured and compared as the total stimulus duration is increased. When the response level for the double-pulse stimulus becomes the same as that obtained for the half-energy stimulus, it is possible to say that none of the luminous energy of the second pulse (or perhaps the first pulse) is being integrated. Inspection of Figure 4 indicates that even though the response frequency for the longer duration stimuli has reached a constant level, it has not become the same as that for the half-energy, single-pulse stimulus. This increased detectability, above that for the half-energy stimulus can be fully accounted for (in this case) by postulating the existence of probability summation (see p. 16). The duration of the double-pulse stimulus at this point provides an estimate of utilization time and depicts the end of all integration of the luminous energy of the second pulse. Probability summation has been recognized as an alternative to physiological integration. In some two-pulse studies (Bouman & Van den Brink, 1952; Van den Brink & Bouman, 1954), only two-pulse performance above the level computed for probability summation is considered as exhibiting physiological integration. Furthermore, two-pulse performance below the level computed for probability summation is interpreted as evidencing inhibition (see Meijer, Van der Wildt, & Van den Brink, 1978).

Single Variables Affecting the Time Course of Integration

The duration of the stimulus displaying intensity-time reciprocity has not yet been shown to have a lower limit, although there is some disagreement (see Pulling, 1951). Four studies (Beams, 1935; Brindley, 1952; Dawson & Harrison, 1973; Gilmer, 1937) have demonstrated that there is no failure of Bloch's law at the shortest pulse durations that these experimenters could obtain, the shortest being 10^{-6} msec in Gilmer's study. The upper limit of Bloch's law, the longest duration of the critical duration, is much more controversial. Often, the transition from complete integration to partial integration is a gradual one (see Tayal, 1978) as pulse length increases, making it very difficult to judge when a horizontal line describing log IT vs. log T at threshold begins to depart from the baseline (Boynton, 1972). Thus, while most studies of visual temporal integration are in agreement with the general form of the integration functions described above, the exact values of the critical duration and utilization time, as well as the sharpness of the transition from complete to no integration (i. e., the period of partial integration), vary from study to study and have been shown to depend upon numerous stimulus, data analyses, subject, and response or task factors.

Stimulus Factors. The following stimulus conditions have been shown to have an effect upon the time course of integration: (a) Stimulus Size. The often cited value of 100 msec for the critical duration may be shortened by using large stimuli (Graham & Margaria, 1935; Karn, 1936); however, other investigations have not found stimulus area to influence the magnitude of the critical duration but the period of partial integration (Baumgardt & Hillman, 1961; Meijer, Van der Wildt, & Van den Brink, 1978; Sperling & Jolliffe, 1965). For example, Baumgardt and Hillman demonstrated that summation is complete up to 100 msec and independent of area at least up to 8° (diameter of the target). However, they also found that between 100 and 1000 msec, the thresholds had a very different slope, depending upon whether the diameter of the test field was within the range up to and including 3° or was equal to 8°. Thus, their data indicate more partial integration for larger stimuli. (b) Background Illumination or State of Adaptation. The magnitude of the critical duration may be shortened by increases in the background illumination which changes the state of dark adaptation (Barlow, 1958; Biersdorf, 1955; Clark & Blackwell, 1959; Graham & Kemp, 1938; Herrick, 1972, 1973a, Keller, 1941; Rashbass, 1970; Saunders, 1975; Van den Brink & Bouman, 1954). The period of partial integration appears to be affected in a more complicated way by changes in the background luminance. For example, Clark and Blackwell found that complete integration for two-pulse stimuli was longer in the dark vs. light (10-ft-L) adapted eye; however, while the light adapted eye evidenced a period of complete, partial, and no integration followed by a period of probability summation, no period of partial integration seemed to exist for the dark adapted eye. In the dark adapted eye there was a relatively sharp departure from complete integration to a level indicative of probability summation. Contrary results were reported by Van den Brink and Bouman who found that the temporal extent of partial integration was constant across all background levels. Still other investigations (Ikeda, 1965; Uetsuki & Ikeda, 1970) found the critical duration to be approximately constant across background levels while the region of partial integration became more and more constricted as the state of light adaptation increased. (c) Number of Pulses. In those studies in which single-pulse and double-pulse thresholds were compared (Herrick, 1972; Herrick, 1973a; Rashbass, 1970), substantially shorter critical durations were demonstrated for double-pulse than for single-pulse stimuli. (d) Wavelength. Bouman and Van den Brink (1952) and Rouse (1952) found no differences in the time course of temporal integration for different wavelength stimuli. Contrary results were obtained by Ronchi (1974) in the peripheral retina. She found that the luminance-duration relationship, recorded by the use of a small test spot (either 6.0' or 4.5' in diameter) evidenced a complicated wavelength-dependence across the visible spectrum. (e) Spatial Frequency. Brown and Black

(1976) found the magnitude of the critical duration to vary non-monotonically as a function of increasing spatial frequency of the target (1.9 to 100 cycles/degree). Somewhat different results were obtained by Legge (1978). He found no period of complete integration for several spatial frequencies (.375 to 12 cycles/degree); however, the extent of partial integration seemed to increase as a function of spatial frequency. (f) Retinal Locus. Although measures of temporal integration have been obtained at numerous retinal loci in different experiments, few studies have had as their express purpose an investigations of temporal integration as a function of retinal locus. The relationship between the time course of temporal integration and retinal locus is the major concern of this dissertation; therefore, a more thorough examination of the literature pertaining to this topic will be undertaken in a later section.

Data Analysis Factors. The use of different stimulus manipulations or data analysis procedures can lead to different estimates of the critical duration or even to different conclusions about the presence or absence of temporal integration (Kietzman, 1968). Thus, Kietzman found that a "just-detectable energy difference" response and a "constant-energy difference" response led to different conclusions about the magnitude of the critical duration.

Subject Factors. Differences in temporal integration may reflect physiological differences or differences in the observer's response criterion. Thus, several researchers have demonstrated relationships between integration and chronological age (Eriksen, Hamlin, & Breitmeyer, 1970), brain damage (Wilson, 1967), and psychopathology (Collins, Kietzman, Sutton, & Shapiro, 1978). That the time course of temporal integration may also be related to the observer's response criterion was shown by Bruder(1971) and Levine and Kietzman (1972).

Response and Task Factors. The time course of visual temporal integration may vary as a function of the particular response measure used (Bruder & Kietzman, 1973; Grossberg, 1968, 1970; Kahneman & Norman, 1964; Raab & Fehrer, 1962). Thus, when Bruder and Kietzman compared the characteristics of temporal integration for three different response measures --- frequency-of-seeing, signal detectability (as measured by receiver-operating characteristic curves), and simple reaction time --- all three measures showed a period of luminance-duration reciprocity (i. e., Bloch's law held), followed by a period of partial integration; however, the endpoints of luminance-duration reciprocity (the critical duration) and partial integration (utilization time) were shorter for reaction time than for the frequency-of-seeing and signal detectability measures.

Interactions Among Stimulus Variables Affecting the Time Course of Visual Temporal Integration

The influence of stimulus conditions on temporal integration has proved to be complex, and conflicting findings may be due to complex interactions among stimulus variables. For example, an interaction between stimulus area and wavelength has been demonstrated by Sperling and Jolliffe (1965). Some investigations (Bouman & Van den Brink, 1952; Rouse, 1952) had found that wavelength did not seem to affect the time course of integration; however, Sperling and Jolliffe showed this to be the case only for very small stimuli (4.5' in diameter). More specifically, they found differences in partial integration and utilization time for longer wavelength stimuli (650 nm) when using a 45' stimulus but not with a 4.5' target. Furthermore, this difference in integration was only evident in the fovea and not in the periphery (15°).

CHAPTER III

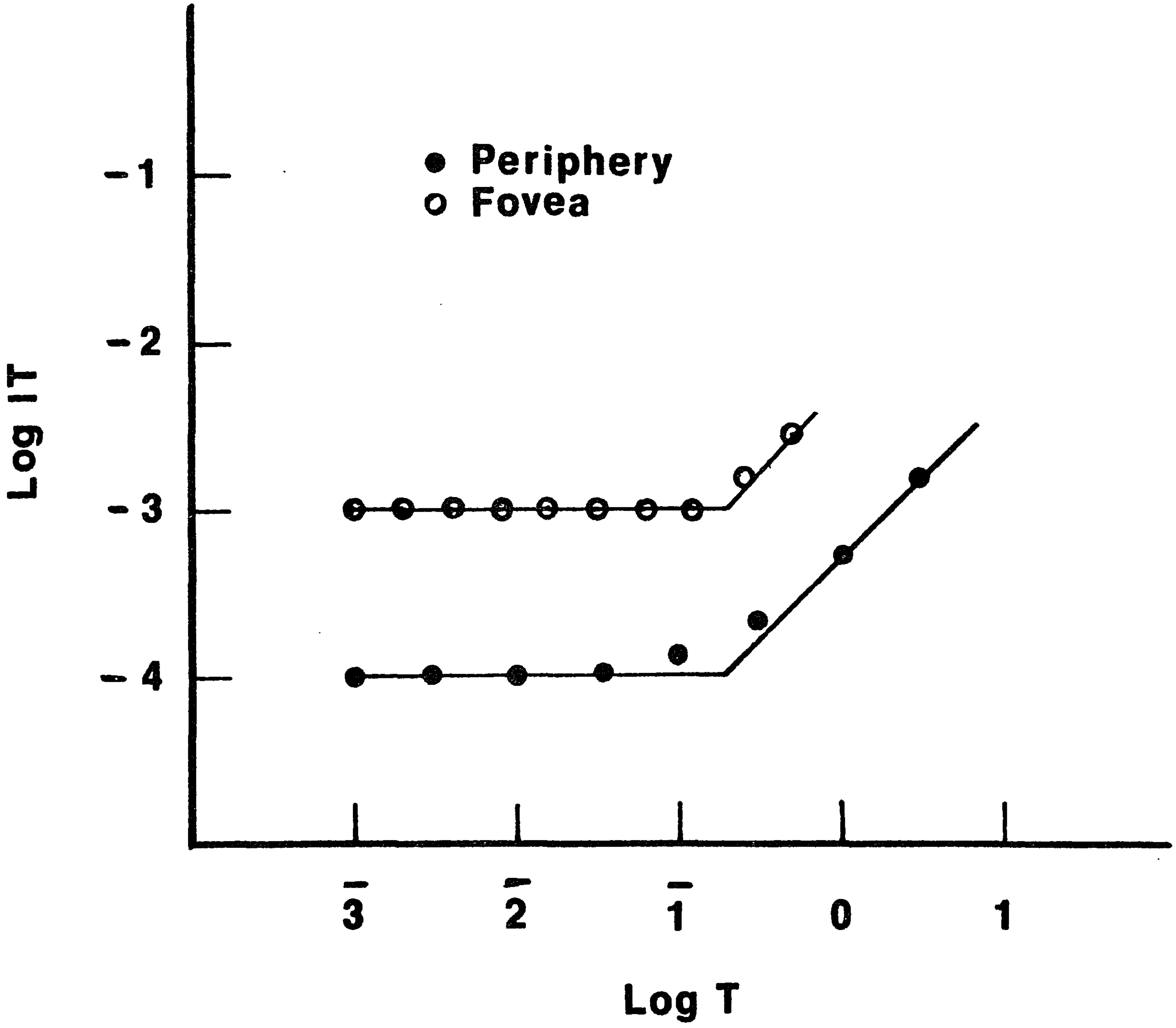
BACKGROUND LITERATURE SPECIFIC TO THE PRESENT STUDY

Visual Temporal Integration as a Function of Retinal Locus

It presumably was not Bartlett's intention to illustrate differences in temporal integration as a function of retinal locus, but Figure 5 (taken from Bartlett, 1965, p. 171) invites the reader to make such a comparison. This figure indicates that the foveal data of Karn evidence a longer period of complete integration and an abrupt transition from complete integration to no integration (i. e., there is no partial integration). By comparison, the peripheral data of Blondel and Rey (also Figure 5) evidence a shorter period of complete integration, a subsequent period of partial integration, and a longer utilization time (endpoint of all integration).

Perhaps the first study which attempted to measure visual temporal integration at more than one retinal locus was by Granit and Davis (1931). They used a two-pulse paradigm to investigate the time course of integration in the fovea and at 10° in the periphery. A conditioning light pulse (11.3 msec) was adjusted to a strength just below the absolute threshold. When this light pulse was followed by a second subliminal pulse of still shorter duration, it was found that the second pulse (which was varied either in intensity or duration) sums with the aftereffect

Figure 5. Thresholds in logarithmic units of millilamberts-seconds and flash duration. Foveal data for 3' area, mean for three subjects, lowered one logarthmic unit (after Karn, 1936). Peripheral data, mean for 17 subjects, for a punctiform stimulus (after Blondel & Rey, 1911). IT values are in arbitrary units. (This figure was taken from Bartlett, 1965, p. 171.)


● Periphery
○ Fovea
Log IT
-1
-2
-3
-4
$\bar{3}$
$\bar{2}$
$\bar{1}$
0
1
Log T

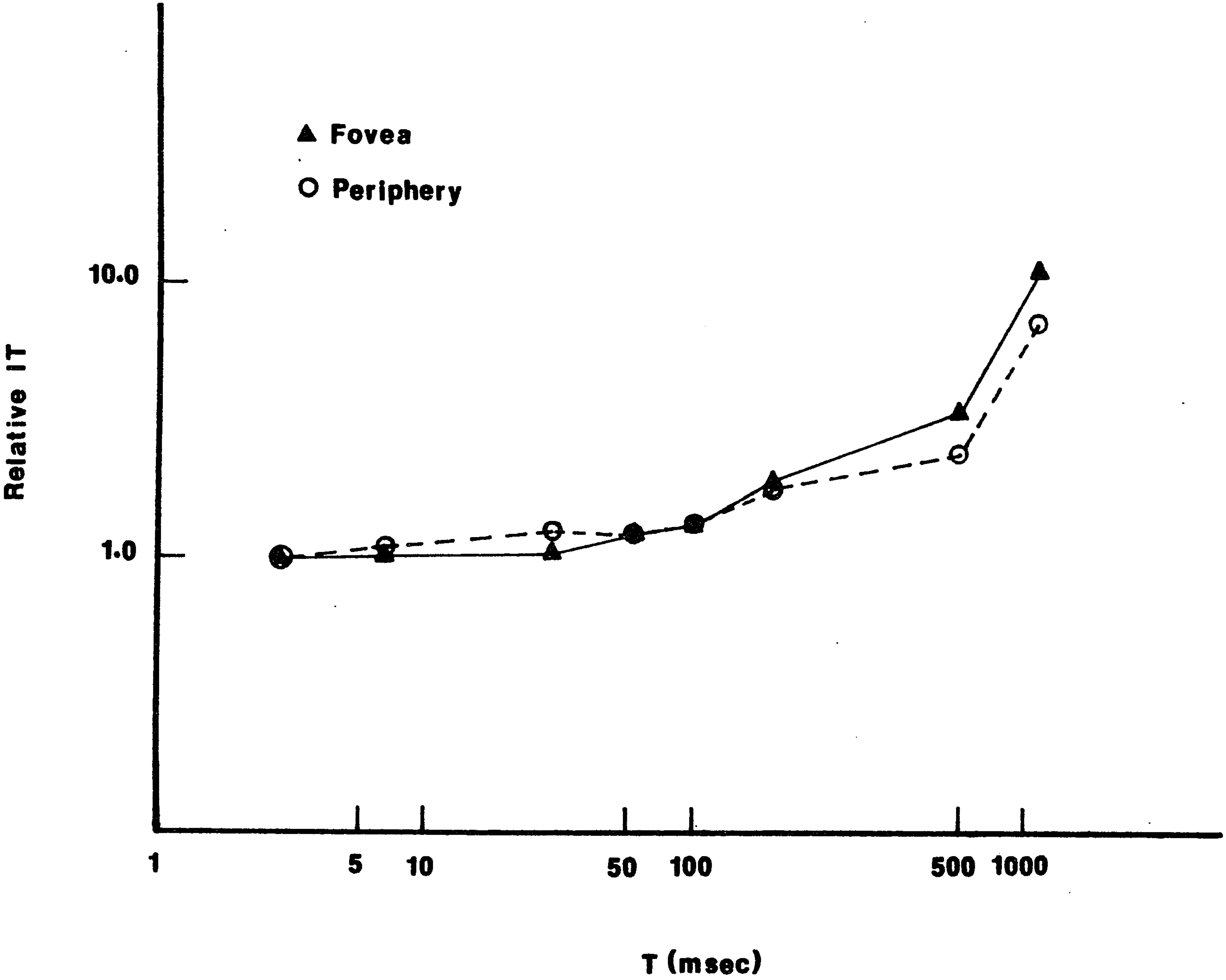
of the first to give a constant effect (i. e., threshold). The shorter the interval between the pulses, the smaller the quantity (I x T) with which the second subliminal pulse was capable of raising the affereffect of the first to threshold. By measuring this quantity (I x T) at various intervals between the pulses, it was possible to determine the level of the excitatory remainder as a function of time. The foveal-peripheral comparison made by Granit and Davis, however, did not refer to identical background conditions or target sizes and"only serves to emphasize the general similarity of the two" functions. They did note that the actual time relations of the corresponding phases of their integration functions differed somewhat in that there appeared to be a region of complete integration for the foveal data but not for the peripheral data. Also, the peripheral data evidenced more partial integration than the foveal data (see Granit & Davis, 1931, Figure 4, top).

Sperling and Jolliffe (1965) used a single-pulse paradigm to investigate temporal integration in the fovea and at 15° eccentricity. Using the method of constant stimuli in the fovea and the method of limits in the periphery, they obtained thresholds for two spectral stimuli (450 and 650 nm) of various sizes (4.5', 45', and 3°) at eight durations (from 2.8 to 2000 msec) under dark adapted conditions. The foveal data were collected first and then the peripheral data. Figure 6 shows the data (the average of three subjects) for the 4.5' 450 nm stimulus regraphed in order to permit a foveal-peripheral comparison of integration functions. The thresholds for the briefest duration stimuli at each retinal locus were set equal to unity. Interestingly, at the shorter stimulus durations, the peripheral data evidenced a very brief period of complete integration. Also, at intermediate durations the peripheral data evidenced less integration than the foveal data while at the longer stimulus durations there was a tendency for the peripheral data to evidence more integration than the foveal data. Similar results held for their other stimulus conditions.

Van den Brink and Bouman (1954) investigated temporal integration by measuring the frequency-of-seeing a 1' red or green stimulus presented at various retinal eccentricities (fovea, 2°, 4°, 7°, and 10°). Their stimuli consisted of two, 10-msec light pulses separated by intervals of darkness which ranged from 0 to 300 msec. The luminance level was set such that the chance of seeing one of the 10-msec light pulses was between 22 and 37%. Their results led them to conlcude that the critical duration was independent of the retinal locus stimulated, and the amount of partial integration was constant across retinal loci.

Dannheim and Drance (1971) investigated temporal integration by measuring (via the method of limits) differ-

Figure 6. The luminance-duration relationship in the fovea and at 15° eccentricity obtained by Sperling and Jolliffe (1965) using a 4.5' diameter 450 nm stimulus. These data were regraphed in order to permit a foveal-peripheral comparison.


▲ Fovea
○ Periphery
Relative IT
10.0
1.0
1
5
10
50
100
500
1000
T (msec)

ence thresholds for a 45' white-appearing target presented on either a 10.0 (photopic range) or 0.10 (mesopic range) apostilb background. Difference thresholds were obtained for one subject at seven retinal loci (fovea, 5°, 10°, 15°, 20°, 25°, and 30°) for six stimulus durations (3.2 to 1000 msec). At photopic levels, the curves for the different retinal locations were very similar and showed a period of complete integration ($I \times T = K$) and a period of no integration ($I = C$), with a relatively abrupt break between them. The curve for the fovea showed the break with target presentations of 32 msec while the curves for the peripheral loci broke at 100 msec. Thus, temporal integration was complete for presentation times up to 32 msec in the fovea and up to 100 msec in the periphery. The shape of the integration functions for the mesopic condition was very similar to those found for the photopic condition; however, the break from complete to almost no integration occurred in the mesopic state with target presentations between 320 and 1000 msec at all retinal loci tested. Thus, as the background illumination was decreased, the period of complete integration seemed to increase. Unfortunately, the lack of data points between 320 and 1000 msec prevents one from drawing conclusions as to the actual values of the critical duration at different retinal loci. The results of Dannheim and Drance (1971) differ from those of Granit and Davis (1931) and Sperling and Jolliffe (1965) in that Dannheim and Drance found a relatively abrupt transition between complete integration and no integration. They also found a longer period of complete integration in the periphery than in the fovea.

Ronchi and Novakova (1971) used single-pulse stimuli, 7' in diameter, to investigate the luminance-time relation in the dark adapted eye at a number of retinal eccentricities (fovea, 1.5°, 5°, 10°, 25°, 30°, 40°, 50°, and 60°). They used the method of constant stimuli to determine the threshold luminance for a number of stimulus durations (from 5 to 400 msec). "For both observers, the critical duration increases from central to peripheral vision (p. 115)." However, an inspection of their log IT vs. log T plots at each retinal locus indicates that the critical duration does not increase monotonically as a function of eccentricity but changes in a complicated fashion. They also reported that the luminance-duration relation is complicated by strong individual differences. The fact that Ronchi and Novakova obtained one integration function per session per retinal locus per subject limits the confidence that one can have in their data for Berenhaus (Note 1) has shown that the critical duration can vary over a twofold range (e. g., from 58 to 133 msec) upon repeated testing at the same retinal locus.

Ronchi (1974) investigated temporal integration in the dark adapted eye using the method of constant stimuli at three retinal loci (15°, 30°, and 60°) for stimuli whose durations varied from 10 to 2000 msec. The stimulus was a test spot subtending either 4.5' or 6.0' of arc. She estimated the critical duration for 11 different wavelengths of light (427 to 642 nm) by finding the intersection of the lines of zero slope and + 1. The + 1 slope straight line was arbitarily assumed to pass through the points corresponding to the longest durations (1 and 2 sec). As mentioned before, this procedure, by ignoring the period of partial integration, may result in artificially long estimates of the critical duration. Her estimates of the critical duration as a function of retinal locus evidenced a complicated nonsystematic wavelength-locus dependency --- i. e., no systematic trends were evident across the retinal loci tested.

Lastly, Saunders (1975) examined the temporal integrative properties of the visual system at 40' and 2° from the center of fixation. Thresholds were determined for achromatic (3000° K) test stimuli using exposure durations of from 10 to 500 msec. The method of limits was used to obtain thresholds under dark adapted conditions with test stimuli of 3.2', 10', and 32' diameters. For achromatic stimuli at absolute threshold, the critical duration was

80 msec and was independent of stimulus size and location.

Table 1 summarizes the investigations cited above. Does temporal integration differ as a function of retinal locus? The data are contradictory and difficult to interpret. Perhaps this lack of agreement is due to the existence of complex interactions among several stimulus conditions (e. g., size of target x wavelength x retinal locus). However, it is also possible that these differences may stem from changes in the observer's response criterion across retinal loci (see below).

The Relationship between the Observer's Response Criterion and the Detection Threshold

The detection of a threshold-level light pulse is a complex affair that depends not only upon the obviously important stimulus conditions and procedural variables but also upon response factors as well (Engen, 1972). Boynton (1968, p. 11) gave an excellent description of the role of criterion in a visual task:

> Anyone who has ever observed dim light flashes will realize that merely to judge whether a flash is seen (or not seen) involves a process of decision which goes beyond the immediate sensation. The subject must therefore adopt some criterion according to which he will say "yes" or "no" in response to a given sensation. Different subjects adopt different criteria, and a given subject's criterion varies from one time to another.

SUMMARY OF EXPERIMENTAL CONDITIONS AND RESULTS FOR RETINAL LOCI STUDIES OF TEMPORAL INTEGRATION

Author	Stimulus Diameter	Background	Wavelength	Pulses	Duration	Method	Locus	Conclusions
Granit & Davis (1931)	1°, $2\frac{1}{2}^\circ$ 3°	.02 ml at 0°, 0 ml at 10°	?	Double	11.3 msec + test pulse	?	0° 10°	Conditions across loci were not comparable.
Van den Brink & Bouman (1954)	1'	0 ml	red, green both	Double	10-msec each	Constant Stimuli	0°, 2°, 4° 7°, 10°	Integration is independent of retinal locus.
Sperling & Jolliffe (1965)	4.5' 45', 3°	0 ml & 138 td	450 nm 650 nm	Single	2.8 to 2000 msec	Constant Stimuli, Limits	0° & 15°	Partial integration is greater at 15° than in the fovea.
Dannheim & Drance (1971)	45'	mesopic photopic	white	Single	3.2 to 1000 msec	Limits	0° to 30°	Complete integration is longer in the periphery than in the fovea.
Ronchi & Novakova (1971)	7'	0 ml	white	Single	5 to 400 msec	Constant Stimuli	0° to 60°	Complete integration is longer in the periphery than in the fovea.
Ronchi (1974)	4.5' 6'	0 ml	427 to 642 nm	Single	10 to 2000 msec	Constant Stimuli	15° 30° 60°	Critical duration varies unsystematically as a function of locus.
Saunders (1975)	3.2' 10' 32'	0 ml 100 td	chromatic achromatic	Single	10 to 500 msec	Limits	40' 2°	Integration is independent of locus.

Developments in the psychophysics of signal detection (Egan & Clarke, 1966; Galanter, 1962; Swets, 1964) seriously call into question inferences made about sensory function based on the measurement of thresholds, especially when these thresholds have been secured by classical psychophysical methods. While the numerical value of such a threshold is a property of the observer, it cannot be taken as a property of the sensory system because the classical methods provide threshold estimates that are usually contaminated by nonsensory (i. e., criterion) factors.

Barlow (1956) and Swets, Tanner, and Birdsall (1961) have shown that the criterion that a subject adopts in deciding he has "seen" a stimulus can have a considerable effect on response frequency thresholds or percent "seen" psychophysical functions. More specifically, Barlow showed that if an observer lowered his criterion from "seen" to "possibly seen," he could lower his threshold by 25%. Therefore, if an observer's criterion should vary across retinal loci, then the influence of the subject's criterion might be confounded with that of the stimulus condition being tested.

Some psychophysical methods are believed to be less influenced by the observer's criterion, e. g., the forced-choice procedure (Blackwell, 1953; Green & Swets, 1966). This method eliminates response criterion differences by forcing the observer to respond on each trial. (Each trial contains at least two observation intervals, one of which contains the signal.) Other psychophysical techniques, e. g., the signal detection yes-no procedure (Swets, 1964) permit the separation of the observer's criterion from his organismic sensitivity (see Tanner & Swets, 1954). This can be accomplished via an analysis of the observer's receiver-operating characteristic (ROC) curve which can be obtained by a yes-no rating scale procedure (see McNicol, 1972). The ROC curve is characterized by a single parameter, d' (detectability). d' is a measure of sensitivity which has been found to remain relatively constant in vision (Swets, Tanner, & Birdsall, 1961) regardless of changes in the observer's attitude and changes in the experimental procedure (Corso, 1963). The fact that criterion has been shown to have an effect on response frequency combined with the independence of signal detection measures from criterion may lead to signal detection methods yielding different estimates of temporal integration from previous studies (see Bruder & Kietzman, 1973).

Few experiments have investigated the effects of a change in criterion on the time course of temporal integration (see e. g., Levine & Kietzman, 1972) even though several studies have used signal detection methods

(Blackwell, 1952; Bruder & Kietzman, 1973; Clark & Blackwell, 1959; Stenson, 1965; Zacks, 1970). Bruder and Kietzman actually compared temporal integration using response frequency and signal detectability (as measured by rating ROC curves). Overall, the signal detection measure showed the same characteristics of temporal integration as found for the response frequency measure; however, Bruder and Kietzman did obtain somewhat longer critical durations for the response frequency measure than for the signal detection measure. An explanation for the longer critical duration estimates was suggested by the false alarm rates of the two observers (for details see Bruder, 1971).

Preview

This dissertation compares the temporal integrative capacity of the human visual system at two retinal loci --- the center of fixation (the fovea) and 7° from the center of fixation along the horizontal meridian (the periphery). In monocular experiments, the nasal hemiretina of the right eye was stimulated while in binocular experiments, the nasal and temporal retinae of the right and left eye, respectively were stimulated. Experiment 1 (E1) used an equal-energy stimulus paradigm in conjunction with a yes-no signal detection rating scale procedure. Experiments 2 (E2) and 3 (E3) employed an equal-performance stimulus paradigm in conjunction with a forced-choice procedure.

CHAPTER IV

GENERAL METHODS AND PROCEDURES

In this section those aspects of the experimental situation which are common to all experiments are described. Additional details relating to each particular experiment will be described in subsequent sections.

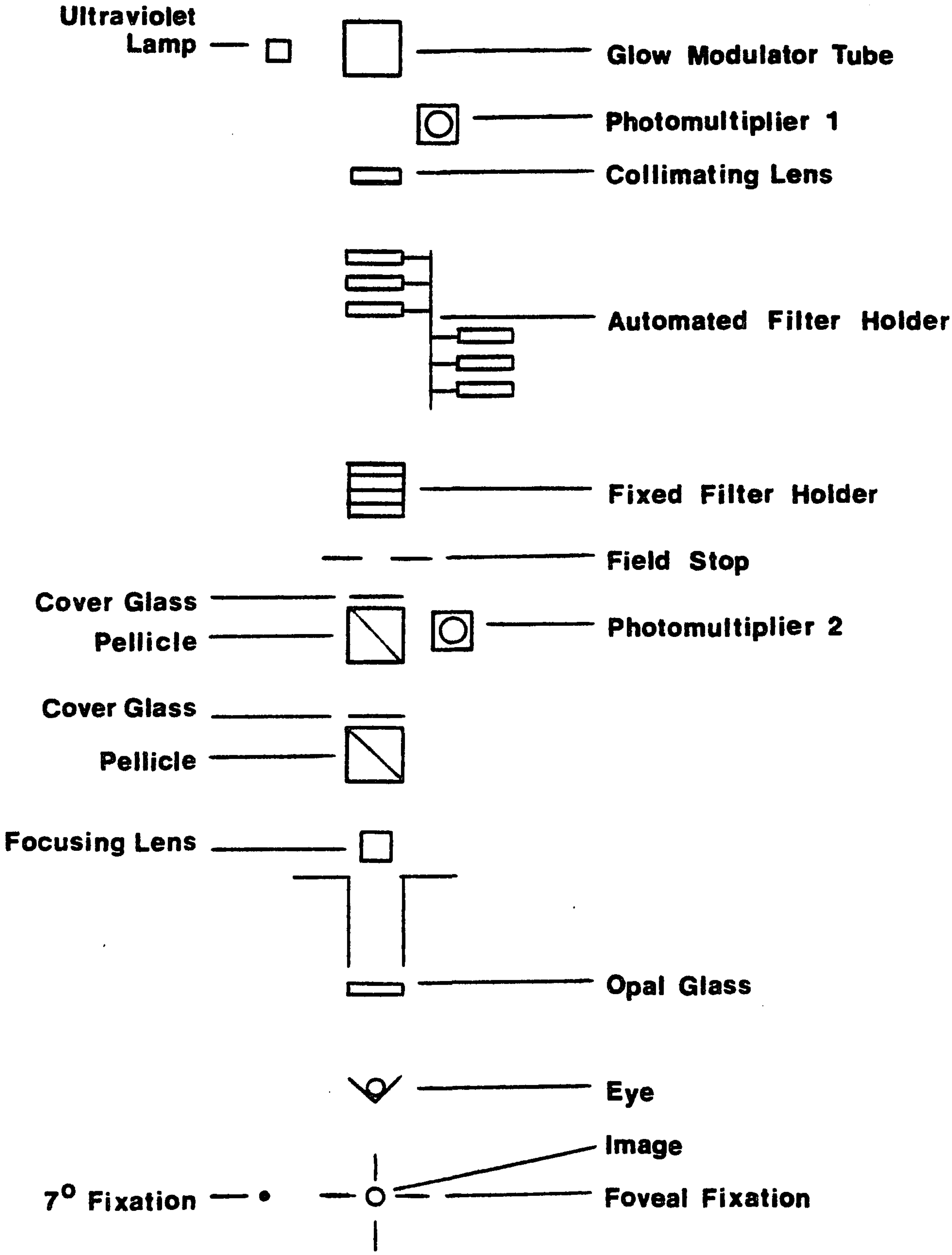
Observers

Eight observers served in the three experiments: three females (*O*:BB, *O*:DG, and *O*:SR) and five males (*O*:AL, *O*:CC, *O*:KK, *O*:MT, and *O*:RP). They had normal (Snellen 20/20) visual acuity (some with the aid of contact lenses) and were not color blind. Participants were between 22 and 32 years old, with the exception of *O*:CC who was 52. *O*:AL, *O*:BB, *O*:KK, and *O*:RP had previous experience as observers in this laboratory. Subjects did not receive any training before being tested, and were given only the information required for the task. All observers were paid for their services.

Apparatus

Optical System. The optical system used to present the light pulses and fixation lights is schematically drawn in Figure 7. The source of the light pulses was a glow modulator gas-discharge tube (Sylvania R1131C) which was operated at a constant current of 23 milliamperes and was activated through timing and gating circuits. The

Figure 7. A block diagram of the optical system.


Ultraviolet Lamp
Glow Modulator Tube
Photomultiplier 1
Collimating Lens
Automated Filter Holder
Fixed Filter Holder
Field Stop
Cover Glass
Pellicle
Photomultiplier 2
Cover Glass
Pellicle
Focusing Lens
Opal Glass
Eye
Image
7° Fixation
Foveal Fixation

glow-tube was irradiated by an argon ultraviolet lamp (General Electric AR-4) to provide short and stable "ionization times" of less than 10 microsec (see Matin, 1964). This resulted in the production of rectangular light pulses with very short rise (approximately 20 microsec) and decay (approximately 10 microsec) times (see Kietzman & Gillam, 1972). The light from the glow-tube, after being collimated, was passed through a series of filters used to control the intensity and spectral composition of the light. Six neutral density metallic filters (Tiffen) were mounted in the arms of a logic controlled, solenoid activated system, which upon command from an electronic keyboard on the experimenter's panel could place any desired combination of these filters into the light path. Using the possible combinations of these filters, the resultant luminance of the light transmitted could be varied in 0.1 log unit steps. Additional metallic filters, as well as neutral density gelatin filters (Kodak Wratten) were mounted in a fixed filter holder. All of these filters and combinations were calibrated in our laboratory (see Appendix II). The filtered light beam was reduced in size using a field stop with a 2.52 mm aperature and then passed through two pellicle beam splitters (National Photocolor Corp.) and two cover glasses. The image of the crater of the glow-tube was focused onto a diffusing glass (opal) producing a white-appearing circular target. An opaque mask on the opal glass outlined the target which subtended a visual angle of 22' in diameter. The duration and intensity of the light pulses were monitored on an oscilloscope (Tektronix 532) display of the outputs of photomultiplier tubes (RCA 1P21) whose light inputs were filtered (Kodak Wratten 106) to approximate the C. I. E. photopic-luminous-efficiency curve.

Foveal stimulation was obtained by fixating on four dim red lines approaching the target in a cross. Peripheral stimulation was obtained by fixation on a dimly lit red light emitting diode located 7° to the left of the target along the horizontal meridian. Thus, the nasal hemiretina of the right eye would be stimulated (monocular condition) or the nasal and temporal hemiretinae of the right and left eye, respectively (binocular condition). The intensity of the fixation lights was set at a dim but comfortable level. An adjustable chin and forehead rest were employed to obtain a stable position for the observer at an accommodative distance of 52 cm. Eye movements were not monitored; however, the participants were cooperative and did their best to maintain fixation (see Clark & Blackwell, 1959, p. 23).

The procedures used in calibrating the light from the glow modulator tube and the percent transmission of the filters were the same as those used by Bruder (1971). These procedures are presented in Appendices I and II.

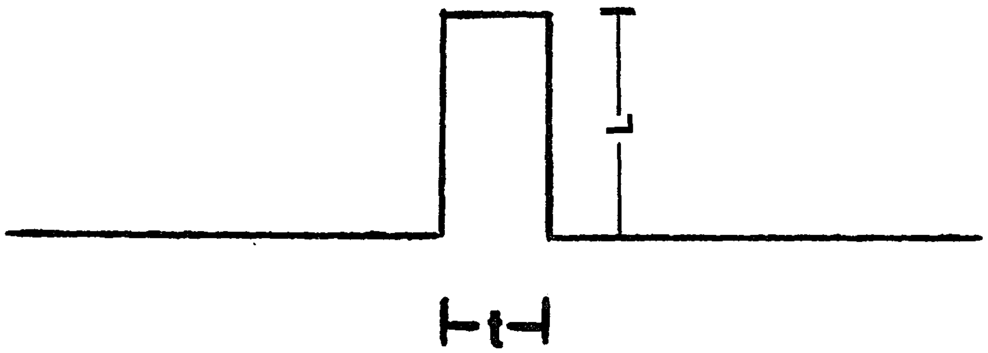
Timers. The durations of the light pulses, as well as the timing of events within each trial, were controlled using a transistorized, nine-channel multivibrator timer with an indeterminancy of 1 part in 10,000 (Logical Instruments Co.). The timer delivered a pulse of the desired duration to a gating device which in turn activated the glow tube for that duration.

Response Recording Apparatus. In Experiment 1, the observer responded verbally with one of six rating categories. In Experiments 2 and 3, the observer made his detection response by pressing one of three buttons which in turn activated a corresponding light on the experimenter's panel. All response manipulanda were located to the right of the observer on a flat shelf. The experimenter recorded all responses on data sheets after each trial. The same apparatus was used in all three experiments.

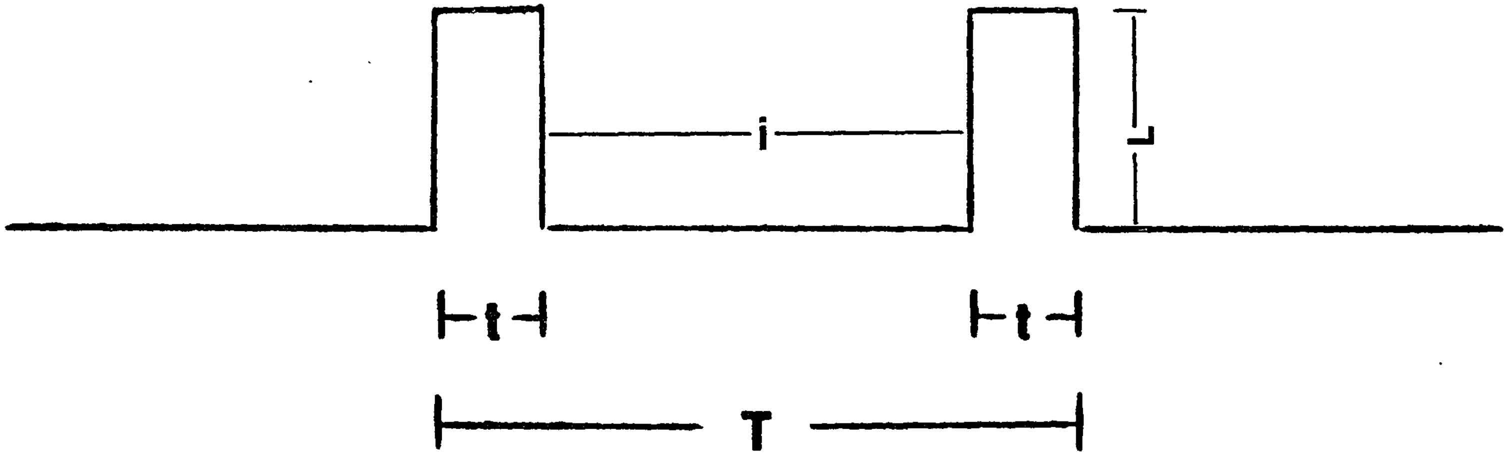
Stimuli

Double-Pulse (Two-Pulse) Stimuli. The double-pulse stimuli used in this study consisted of two, square-wave, 1-msec, equal luminance light pulses separated by various intervals of darkness. If the light time of each 1-msec pulse is designated as t, then the total light time of each double-pulse stimulus is equal to 2-msec or 2t. Figure 8 illustrates the stimuli used in this investigation. Since the total light time of the double-pulse stimulus is held constant, changes in luminance are paralleled

Figure 8. A single-pulse (top) and double-pulse (bottom) stimulus. t = the pulse duration; i = the dark interval between the two light pulses; L = the pulse luminance; T = the total display time.



Single - Pulse Stimulus



Double - Pulse Stimulus

by changes in total summated luminous energy, since I x 2t = K, and 2t is constant. In this dissertation, the double-pulse stimuli are described by their total stimulus duration in msec --- the time elapsing from the onset of the first light pulse to the offset of the second light pulse. For example, a stimulus which has a total stimulus duration of 42 msec consists of two, 1-msec light pulses separated by 40 msec of darkness. The briefest double-pulse stimulus used in this study was 2.1 msec while the longest was 402 msec.

Single-Pulse Stimuli. Some of the experiments also used a 1-msec single-pulse stimulus. In the equal-energy experiment, the 1-msec stimulus was half the total luminous energy of a double-pulse stimulus as it contained only the first pulse (t) of a double-pulse stimulus.

Organization of Each Session

Each session (see Figure 9) consisted of eight blocks of trials (approximately 30 to 46 trials per block) with retinal locus blocked in an ABBABAAB or AABBBBAA design (A = fovea; B = 7° eccentricity). The starting retinal locus was also counterbalanced across sessions and observers when possible. Total testing time per session ranged from 45 to 60 minutes, and one to two minute rests were given between blocks. The length of each trial was approximately three to five seconds, and the time between trials (i. .e,

Figure 9. The organization of each session.

Block 1	Block 2	Block 3	Block 4	Block 5	Block 6	Block 7	Block 8
Fovea	7°	7°	Fovea	7°	Fovea	Fovea	7°
A	B	B	A	B	A	A	B
			or				
Fovea	Fovea	7°	7°	7°	7°	Fovea	Fovea
A	A	B	B	B	B	A	A

the intertrial interval) was approximately five seconds. Observers were usually tested twice per day, and a 30 to 60 minute rest was given between sessions.

Dark Adaptation and Fixation Procedures

In all experiments, observers wore dark adapting red goggles (Polaroid Corp.) for 30 minutes prior to dark adapting for 10 minutes in a light-tight booth with the goggles off. At the beginning of a block of trials, either the four dim red lines (for foveal stimulation) or the dim red circular light emitting diode (for peripheral stimulation) was turned on, and the observer was instructed to fixate. Viewing was with natural pupils.

CHAPTER V

EXPERIMENT 1

Experiment 1 used a signal detection yes-no rating scale procedure in conjunction with an equal-energy stimulus paradigm to generate temporal integration functions in the fovea and at 7° eccentricity. This rating scale procedure allowed for measures of response frequency (i. e., percent seen) and signal detectability (i. e., receiver-operating characteristic curves) to be extracted from the data.

Method

Stimuli

Experiment 1 used both single-pulse and double-pulse stimuli. The double-pulse stimuli were of the following total stimulus durations: 3, 6, 12, 22, 42, 52, 62, 82, 102, 122, and 142 msec. The single-pulse stimulus was 1-msec in duration. All double-pulse stimuli at the same retinal locus were equal in total summated luminous energy, and the single-pulse stimulus was half the summated luminous energy of a double-pulse stimulus. The luminance of the light pulses was set with respect to sensation level at each retinal locus for each observer such that the 3-msec double-pulse stimulus yielded 67% correct responding in a three-interval temporal forced-choice adaptive staircase procedure (for details see Experiment 2). The total summated luminous energy at threshold for the 3-msec stimulus averaged .171 ml x msec in the fovea and .024 ml x msec at 7° eccentricity.

Procedure

The three subjects (O:KK, O:BB, and O:RP) were dark adapted, and in each case a patch was placed over the left eye. Each observer participated in eight test sessions. The stimulus trials and blank trials within a block were randomized with the restriction that an equal number of each stimulus duration and a specified number of blanks (see below) be presented within each block of trials. Block size and the specific make-up of a block differed somewhat for each observer as follows: O:KK was tested on the following stimulus durations: 1, 3, 6, 12, 22, 52, 82, 102, 122, and 142 msec. Each block contained 39 trials --- three of each stimulus duration (30 trials) and nine blanks (23%). Each stimulus duration was presented 96 times along with 288 blanks at each retinal locus for a total of 2496 trials. O:BB was tested on the following stimulus durations: 1, 3, 12, 22, 42, 62, 82, and 102 msec. Each block contained 40 trials --- four of each stimulus duration (32 trials) and eight blanks (20%). Each stimulus duration was presented 128 times along with 256 blanks at each retinal locus for a total of 2560 trials. O:RP was tested on the same stimulus durations as O:KK. Each of his blocks contained 46 trials: 35 stimuli and 11 blanks such that at the end of every two blocks of trials at the same retinal locus, seven of each stimulus duration (70 trials) and 22 blanks (24%) were presented. Each stimulus duration was presented 112 times along with 176 blanks at each retinal locus for a total of 2592 trials.

Each trial was self-initiated and began with a warning signal. After a 2-sec foreperiod either a stimulus or a blank was presented. Observers were informed that there would be blanks; however, the a priori probability was not given. After each trial, the observer was instructed to respond "Yes" if he thought he had seen a light and "No" if he thought that he had not seen a light. The observer was also required to rate his confidence in his response in the following way: "One," not very confident; "Two," moderately confident; "Three," very confident. The experimenter recorded the observer's rating resonse, and an all-clear tone signalled the observer that he could initiate another trial. No feedback was given.

Results

Response Frequency

The percentage of "Yes" responses on stimulus trials was used as the measure of response frequency. Figures 10 (O:KK), 11 (O:BB), and 12 (O:RP) show response frequency

Figure 10. Response frequency for equal-energy double-pulse stimuli in the fovea and at 7° eccentricity graphed as a function of total stimulus duration for O:KK (Experiment 1). The solid symbols (▲ , ●) indicate double-pulse stimuli and the hollow symbols (△ , ○) represent single-pulse (i. e., half-energy) stimuli.

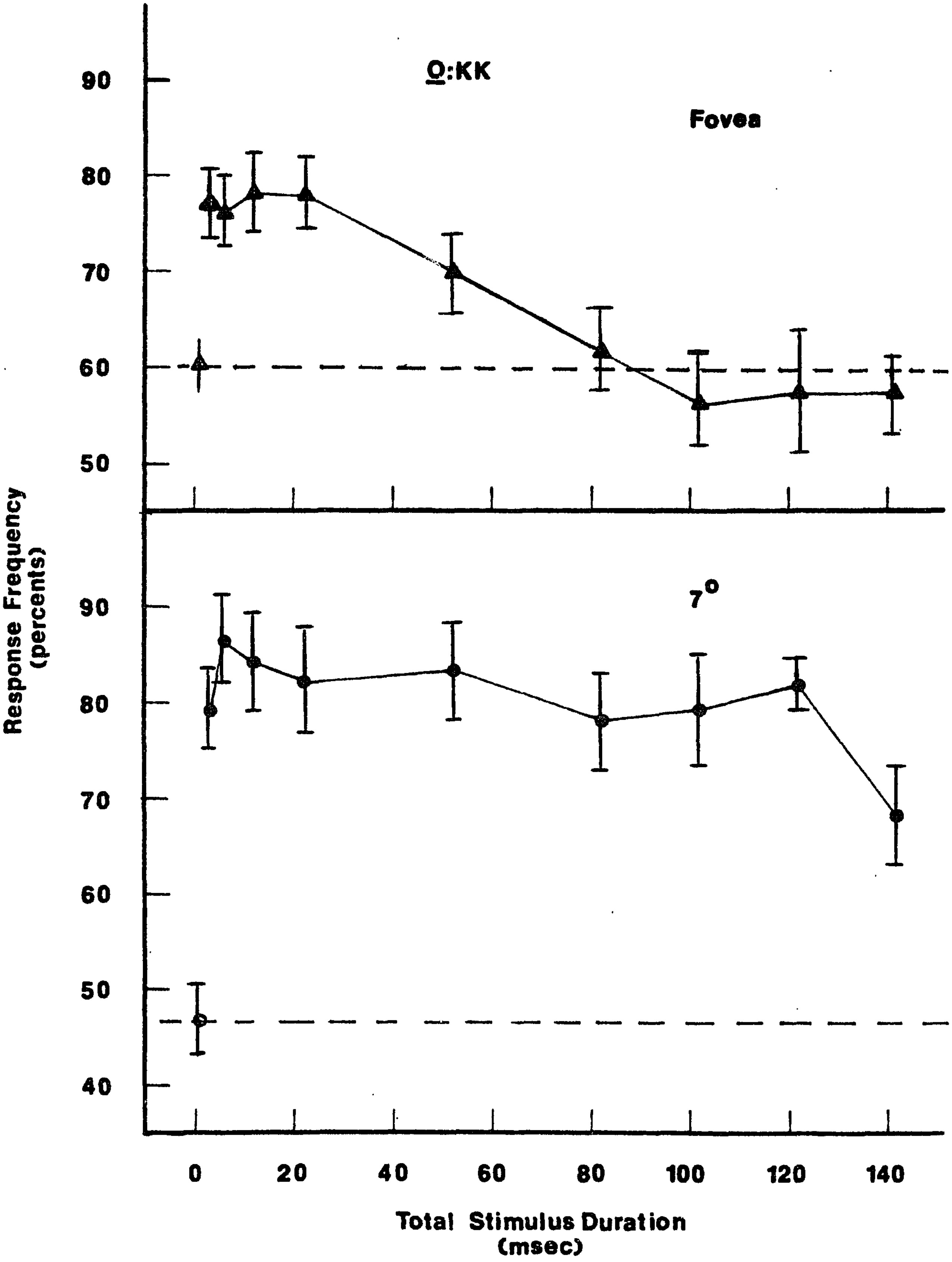

O:KK
Fovea
7°
Response Frequency (percents)
90
80
70
60
50
90
80
70
60
50
40
0
20
40
60
80
100
120
140
Total Stimulus Duration (msec)

Figure 11. Response frequency for equal-energy double-pulse stimuli in the fovea and at 7° eccentricity graphed as a function of total stimulus duration for O:BB (Experiment 1). The solid symbols (▲ , ●) indicate double-pulse stimuli and the hollow symbols (△ , ○) represent single-pulse (i. e., half-energy) stimuli.

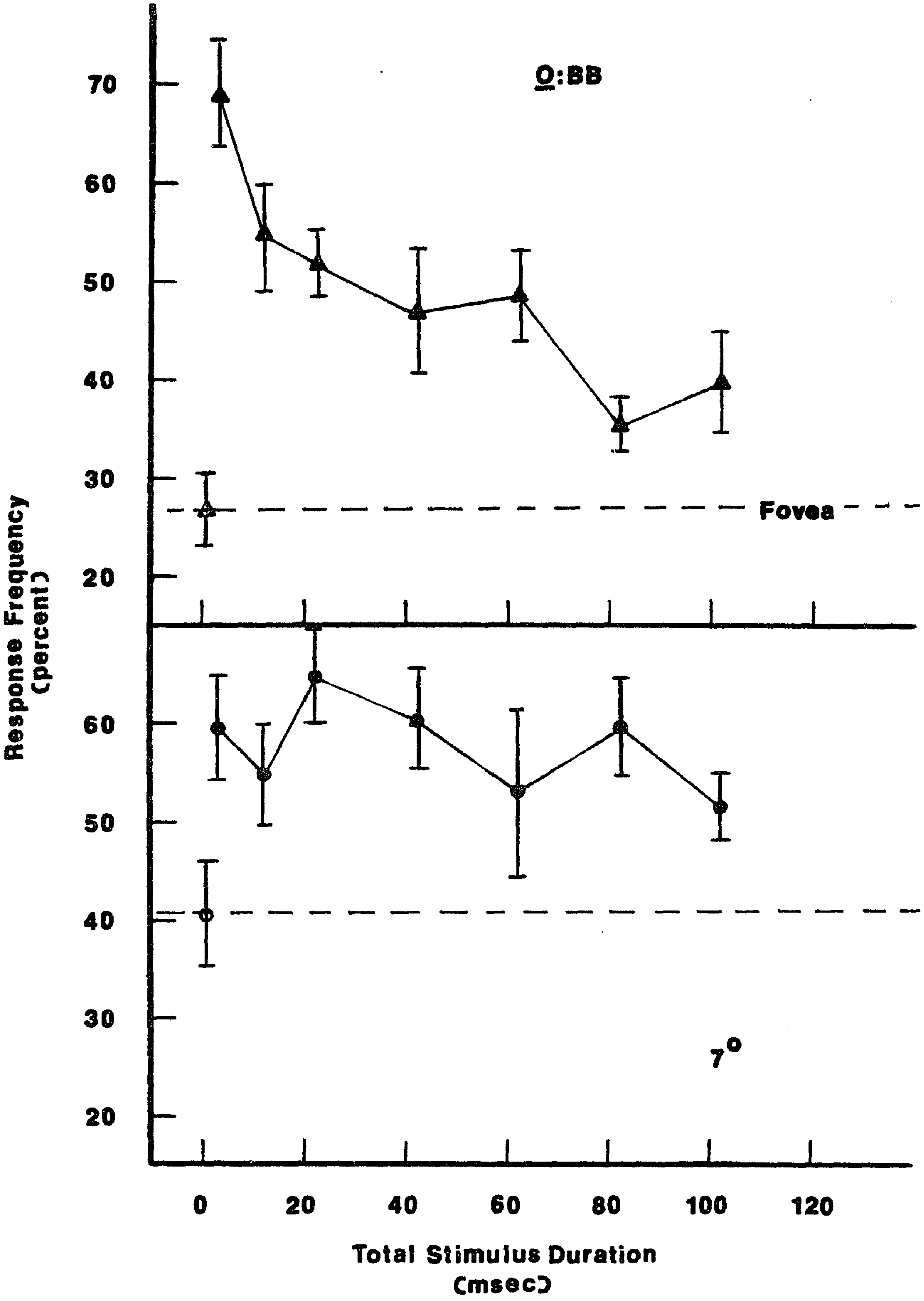
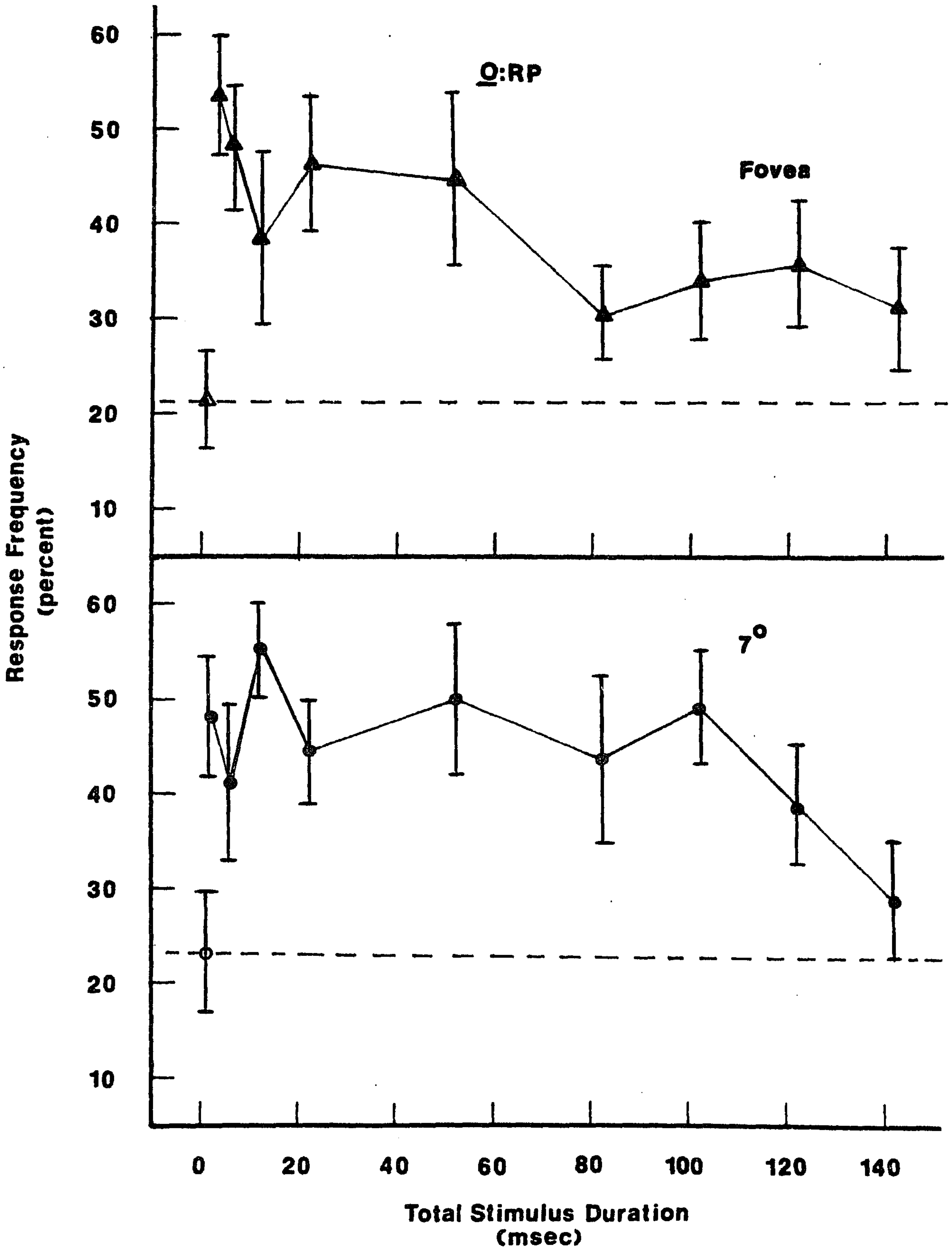

O:BB
Fovea
7°
Response Frequency (percent)
70
60
50
40
30
20
60
50
40
30
20
0
20
40
60
80
100
120
Total Stimulus Duration (msec)

Figure 12. Response frequency for equal-energy double-pulse stimuli in the fovea and at 7° eccentricity graphed as a function of total stimulus duration for O:RP (Experiment 1). The solid symbols (▲ , ●) indicate double-pulse stimuli and the hollow symbols (△ , ○) represent single-pulse (i. e., half-energy) stimuli.


O:RP
Fovea
7°
Response Frequency (percent)
60
50
40
30
20
10
0
20
40
60
80
100
120
140
Total Stimulus Duration (msec)

graphed as a function of total stimulus duration. The brackets surrounding each data point indicate ± 1 S. E. M. Although the 3-msec stimulus was set at 67% correct responding (see Stimuli, p. 55), these figures show that response frequency for this stimulus ranged from 48% to 78%. This difference results from the fact that the procedure used to estimate the 67% threshold (see Experiment 2) was different from that used in the present experiment. The dashed horizontal line indicates the response frequency for the single-pulse, half-energy stimulus.

In the fovea, at the briefest stimulus durations, response frequency remained relatively constant for O:KK and O:RP out to 22 and 52-msec respectively. For O:BB, response frequency immediately decreased as the total stimulus duration increased beyond 3-msec. Thus, at the briefer stimulus durations, the response frequency data of O:KK and O:RP evidenced a period of complete integration --- i. e., equal-energy stimuli of different durations produced a constant visual effect. The data of O:BB, however, did not evidence a period of complete integration. For all observers, as the duration of the double-pulse stimulus was further increased, response frequency also decreased indicating a period of partial integration. Partial integration occurs as long as some of the luminous energy of the second pulse continues to affect the response. This is indicated by a higher level of response frequency with regards to the double-pulse stimulus in the region of partial integration than to a half-energy, single-pulse stimulus. The response frequency does not continue to decrease, as the total stimulus duration is increased, but levels off and remains relatively constant at the longer stimulus durations. This is indicative of a period of no integration. For *O*:KK and *O*:RP, this relatively constant level, at the longer stimulus durations is about the same as that for a half-energy, single-pulse stimulus (as indicated by the confidence limits for these longer duration stimuli overlapping with those for the 1-msec stimulus). Double-pulse stimuli whose performance levels are the same as that for a half-energy, single-pulse stimulus may be evidencing some form of neural inhibition or no integration (see p. 16). The longest double-pulse stimuli of *O*:BB also appear to be at a relatively constant level; however, this level, being somewhat above that for the single-pulse, half-energy stimulus, indicates that these stimuli may still be in the region of partial integration.

The 7° data show that response frequency remained relatively constant out to 122-msec (*O*:KK), 82-msec (*O*:BB), and 102-msec (*O*:RP). Thus, equal-energy double-pulse stimuli of different durations produced a constant visual effect out to much longer durations in the periphery at 7° than in the fovea. Response frequency for double-pulse stimuli longer than the above mentioned values was less than that for completely integrated stimuli but greater than that for a half-energy stimulus. These double-pulse stimuli appear to be in the region of partial integration. In no instance did the longer double-pulse stimuli reach a relatively constant level or descend to the level of the half-energy, single-pulse stimulus.

Table 2 lists the estimates of the critical duration in the fovea and at 7° eccentricity for the response frequency data. The end of the period of complete integration (i. e., the critical duration) was defined as the duration of the longest double-pulse stimulus whose confidence limits overlapped with those for the briefest (3-msec) double-pulse stimulus. The 3-msec stimulus was presumed to be fully-integrated due to its brevity. The critical duration was estimated to lie between the longest stimulus in the region of complete integration and the next longest stimulus, which by definition was outside of the region of complete integration. Table 2 shows that for all three observers, the critical duration was longer in the periphery at 7° than in the fovea.

In this experiment, the observer's response criterion was monitored by measuring the percentage of false alarms ("Yes" responses on blank trials) committed at each retinal locus. Table 3 lists these false alarm rates and shows that an observer's response criterion can vary greatly across retinal loci. Despite this, the false alarm rate per se did

Table 2

Estimates of the Critical Duration

(msec)

Observer	Fovea	7° Eccentricity
O:KK(E1)	52-82	122-142
O:BB(E1)	3-12	100-
O:RP(E1)	52-82	122-142
O:SR(E3)	82-102	102-152
O:DG(E3)	62-82	82-102
O:RP(E3)	42-62	100-

Table 3

False Alarm Rates (and B values) in the Fovea and at 7°

Observer	Fovea	7° Eccentricity
O:KK(E1)	41.9%(2.60)	22.2%(2.95)
O:BB(E1)	18.4%(3.22)	31.6%(3.22)
O:RP(E1)	11.3%(3.30)	10.0%(3.32)

not seem to have any relationship to the time course of temporal integration.

Signal Detectability

ROC Curves. The rating scale data were used to construct receiver-operating characteristic (ROC) curves for each stimulus duration at each retinal locus for each observer. Table 4 summarizes the data used to plot the ROC curves for O:KK. (Tables 5 and 6 summarize the rating scale data for O:BB and O:RP, respectively. See Appendix III.) This table gives the frequencies with which the observer used the six response categories (Yes-3 through No-3) on signal and blank trials and the proportions of hits, P(S/s), and false alarms, P(S/n), derived from these frequencies. To calculate the hit proportions for each stimulus duration, the frequencies of use of each response category were cumulated from left to right (i. e., from Yes-3 to No-3) and then divided by the total number of stimulus presentations. The false alarm proportions (bottom of the table) were calculated in a similar manner but using the frequencies of responses in the six categories that occurred on blank trials. In order to plot an ROC curve, the proportions of hits, P(S/s), are graphed as a function of the corresponding proportions of false alarms, P(S/n), for each stimulus duration. (For a more detailed description of the rating scale procedure see McNicol, 1972.)

Table 8

Frequency (f) of Use of Each Response Category and Estimates of Hit, P(S/s), and False Alarm, P(S/n), Proportions in the Foveas and at 7° Eccentricity for O:KK (Experiment 1)

Total Stimulus Duration (msec)		Fovea						7° Eccentricity					
		Yes			No			Yes			No		
		3	2	1	1	2	3	3	2	1	1	2	3
3	f	20	36	19	10	11	0	29	37	10	5	10	5
	P(S/s)	.208	.583	.781	.885	1.0	1.0	.302	.688	.792	.844	.948	1.0
6	f	22	34	17	12	9	2	37	28	18	4	7	2
	P(S/s)	.229	.583	.760	.885	.979	1.0	.385	.677	.865	.906	.979	1.0
12	f	15	51	12	10	8	0	29	35	17	4	10	1
	P(S/s)	.156	.688	.812	.917	1.0	1.0	.302	.667	.844	.885	.990	1.0
22	f	15	36	12	10	10	0	27	35	17	5	7	5
	P(S/s)	.156	.531	.781	.896	1.0	1.0	.281	.646	.823	.875	.948	1.0
52	f	6	42	19	18	10	2	23	40	17	4	9	3
	P(S/s)	.062	.495	.691	.876	.979	1.0	.240	.656	.833	.875	.969	1.0
82	f	3	26	30	13	22	2	25	34	16	2	16	2
	P(S/s)	.031	.302	.615	.750	.979	1.0	.263	.621	.790	.810	.979	1.0
102	f	0	27	27	19	22	2	12	39	25	3	13	4
	P(S/s)	.000	.278	.557	.753	.979	1.0	.125	.531	.791	.823	.958	1.0
122	f	3	23	29	18	20	3	12	39	25	3	13	4
	P(S/s)	.031	.271	.573	.760	.969	1.0	.198	.615	.812	.906	.927	1.0
142	f	3	25	27	21	16	2	18	30	18	6	18	3
	P(S/s)	.032	.298	.585	.808	.979	1.0	.194	.516	.710	.774	.968	1.0
1	f	0	24	34	16	19	2	6	16	23	16	25	10
	P(S/s)	.000	.253	.610	.779	.979	1.0	.062	.229	.469	.635	.896	1.0
Blamks	f	3	32	86	64	94	10	0	13	51	47	124	53
	P(S/n)	.010	.121	.419	.640	.965	1.0	.000	.045	.222	.385	.816	1.0

Figures 13 (peripheral data) and 14 (foveal data) show the ROC curves constructed from the rating scale data of O:KK (Table 4). Similar results were obtained for O:BB and O:RP (see Figures 15 through 18). The solid 45° diagonal line in each graph indicates chance performance --- i. e., chance detectability. The greater the distance above and to the left of the chance diagonal, the greater is the sensitivity of the observer. The ROC curve data points for the briefest double-pulse stimulus (3-msec) have been included in each graph to serve as a reference against which the other ROC curve data points can be compared. This stimulus is presumed to be completely integrated due to its brevity. The data points for the 3-msec stimulus have been connected by solid lines. The ROC curve data points for the briefer double-pulse stimuli are shown in the lower graphs of each figure; those for the longer stimuli and the half-energy stimulus (indicated by the dashed lines) are shown in the upper graphs of each figure.

O:KK's peripheral data show that double-pulse stimuli as long as 122-msec have ROC curve data points which overlap with those for the 3-msec stimulus. This indicates that equal-energy double-pulse stimuli of different durations were equally detectable, regardless of how the luminous energy was distributed below 122-msec. Only the ROC curve data points for the longest stimulus (144-msec) fell below those for the 3-msec stimulus. Also, none of the ROC curve data points over-

Figure 13. ROC curves constructed from the rating scale data (7° eccentricity) of Table 4 for O:KK (Experiment 1).

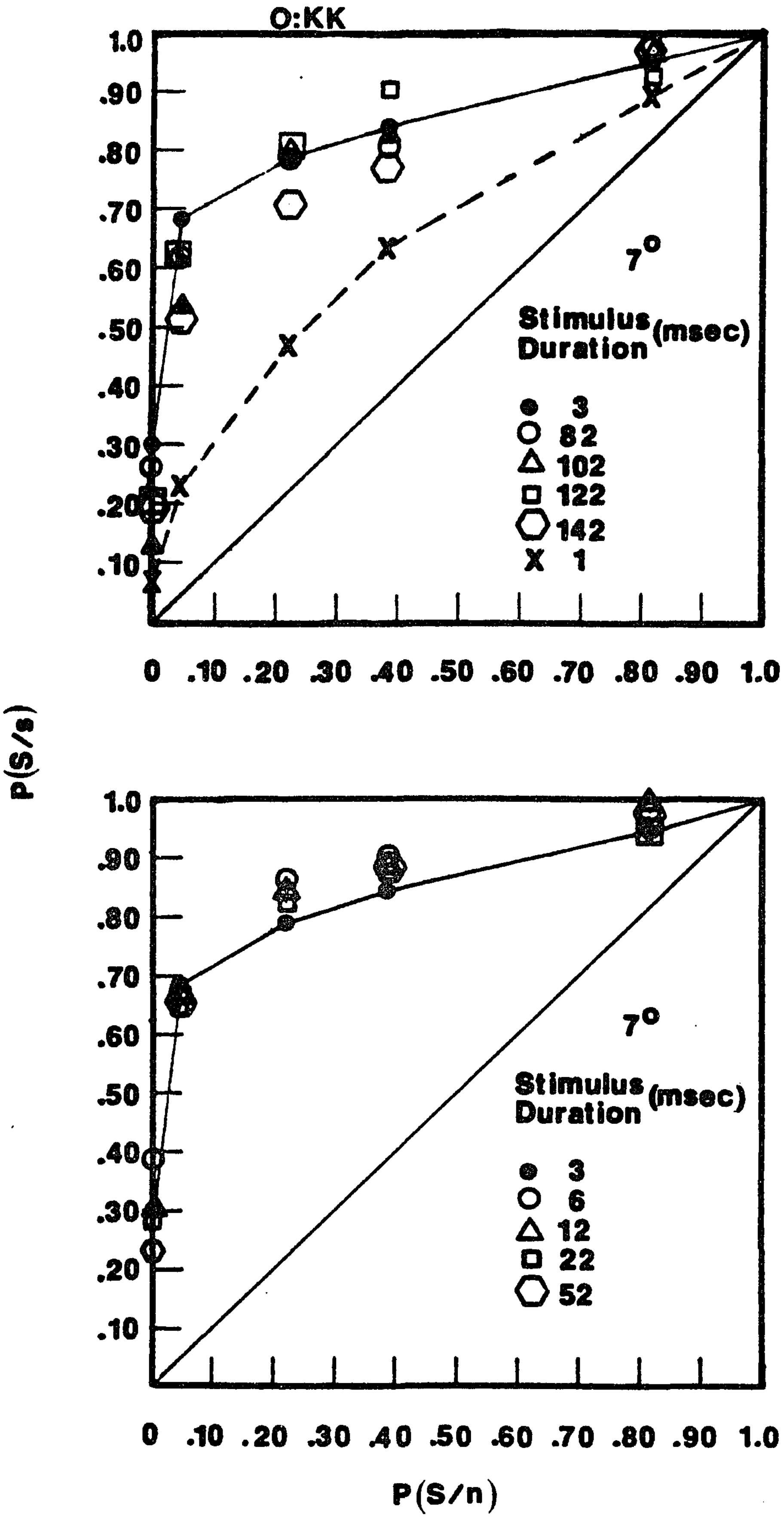

O:KK
1.0
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
.10
.20
.30
.40
.50
.60
.70
.80
.90
1.0
7°
Stimulus Duration (msec)
● 3
○ 82
△ 102
□ 122
⬡ 142
X 1
P(S/s)
1.0
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
.10
.20
.30
.40
.50
.60
.70
.80
.90
1.0
7°
Stimulus Duration (msec)
● 3
○ 6
△ 12
□ 22
⬡ 52
P(S/n)

Figure 14. ROC curves constructed from the rating scale data (foveal condition) of Table 4 for O:KK (Experiment 1).

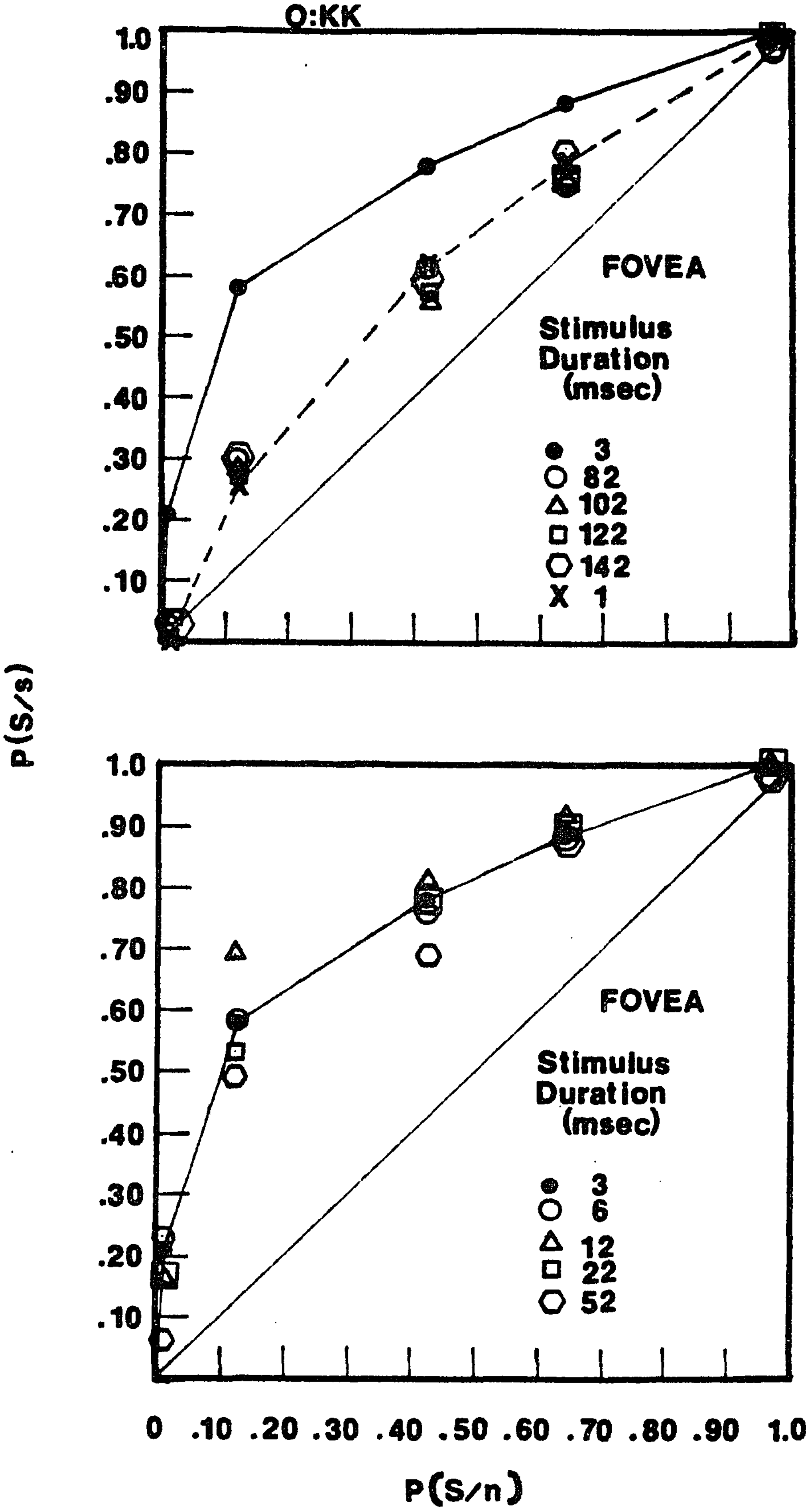

O:KK
1.0
.90
.80
.70
.60
.50
.40
.30
.20
.10
FOVEA
Stimulus
Duration
(msec)
● 3
○ 82
△ 102
□ 122
⬡ 142
X 1
P(S/s)
1.0
.90
.80
.70
.60
.50
.40
.30
.20
.10
FOVEA
Stimulus
Duration
(msec)
● 3
○ 6
△ 12
□ 22
⬡ 52
0 .10 .20 .30 .40 .50 .60 .70 .80 .90 1.0
P(S/n)

Figure 15. ROC curves constructed from the rating scale data (7° eccentricity) of Table 5 for O:BB (Experiment 1).

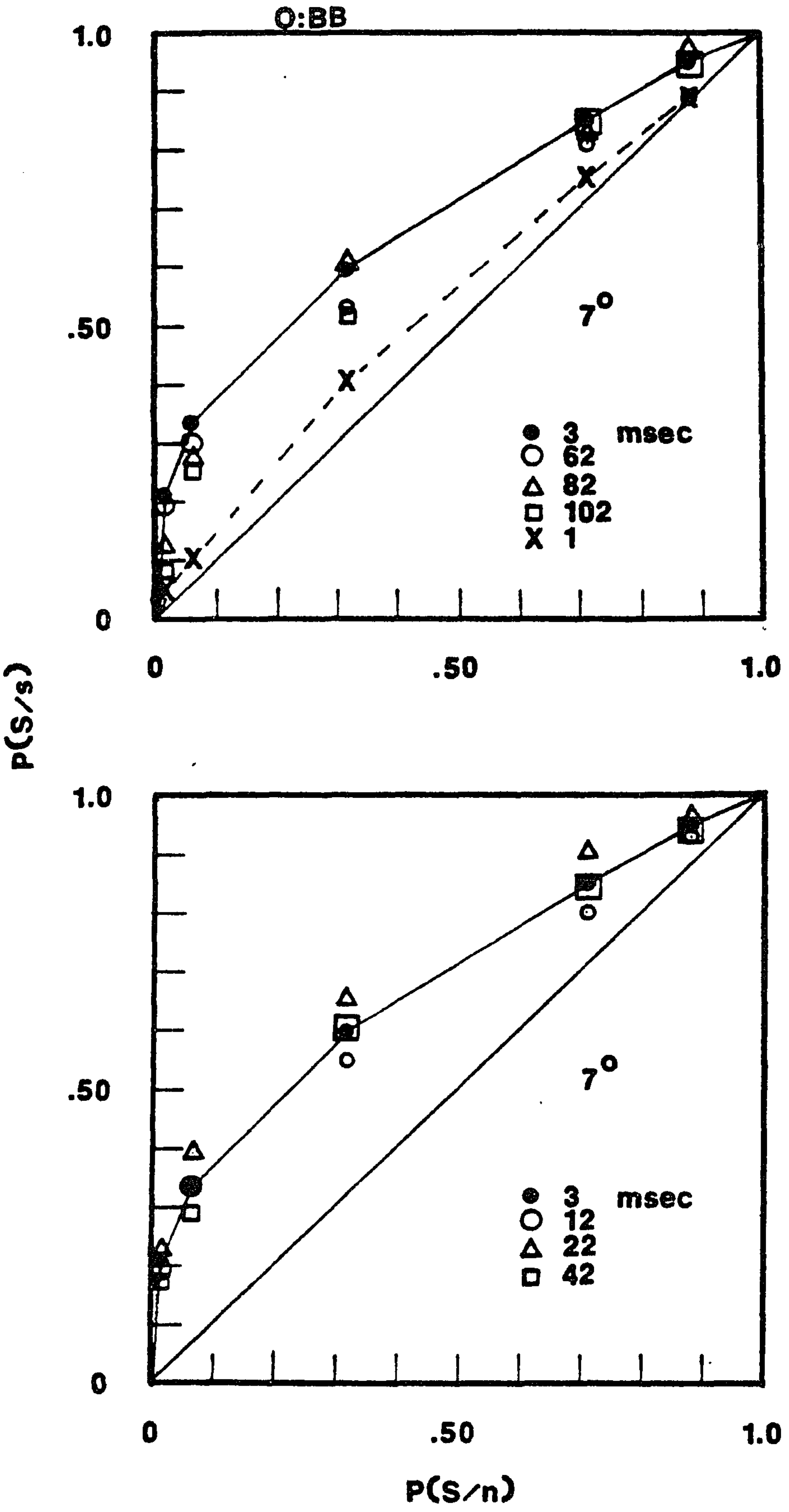

Q:BB
1.0
.50
0
0
.50
1.0
7°
3 msec
62
82
102
1
P(S/s)
1.0
.50
0
0
.50
1.0
7°
3 msec
12
22
42
P(S/n)

Figure 16. ROC curves constructed from the rating scale data (foveal condition) of Table 5 for O:BB (Experiment 1).

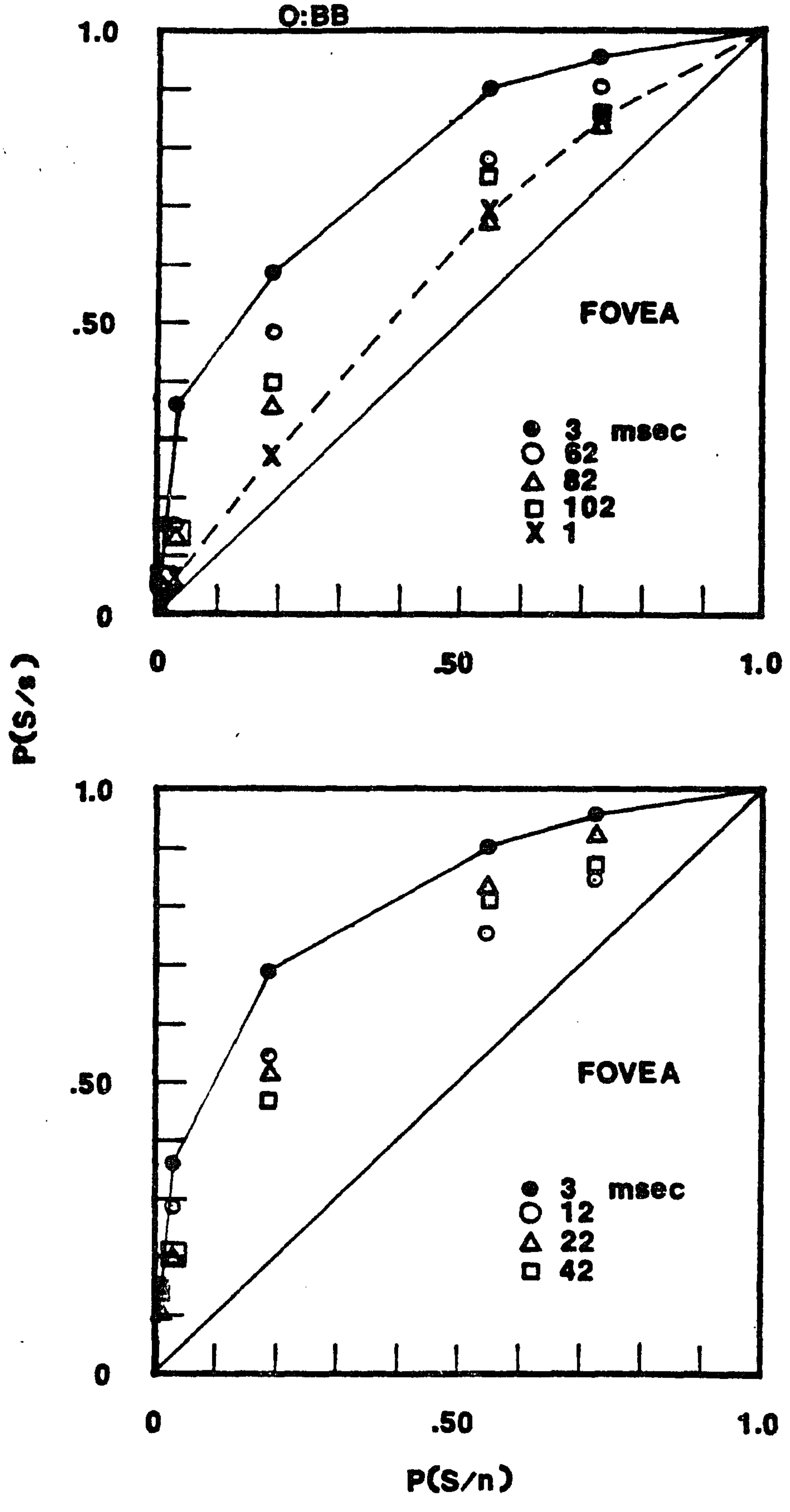

O:BB
1.0
.50
0
FOVEA
● 3 msec
○ 62
△ 82
□ 102
X 1
0
.50
1.0
P(S/s)
1.0
.50
0
FOVEA
● 3 msec
○ 12
△ 22
□ 42
0
.50
1.0
P(S/n)

Figure 17. ROC curves constructed from the rating scale data (7° eccentricity) of Table 6 for _O_:RP (Experiment 1).

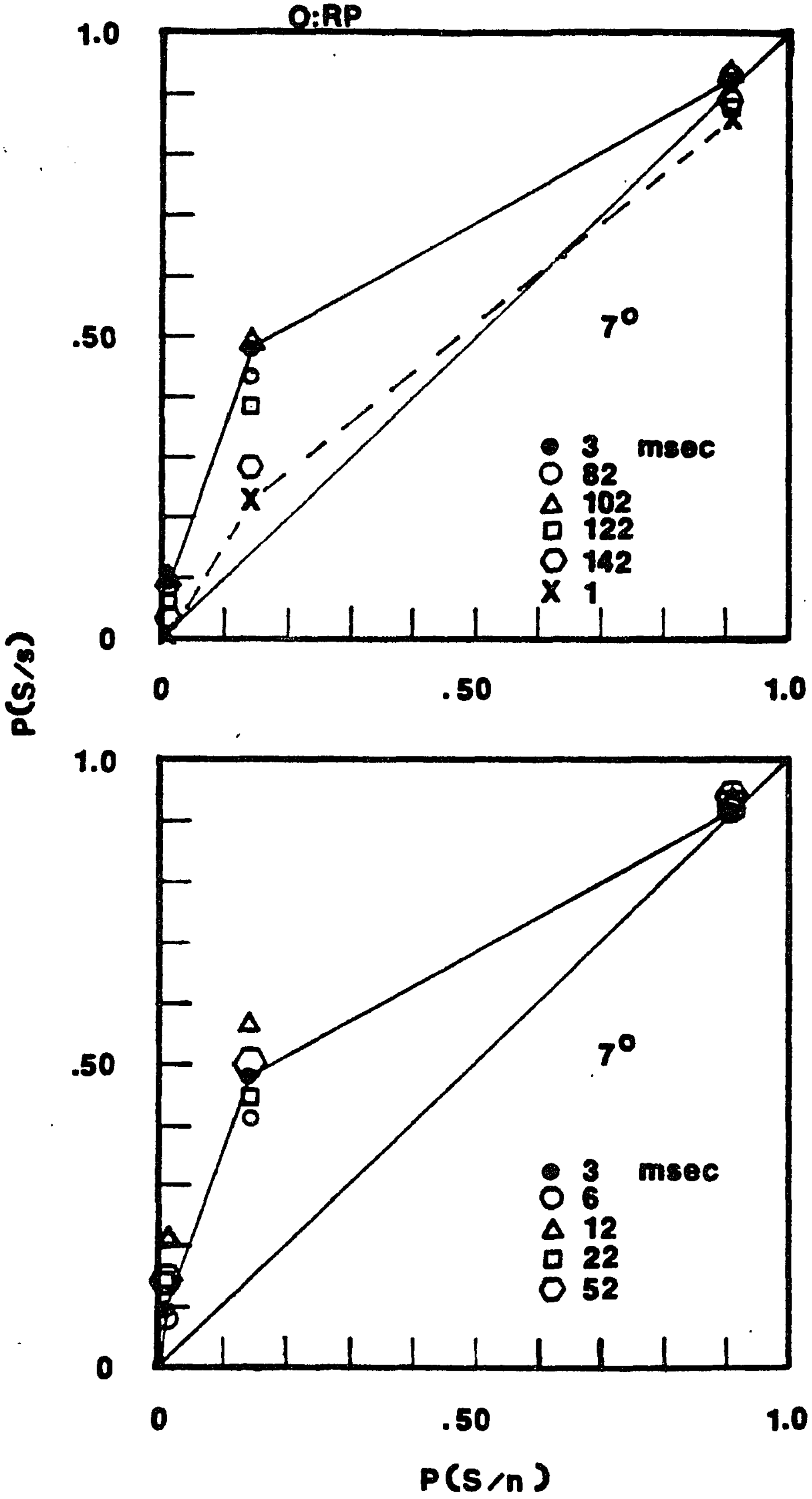
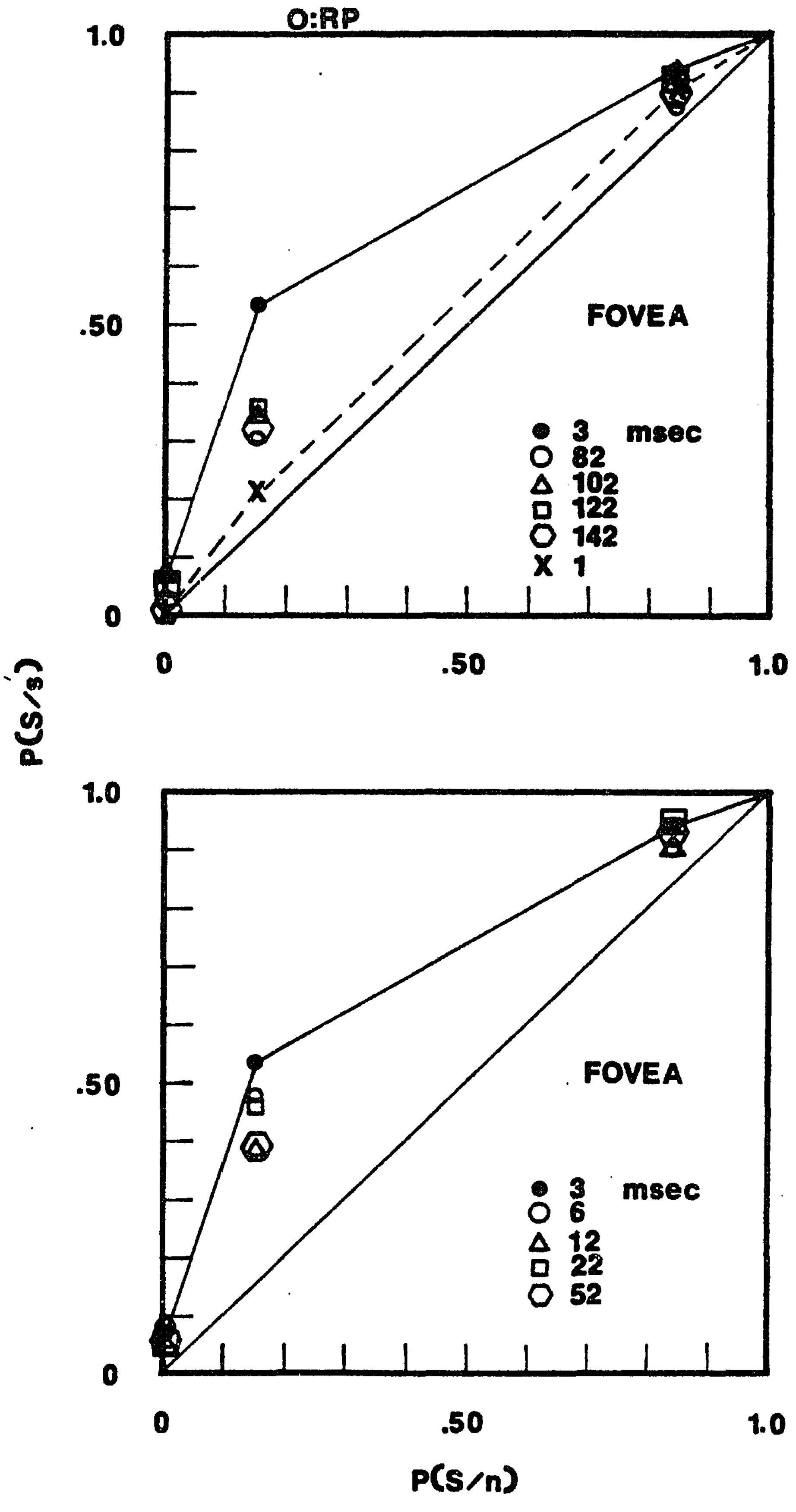

O:RP
1.0
.50
0
0
.50
1.0
7°
● 3 msec
○ 82
△ 102
□ 122
⬡ 142
X 1
P(S/s)
1.0
.50
0
0
.50
1.0
7°
● 3 msec
○ 6
△ 12
□ 22
⬡ 52
P(S/n)

Figure 18. ROC curves constructed from the rating scale data (foveal condition) of Table 6 for _O_:RP (Experiment 1).


O:RP
1.0
.50
0
FOVEA
● 3 msec
○ 82
△ 102
□ 122
⬡ 142
X 1
0
.50
1.0
P(S/s)
1.0
.50
0
FOVEA
● 3 msec
○ 6
△ 12
□ 22
⬡ 52
0
.50
1.0
P(S/n)

lap with those for the half-energy, single-pulse stimulus.

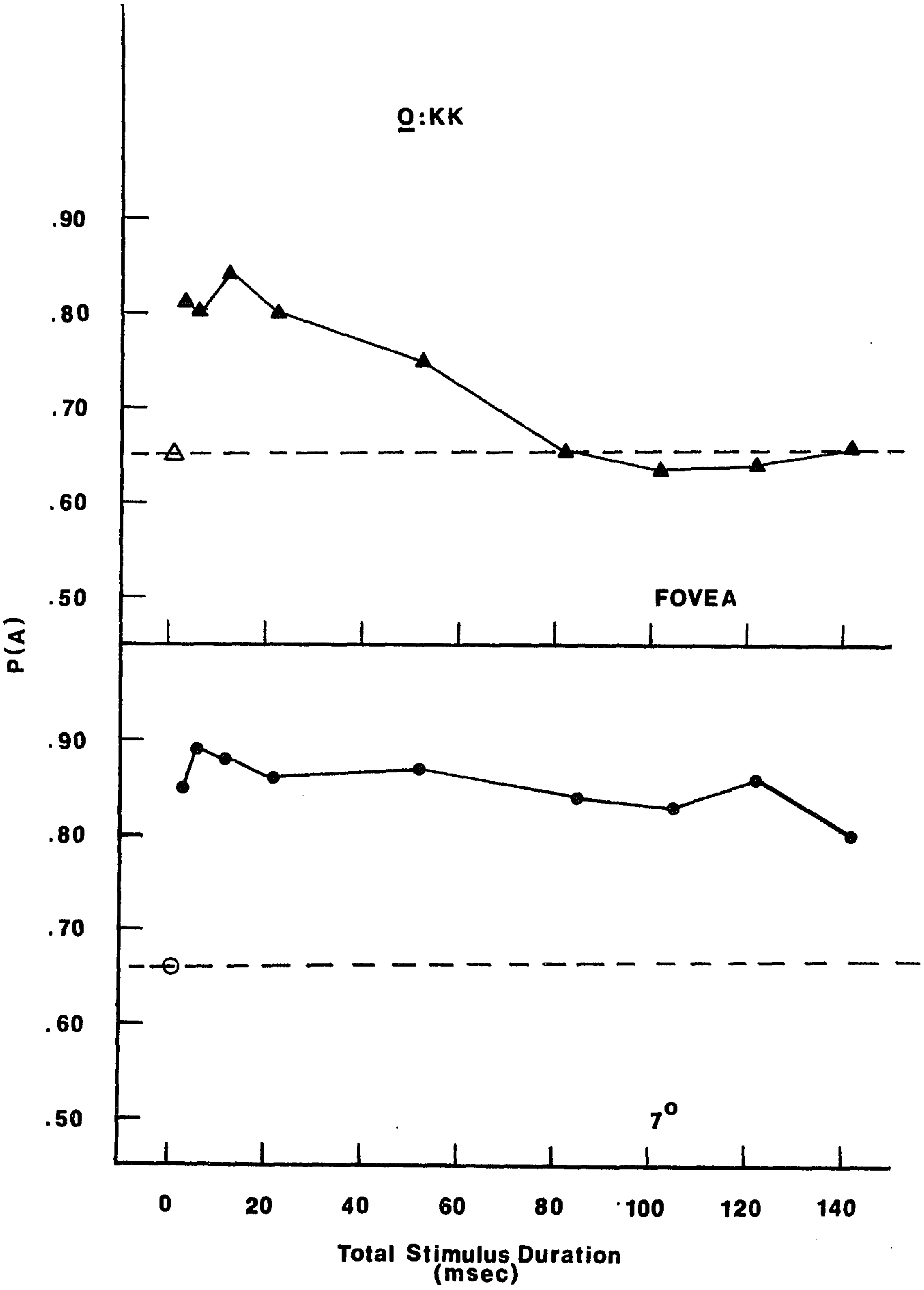
The ROC curves constructed from O:KK's foveal rating scale data indicate that equal-energy double-pulse stimuli were equally detectable (i. e., completely integrated) out to only 22-msec. The ROC curves for double-pulse stimuli longer than 22-msec did not overlap with that for the 3-msec double-pulse stimulus but fell closer to the chance diagonal. This indicates that these stimuli were less detectable than the briefest double-pulse stimulus even though they were of the same total luminous energy. Also, unlike the 7° data, the ROC curve data points for the longer foveal stimuli do overlap with the data points for the single-pulse half-energy stimulus. Thus, these long double-pulse stimuli were no more detectable than a single-pulse stimulus which was of half the total luminous energy.

P(A). The ROC curve data points for each stimulus duration at each retinal locus for each observer were plotted on double-probability paper and straight lines were fitted to the data points using a mutual regression formula (see Grice, 1966, p. 494). In general, the slopes of these lines were less than unity indicating that the variance of the signal distribution was greater than that of the noise distribution (Swets, 1973). When variances are unequal, the signal detection measure P(A) can be used as an alternative to d'. P(A) is the area under the ROC curve and is a distribution-free measure of signal detectability (see Green & Swets, 1966; McNicol, 1972). To compute the area under an ROC curve, the data points of each ROC curve, the lower left origin, and the upper right origin are connected by straight lines (as shown for the 3-msec stimulus in Figure 13). The ROC curve is then divided into trapezoids by dropping perpendicular lines from the data points to the x-axis. The area of the ROC curve can then be calculated using the trapezoidal rule (for details see McNicol, 1972).

Figures 19 (O:KK), 20 (O:BB), and 21 (O:RP) show P(A) graphed as a function of total stimulus duration. The dashed horizontal line indicates the P(A) value for the single-pulse half-energy stimulus. In general, the P(A) data were highly similar to the response frequency data. In the fovea, at the briefer stimulus durations, P(A) remained relatively constant (except for O:BB). At the intermediate durations, P(A) decreased as the total stimulus duration increased. At the longest stimulus durations, P(A) levelled off again and remained relatively constant. This relatively constant level was approximately the same as that for a single-pulse, half-energy stimulus. The P(A) data obtained in the periphery evidenced a relatively long period of complete integration (compared to the foveal data) and just the beginning of what appears to be partial integration.

B, a non-parametric assessment of response bias analo-

Figure 19. P(A) graphed as a function of total stimulus duration in the fovea (top) and at 7° eccentricity (bottom) for O:KK (Experiment 1). The solid symbols indicate the double-pulse stimuli, and the hollow symbol indicates the half-energy, single-pulse stimulus.



O:KK
P(A)
.90
.80
.70
.60
.50
FOVEA
.90
.80
.70
.60
.50
7°
0
20
40
60
80
100
120
140
Total Stimulus Duration (msec)

Figure 20. P(A) graphed as a function of total stimulus duration in the fovea (top) and at 7° eccentricity (bottom) for _O_:BB (Experiment 1). The solid symbols indicate the double-pulse stimuli, and the hollow symbol represents the half-energy, single-pulse stimulus.

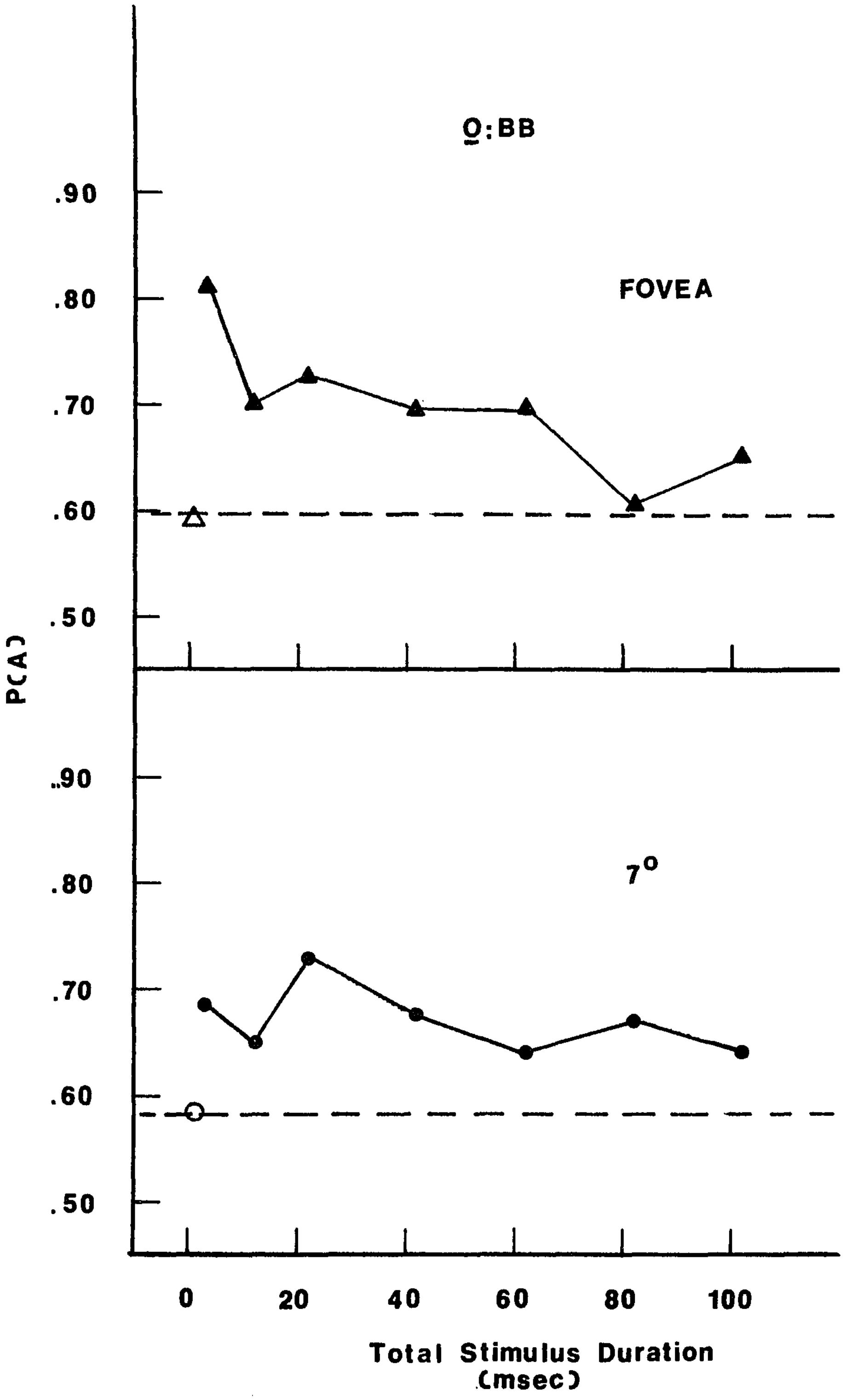
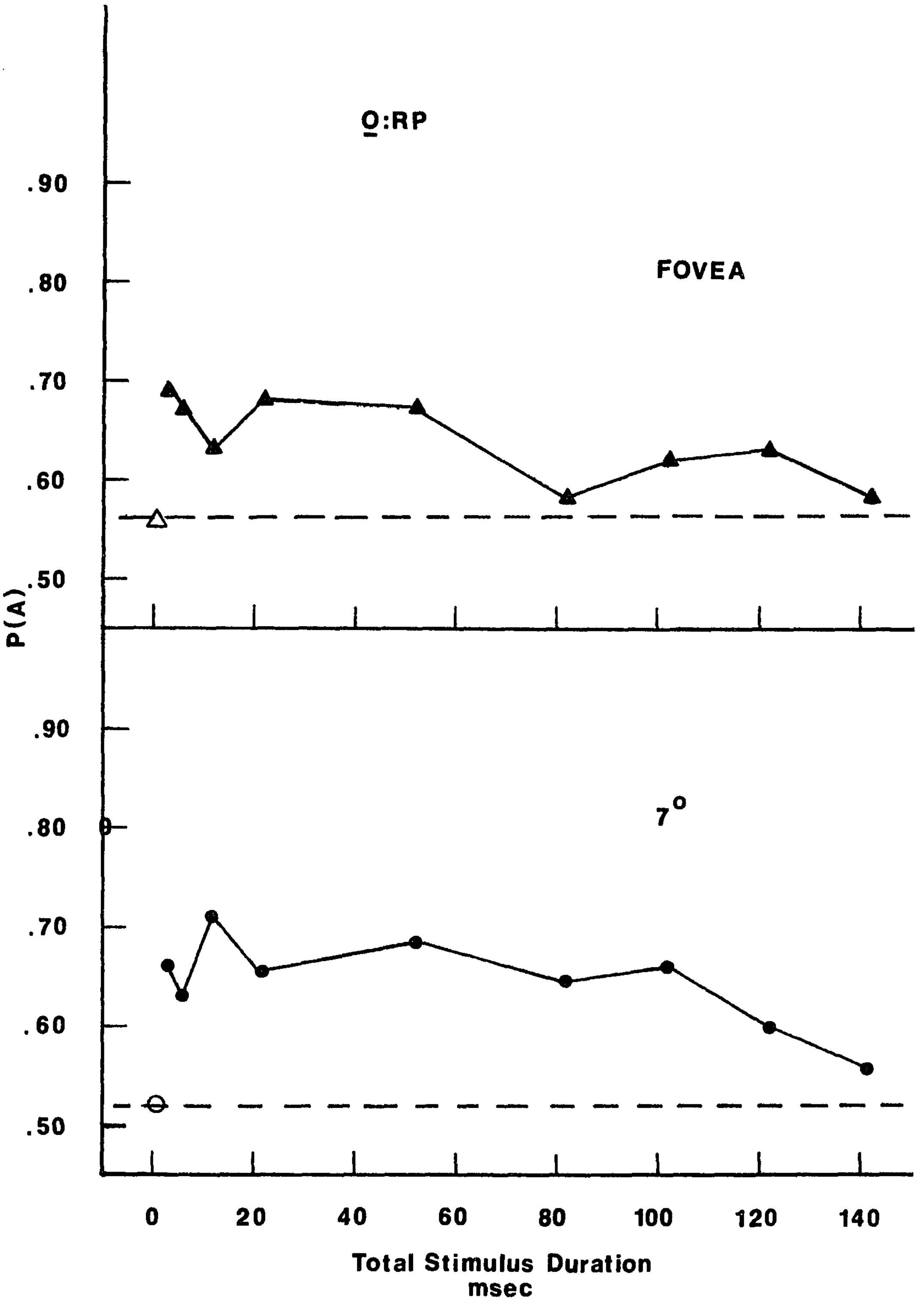

O:BB
FOVEA
7°
P(A)
.90
.80
.70
.60
.50
0
20
40
60
80
100
Total Stimulus Duration
(msec)

Figure 21. P(A) graphed as a function of total stimulus duration in the fovea (top) and at 7° eccentricity (bottom) for O:RP (Experiment 1). The solid symbols indicate the double-pulse stimuli, and the hollow symbol indicates the half-energy, single-pulse stimulus.


O:RP
FOVEA
7°
P(A)
.90
.80
.70
.60
.50
.90
.80
.70
.60
.50
0
20
40
60
80
100
120
140
Total Stimulus Duration
msec

gous to the signal detection measure of criterion β (see McNicol, 1972, p. 123), was calculated from the rating scale data of Tables 4, 5, and 6. Table 3 (p.72) lists these B values for all three observers at each retinal locus. High B values are indicative of a strict criterion, and low B values are indicative of a lax criterion. Inspection of Table 3 shows that the B values and the false alarm rates were highly correlated --- i. e., a high false alarm rate was associated with a low B value and vice versa.

EXPERIMENT 2

The previous experiment made no attempt to control for differences in response criterion across the two retinal loci. Instead, response criterion was monitored at each locus via the number of false alarms, and this information was used to extract a measure of signal detectability which is purported to be independent of the observer's response criterion. Experiment 2 used an equal-performance stimulus paradigm to investigate temporal integration in the fovea and at 7° eccentricity. A forced-choice procedure was used to estimate the threshold luminance for a brief and longer duration double-pulse stimulus at each retinal locus. The forced-choice procedure eliminates possible response criterion differences across retinal loci by requiring the observer to respond on each trial. By comparing the thresholds for a brief and longer duration stimulus, it was possible to determine whether the luminous energy of the second pulse of the longer double-pulse stimulus was completely integrated, partially integrated, or not integrated at all.

Method

Observers and Stimuli

Eight observers participated in Experiment 2. Table 7 lists the brief and longer stimuli on which each subject was tested, the number of test sessions, and whether the participant was tested monocularly or binocularly.

Table 7

Test Conditions for Experiment 2

Observer	Double-Pulse Stimuli (msec) Brief	Double-Pulse Stimuli (msec) Longer	Number of Sessions	Monocular or Binocular
_O_:AL	2.1	82.1	5	Monocular
_O_:CC	2.1	82.1	1	Monocular
_O_:MT	2.1	82.1	1	Monocular
_O_:BB	3.0	102.0	4	Monocular
_O_:KK	3.0	102.0	4	Monocular
_O_:DG	3.0	82.0	3	Binocular
_O_:DG	3.0	102.0	3	Binocular
_O_:SR	3.0	82.0	3	Binocular
_O_:SR	3.0	102.0	3	Binocular
_O_:RP	3.0	82.0	1	Binocular
_O_:RP	3.0	102.0	1	Binocular

Procedure

A three-interval temporal forced-choice adaptive staircase procedure (Bruder, Sutton, Babkoff, Gurland, Yozawitz, & Fleiss, 1975) was used to obtain detection thresholds for brief and longer double-pulse stimuli at each retinal locus.

The forced-choice procedure consists of presenting a light signal in one of three observation intervals. The observer's task is to indicate which one of the three intervals contained the signal. The forced-choice procedure eliminates possible response criterion differences across retinal loci which may be a confounding factor in a foveal-peripheral comparison of visual temporal integration. Another advantage of this method is that the observer need not be dependent upon his memory of the signal from prior trials. This may reduce the influence of a nonsensory memory factor on the subject's performance on a threshold task.

The descending staircase of an "up-down" staircase procedure (see Levitt, 1971) was used in conjunction with the above described forced-choice procedure in order to obtain efficient estimates of thresholds. Campbell (1963, p. 1733) introduced a Block-Up-and-Down Two-Interval Forced-Choice (BUDTIF) procedure, and he obtained data suggesting that "... in spite of the essential naivete and lack of selection of the subjects used, the BUDTIF method quickly provided information comparable in precision and magnitude to that obtained by utilizing the most exhaustive experimental procedure in general use." The BUDTIF procedure was adapted to permit the estimation of the light intensity needed to obtain 67% correct responses (50% correct when adjusted for chance) in the three-interval forced-choice task. The particular details of this procedure were as follows:

(a) On each trial, a signal was presented in one of three observation intervals, and the observer indicated which interval contained the signal.

(b) A constant signal intensity was used during each block of three trials (triads).

(c) The signal level used in a block depended upon the subject's performnace on the prior block. The "stepping rules" for estimating the 67% correct point are as follows:

0 or 1 correct --- increase the level by one step
2 correct --- stay at the same level
3 correct --- decrease the level by one step

(d) A down (descending) staircase was used. The descending staircase was started at a signal level well above the observer's threshold.

(e) Staircases were started using a step size of 0.2 log units filter density, and the step size was reduced to 0.1 log unit when the same signal level was revisited three times.

(f) The staircases for O:AL, O:BB, and O:KK were terminated after 72 trials (24 triads). The staircases for the other observers were terminated after the same signal level was revisited for three blocks (triads) using 0.1 log unit steps. Thus, there was no set number of trials for termination of testing for the latter subjects but a set criterion for termination.

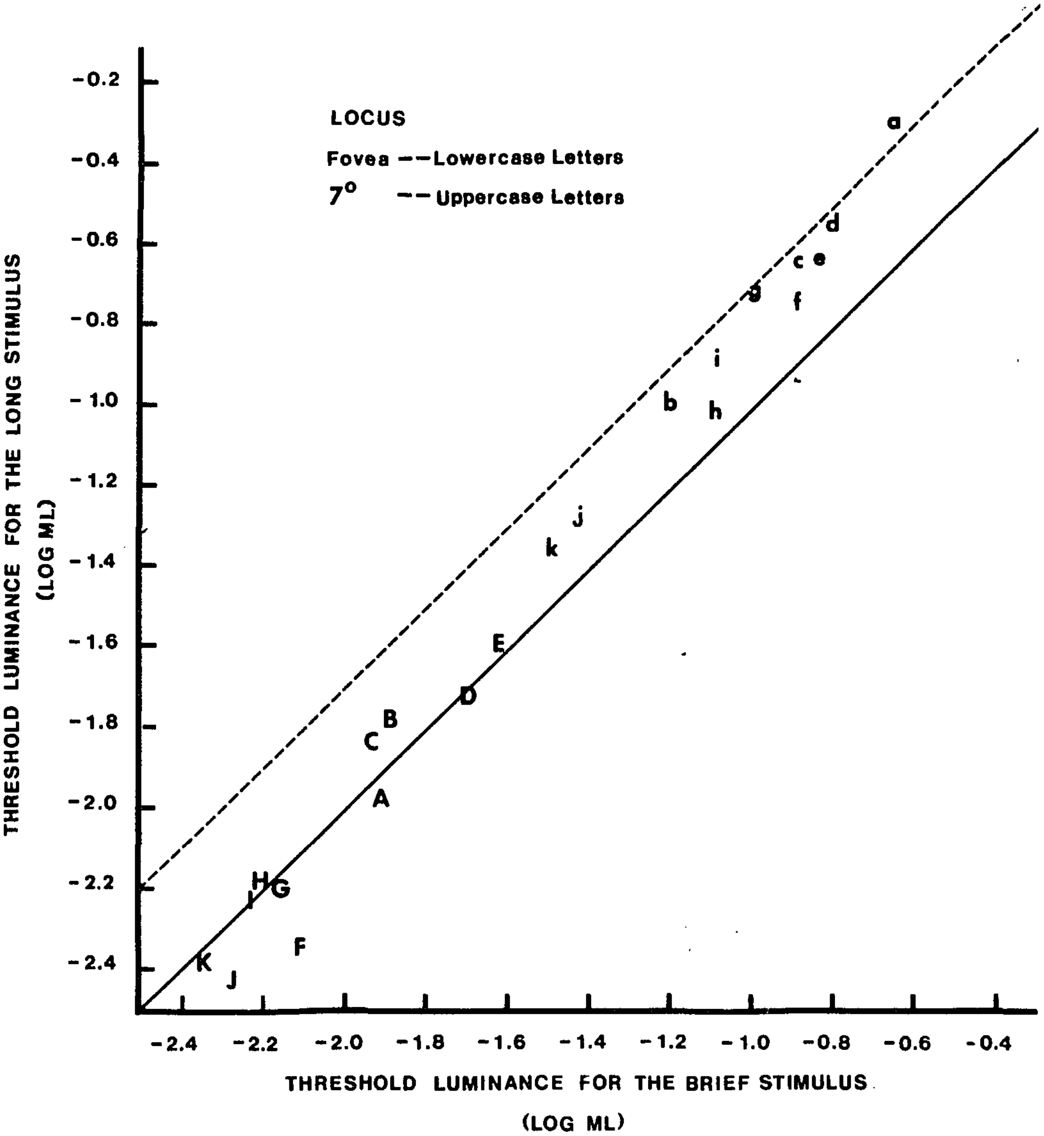
(g) An estimate of the signal level yielding 67% correct responses was given by the median of the signal levels revisited in the descending staircase.

Retinal locus was blocked in an ABBABAAB or AABBBBAA design (see Figure 9). The specific forced-choice procedure used in this experiment permitted the estimate of one threshold per block. Thus, eight thresholds were obtained per session --- four for a brief double-pulse stimulus (two in the fovea and two in the periphery) and four for a longer double-pulse stimulus (two in the fovea and two in the periphery).

Results

The two threshold estimates for the brief stimulus were averaged, and a similar treatment was applied to the two threshold estimates for the longer stimulus. Figure 22 shows the data of all eight observers. Each point represents a comparison of the amount of total luminous energy needed by that observer to yield 67% correct responding in this threshold task for the brief (x-axis) and longer (y-axis) stimulus. Data points that fall on or near the 45° solid diagonal

Figure 22. Log threshold luminance for a brief vs. longer double-pulse stimulus in the fovea and at 7° eccentricity (Experiment 2). Each letter refers to one observer tested on a specific brief and longer stimulus.


LOCUS
Fovea --Lowercase Letters
7° --Uppercase Letters
THRESHOLD LUMINANCE FOR THE LONG STIMULUS (LOG ML)
THRESHOLD LUMINANCE FOR THE BRIEF STIMULUS (LOG ML)
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.4
-1.6
-1.8
-2.0
-2.2
-2.4
-2.4
-2.2
-2.0
-1.8
-1.6
-1.4
-1.2
-1.0
-0.8
-0.6
-0.4
a
d
c
e
g
f
i
b
h
j
k
E
D
B
C
A
H
G
I
F
K
J

line indicate that the brief and longer stimuli were of approximately the same total luminous energy at threshold. This indicates complete or almost complete integration of the luminous energy of the second pulse of the longer double-pulse stimulus. (The second pulse of the briefer stimulus is presumed to be fully-integrated due to its brevity.) Data points that fall above the 45° solid diagonal line indicate that the observer required more luminance (and therefore more total luminous energy) to reach threshold for the longer duration stimulus than for the briefer stimulus. Data points that are approximately 0.3 log units above the solid diagonal line (i. e., approximating the dotted line) indicate no integration of the luminous energy of the second pulse of the double-pulse stimulus or perhaps inhibition (see Appendix IV). Data points 0.2 log units above the solid diagonal but less than 0.3 log units indicate double-pulse stimuli in the region of partial integration and/or probability summation (Clark & Blackwell, 1959; Herrick, 1973b; Tittarelli & Marriott, 1970).

Figure 22 shows that the thresholds obtained at 7° were approximately 1 log unit lower than the thresholds obtained in the fovea (see Bartlett, 1965, p. 167). Also, the peripheral data points fall either on or close to the 45° solid diagonal line indicating that threshold luminance (and therefore total luminous energy) for both the brief and longer duration peripheral stimuli was approximately equal. The longer double-pulse stimuli required 0.04 log units more luminous energy, on the average, to reach threshold than the briefer double-pulse stimuli. Quite different were the foveal data points which fall well above the solid diagonal line. This indicates that for foveal stimuli at threshold, the longer stimuli were of greater total luminous energy than the briefer stimuli. In the fovea, the longer stimuli required 0.19 log units more luminous energy to reach threshold, on the average, than the briefer double-pulse stimuli. To see whether there was a statistically reliable difference in integration between the fovea and periphery, the threshold luminance for the brief stimulus was subtracted from that for the longer stimulus for each observer at each retinal locus. This resulted in two sets of difference scores. If the mean of the difference of these difference scores is reliably greater than zero, then integration in the fovea is different from integration in the periphery at 7°. A t-test for matched pairs yielded the following results: $t(10) = 2.67$, $\underline{p} < .05$, 2-tailed. Thus, the two loci are different with respect to integration, and inspection of the graph shows that the foveal condition displayed less integration than the peripheral condition.

The monocular and binocular conditions yielded similar results except for the finding of somewhat lower bincoular vs. monocular thresholds (see Young & Cole, 1973).

EXPERIMENT 3

Experiment 2 showed that the equal-performance stimulus paradigm in conjunction with a forced-choice adaptive staircase procedure could be used to measure visual temporal integration. In this experiment, the forced-choice procedure was used to estimate thresholds for each of a number of stimulus durations in order to generate integration functions in the fovea and at 7° eccentricity. The dependent variable was luminance. In order to obtain estimates of both the duration of complete integration and partial integration, double-pulse stimuli as long as 402-msec were used.

Method

Stimuli

Thresholds were obtained for several double-pulse stimuli and one single-pulse stimulus. The double-pulse stimuli consisted of two, 1-msec, equal luminance light pulses which were of the following total stimulus durations: 3, 12, 22, 42, 62, 82, 102, 152, 202, and 402-msec. The single-pulse stimulus was 1-msec in duration.

Procedure

The three observers (_O_:SR, _O_:DG, and _O_:RP) were dark adapted and tested binocularly. _O_:SR and _O_:DG were tested on the above listed stimulus durations. _O_:RP was tested on the following stimulus durations: 3, 42, 62, 82, and 102-msec.

A three-interval temporal forced-choice adaptive staircase procedure was used to estimate the luminance necessary to yield 67% correct responding for each stimulus duration at each retinal locus. (The specific details of this procedure can be found in Experiment 2.)

A typical test session had retinal locus counterbalanced in an AABBBBAA design (see Figure 9). Eight thresholds were obtained per session --- four for the 3-msec double-pulse stimulus (two at each retinal locus) and four for one of the other stimulus durations (two at each retinal locus). A flip of a coin determined which retinal locus was tested first, and another flip of a coin determined whether the threshold for the 3-msec stimulus or for the other duration stimulus would be obtained first at that locus. A quasi-randomized procedure determined the order in which the other stimulus durations were to be tested.

Each of the ten other stimulus durations was paired with the 3-msec stimulus three times (i. e., for three sessions). O:SR and O:DG each participated in 30 sessions of testing. Thus, a total of 240 forced-choice thresholds were obtained for each observer --- 60 for the 3-msec stimulus and 6 for each of the other stimulus durations at each retinal locus. O:RP participated in four test sessions, and a total of 32 thresholds were obtained --- eight for the 3-msec stimulus and two each for the other stimulus durations at each retinal locus.

Results

The threshold data were analyzed using difference scores in order to minimize the effects of day to day shifts in threshold. Each session provided two threshold estimates for the 3-msec stimulus and two threshold estimates for another duration stimulus at each retinal locus. The two threshold estimates (in log filter density) for the other stimulus duration were averaged and then subtracted from the average of the two 3-msec thresholds (in log filter density). Thus, each session yielded two difference scores --- one for the fovea and for 7° eccentricity. The difference score indicated the difference in threshold luminance (and therefore total luminous energy) between the 3-msec stimulus and another stimulus.

Figures 23 (O:SR), 24 (O:DG), and 25 (O:RP) show these difference scores graphed as a function of total stimulus duration. The upper graph of each figure displays the foveal data, and the lower graph displays the peripheral data. The solid horizontal line indicates the difference score for a double-pulse stimulus predicted on the basis of probability summation --- i. e., if the two pulses act upon the visual system independently (Clark & Blackwell, 1959; Herrick, 1972; 1974; Tittarelli & Marriott, 1970). The dashed horizontal line indicates complete integration

Figure 23. Difference scores (in log filter density) graphed as a function of total stimulus duration in the fovea and at 7° eccentricity for O:SR (Experiment 3). The solid symbols indicate double-pulse stimuli, and the hollow symbols indicate the single-pulse stimulus.

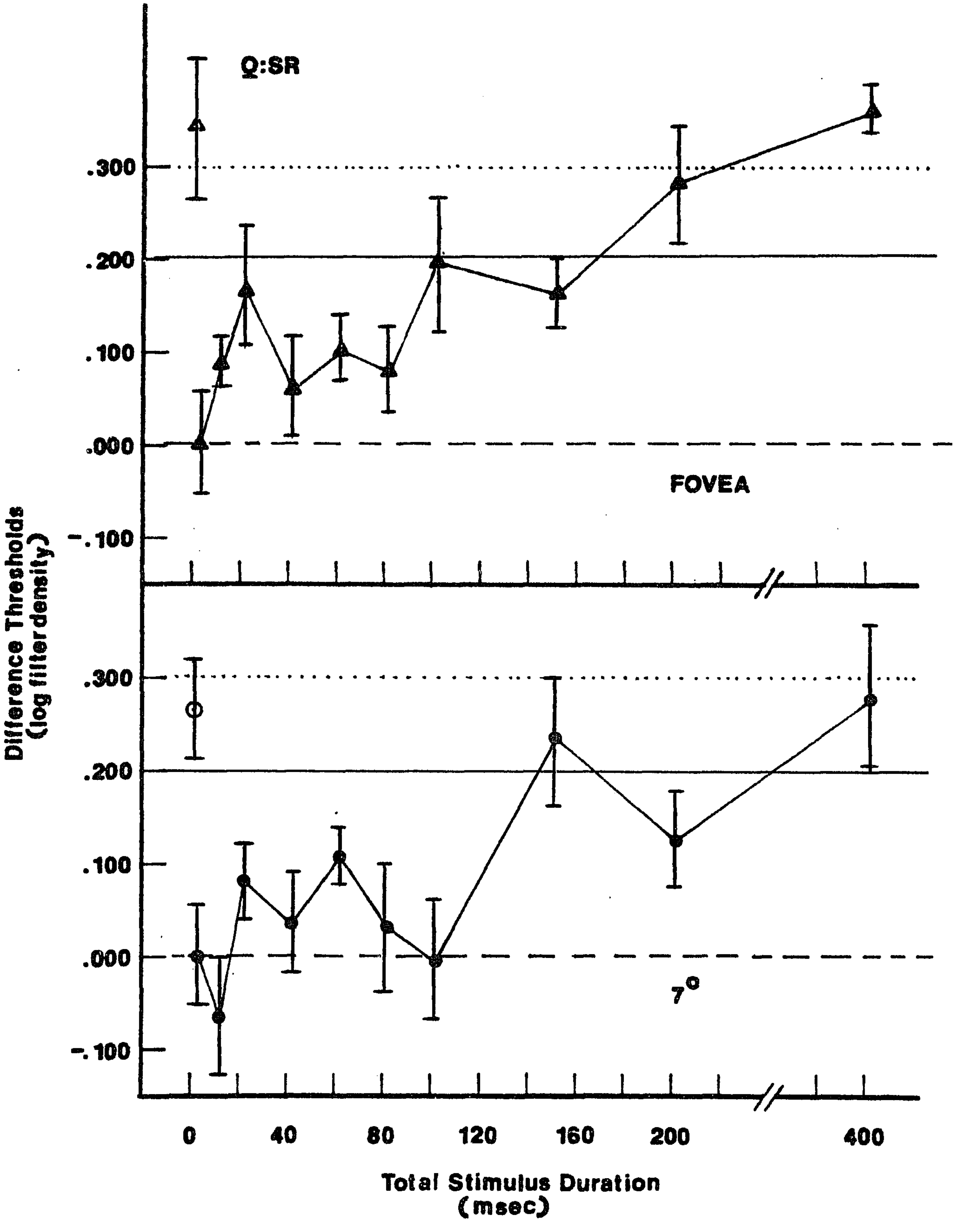

Q:SR
.300
.200
.100
.000
-.100
FOVEA
.300
.200
.100
.000
-.100
7°
Difference Thresholds
(log filter density)
0
40
80
120
160
200
400
Total Stimulus Duration
(msec)

Figure 24. Difference scores (in log filter density) graphed as a function of total stimulus duration in the fovea and at 7° eccentricity for O:DG (Experiment 3). The solid symbols indicate double-pulse stimuli, and the hollow symbols indicate the single-pulse stimulus.

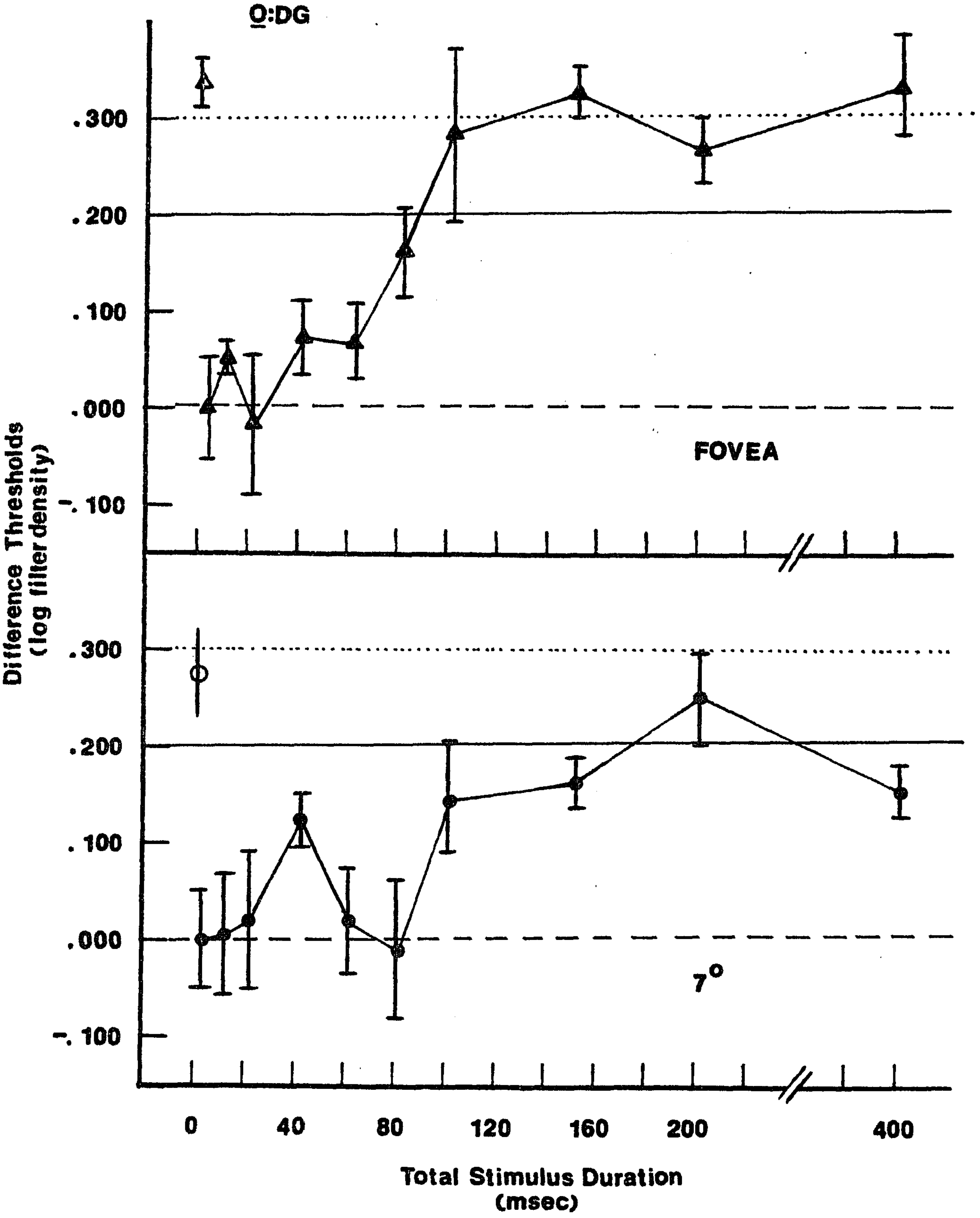
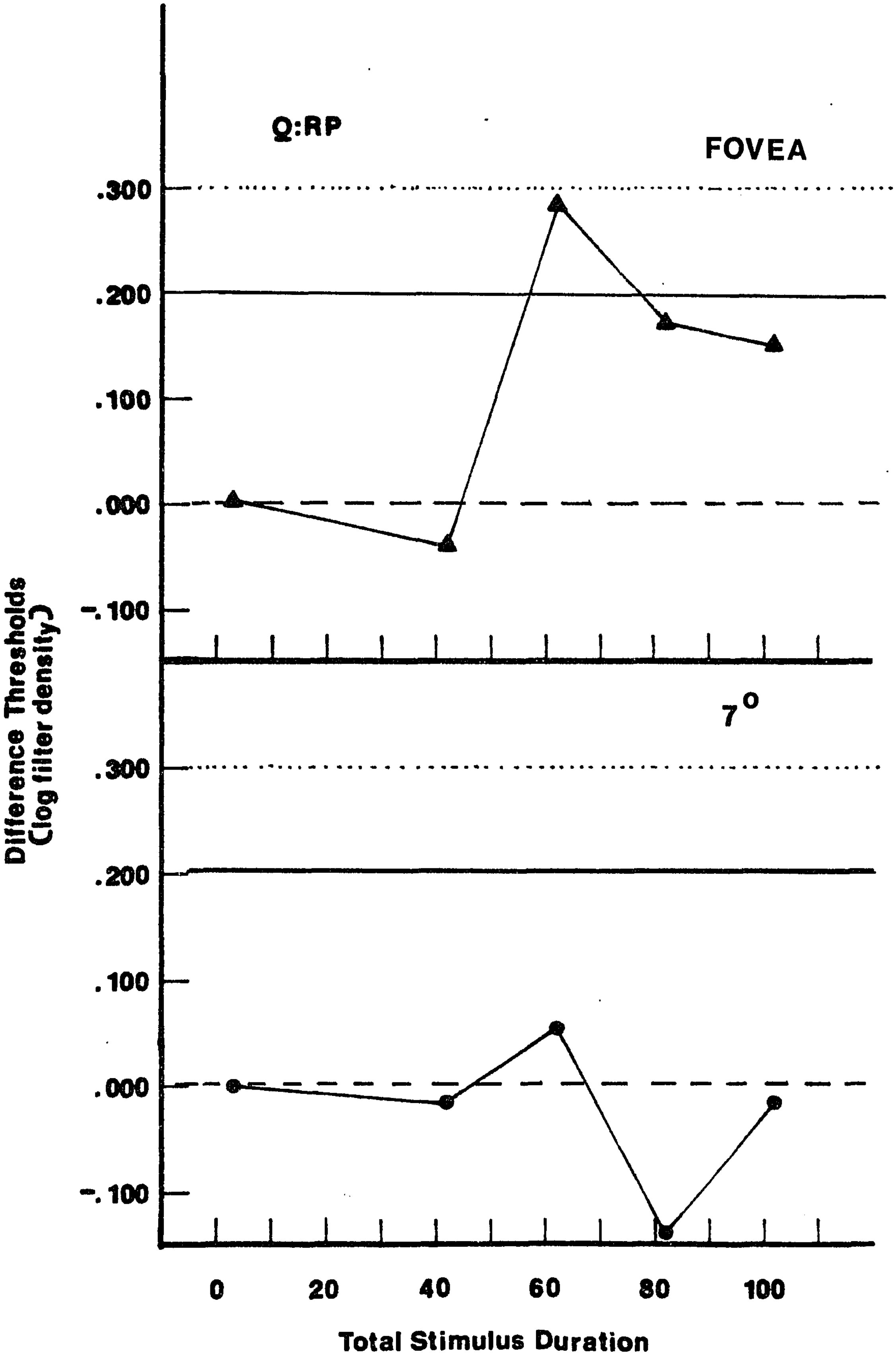

O:DG
FOVEA
7°
.300
.200
.100
.000
-.100
Difference Thresholds
(log filter density)
0
40
80
120
160
200
400
Total Stimulus Duration
(msec)

Figure 25. Difference scores (in log filter density) graphed as a function of total stimulus duration in the fovea and at 7° eccentricity for O:RP (Experiment 3). The solid symbols indicate double-pulse stimuli.


Q:RP
FOVEA
.300
.200
.100
.000
-.100
7°
.300
.200
.100
.000
-.100
Difference Thresholds
(log filter density)
0
20
40
60
80
100
Total Stimulus Duration
(msec)

--- i. e., a longer double-pulse stimulus required the same summated luminous energy as the briefest (3-msec) stimulus. The dotted horizontal line indicates the difference score expected for a 1-msec stimulus. The brackets around each data point indicate ± 1 S. E. M.

The foveal data of O:SR (Figure 23) indicate that even at the briefest stimulus durations, double-pulse stimuli longer than 3-msec required additional luminous energy to reach threshold as compared to the 3-msec stimulus. Thus, no stimulus longer than 3-msec appears to have been completely integrated. The foveal data of O:DG and O:RP (Figures 24 and 25, respectively) indicate that double-pulse stimuli longer than 3-msec (i. e., out to 22 and 42-msec, respectively) were in the region of complete integration. The foveal data of O:SR and O:DG also show that as the total stimulus duration increased, the total luminous energy required at threshold also increased, until, at the longest stimulus durations, the total luminous energy at threshold was approximately 0.3 log units greater (i. e., twice) than that for a 3-msec stimulus. Thus, at threshold, summated luminous energy for the longest duration double-pulse stimuli in the fovea was approximately twice that for the briefest double-pulse stimulus. The threshold luminance for these longer double-pulse stimuli was about the same as that predicted for a 1-msec, single-pulse stimulus (indicated by the dotted horizontal line).

This increase in threshold summated luminous energy was approximately 0.1 log units above that which would have been predicted on the basis of probability summation (indicated by the solid horizontal line). Double-pulse thresholds above that predicted on the basis of probability summation may be indicative of neural inhibition or a period of no integration (see p. 16). O:RP's foveal data also show that double-pulse stimuli longer than 42-msec required additional luminous energy to reach threshold compared to the 3-msec stimulus (see Figure 25).

The 7° data indicate that double-pulse stimuli as long as 102-msec (O:SR and O:RP) and 82-msec (O:DG) required approximately the same total luminous energy to reach threshold as the briefest stimulus. This indicates that a constant visual effect (67% correct responding) was produced by a constant amount of summated luminous energy regardless of how that luminous energy was distributed below the above stated durations. Unlike the foveal data, double-pulse stimuli considerably longer than 3-msec were in the region of complete integration. Two-pulse stimuli longer than 102-msec (O:SR and O:RP) and 82-msec (O:DG) required approximately 0.2 log units more total luminous energy to reach threshold as compared to a fully-integrated stimulus. Thus, threshold luminous energy for these longer stimuli was not twice (i. e., 0.3 log units) that for the briefest double-pulse stimulus nor was the threshold luminance equal to that predicted for a 1-msec stimulus (indicated by the dotted horizontal line), as was found for the foveal data. While the confidence limits for some of the longer duration double-pulse stimuli do overlap with the dotted horizontal line (indicative of no integration or inhibition), these longer duration double-pulse stimuli cluster much more closely around the solid horizontal line, which is indicative of probability summation.

As in Experiment 1, the confidence limits can be used to obtain estimates of the critical duration. Table 2 (p. 71) lists these estimates of the critical duration for the three observers in this experiment and shows that the endpoint of complete integration was always longer in the periphery at 7° eccentricity than in the fovea. Thus, these results are consistent with those of Experiment 1.

CHAPTER VI

DISCUSSION

Taken together, the findings of these three experiments support the hypothesis that visual temporal integration differs as a function of retinal locus. In general, the integration functions generated in the fovea evidenced a relatively brief period of complete integration, a subsequent period of partial integration, and at the longest stimulus durations a period of no integration or inhibition. By comparison, the integration functions generated at 7° eccentricity evidenced a relatively long period of complete integration which was followed by a period of probability summation.

Only two other double-pulse studies have investigated foveal-peripheral differences in temporal integration (Granit & Davis, 1931; Van den Brink & Bouman, 1954), and the results of these studies differ from those of the present research. Granit and Davis stated that their experiments indicated a failure of Bloch's "rule" at the briefest stimulus durations in both the fovea and periphery (15° eccentricity) while Van den Brink and Bouman reported that the critical duration (the endpoint of the period of complete integration) was independent of the retinal locus stimulated. Thus, the present two-pulse study is perhaps the only two-pulse investigation to have demonstrated a foveal-peripheral difference in the period of complete integration.

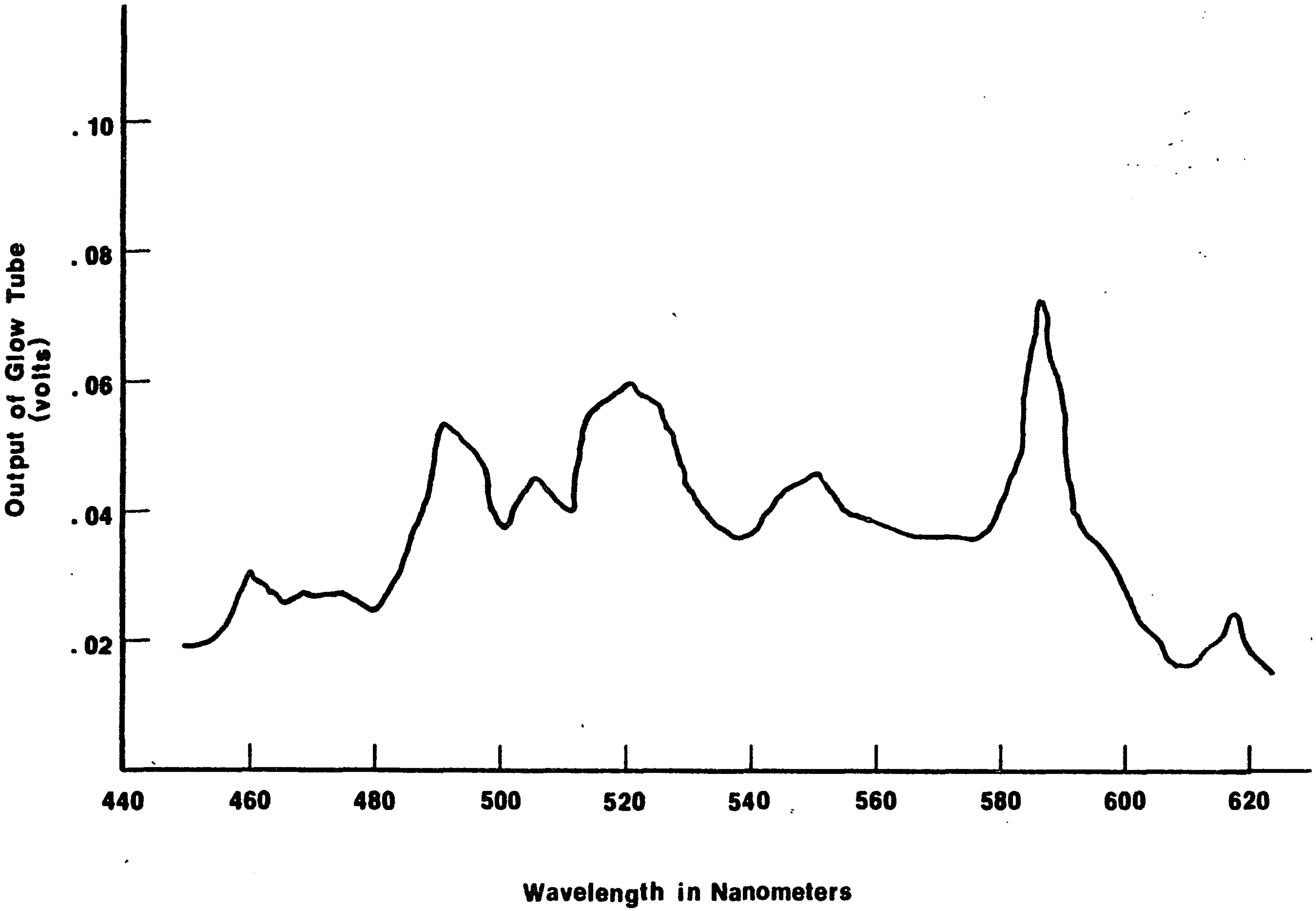
Two single-pulse studies also found no foveal-peripheral difference in the extent of the duration of complete integration (Saunders, 1975; Sperling & Jolliffe, 1965). Moreover, when the data of Sperling and Jolliffe were regraphed in order to permit a comparison of foveal and peripheral integration functions, not only do the peripheral functions not evidence a longer period of complete integration, but the critical duration actually appears to be somewhat longer in the fovea than at 15° eccentricity (see Figure 6). Interestingly, Granit and Davis (1931) also noted that when a period of complete integration was found in their data, it usually appeared for the foveal data.

On the other hand, two other single-pulse investigations of temporal integration did find foveal-peripheral differences (Dannheim & Drance, 1971; Ronchi & Novakova, 1971) in the same way reported here. All the above cited experiments investigated temporal integration in the dark adapted eye; however, Dannheim and Drance generated integration functions at mesopic and photopic background levels of illumination. They found (under photopic conditions) a foveal-peripheral difference in the period of complete integration such that the critical duration increased from 32 msec in the fovea to 100 msec in the periphery (at several retinal eccentricities). Ronchi and Novakova also reported that the critical duration (in the dark adapted eye) increased from central to peripheral vision; however, an inspection of their functions shows that the critical duration did not increase monotonically as a function of eccentricity but changed in a much more complicated fashion. The fact that they obtained one integration function per session per retinal locus per subject limits the confidence one can have in their data, for Berenhaus (Note 1) has shown that the critical duration can vary over a twofold range (e. g., from 58 to 133 msec) upon session to session testing at the same retinal locus. Thus, their experimental design may have confounded temporal factors (e. g., biological variability in the integrative capacity of the visual system over time and/or possible shifts in the subject's response criterion over time) with retinal locus. Perhaps the fact that Ronchi and Novakova found the critical duration not to increase monotonically as a function of retinal eccentricity lends support to this hypothesized confounding. Furthermore, it is also interesting that while Ronchi and Novakova found the critical duration to vary across retinal loci, Dannheim and Drance found the critical duration to remain constant at all peripheral eccentricities tested. Despite the many differences in stimulus conditions and procedures, the present research supports the general findings of Dannheim and Drance and Ronchi and Novakova of a longer critical duration in the periphery than in the fovea and increases the generalizability of their findings to two-pulse work.

What factor(s) are responsible for the differences among the results of the above cited studies and this study? Inspection of Table 1 indicates that no one stimulus condition or procedural variable appears to be able to account for this diversity in results. For example, studies using "larger" stimuli have either found no differences (Saunders, 1975) or differences (Dannheim & Drance, 1971) in temporal integration as a function of retinal locus. Similarly, studies using "smaller" stimuli have also found both no differences (Van den Brink & Bouman, 1954) and differences (Ronchi & Novakova, 1971) in integration. Evidence that these diverse results may be due to some complex interaction among stimulus variables is suggested by the experiment of Sperling and Jolliffe (1965). They found foveal-peripheral differences in partial integration and utilization time for longer wavelength stimuli (650 nm) when using a 45' diameter target but not when using a 4.5' stimulus. Can the foveal-peripheral differences in integration found in this paper also be due to an interaction between stimulus size and wavelength? If the stimulus used in this research was greater than some critical size (e. g., 4.5') and the spectral output of the source was composed of "long" wavelengths (i. e., around 650 nm), then the foveal-peripheral differences in integration found in these experiments could also be the result of an interaction similar to that found by Sperling and Jolliffe.

Figure 26 shows the spectral output of a "typical" glow modulator tube (Sylvania R1131C) as measured by Nilsson

Figure 26. The spectral output of a "typical" glow modulator tube (Sylvania R1131C) as measured by Nilsson (1968).


Output of Glow Tube
(volts)
.10
.08
.06
.04
.02
440
460
480
500
520
540
560
580
600
620
Wavelength in Nanometers

(1968). The spectral output is broad-band and peaks in several ranges; however, it does not appear to be a "long" wavelength stimulus. Further support for the glow modulator tube not being a "long" wavelength source is provided by the threshold values obtained in the fovea (which is composed entirely of cones) and at 7° eccentricity (which is composed of both rods and cones). A "long" wavelength source would have resulted in the thresholds obtained at 7° being approximately equal to the thresholds obtained in the fovea as both rods and cones are equally sensitive to "long" wavelength light (see Cornsweet, 1971). However, Figure 22 clearly shows that the thresholds at 7° eccentricity were approximately 1 log unit less than in the fovea (also see Bartlett, 1965, p. 167). Thus, an interaction between stimulus size and wavelength as found by Sperling and Jolliffe (1965) cannot explain the foveal-peripheral differences obtained in this dissertation.

Perhaps Sperling and Jolliffe's (1965) findings were the result of using two different methods of data collection at the two retinal loci. More specifically, they used the method of constant stimuli in the fovea and the method of limits in the periphery. Also, they collected the foveal data first and then the peripheral data. Thus, it is very possible that their foveal-peripheral integration differences rest upon a foveal-peripheral difference in the observer's response criterion which shifted over time (and therefore over loci).

The criterion that an observer adopts in deciding he has "seen" a stimulus can have a considerable effect on response frequency thresholds or percent "seen" psychophysical functions (Barlow, 1956; Swets, 1964; Swets, Tanner, & Birdsall, 1961). The present study sought to overcome the criterion problem by using signal detection techniques. These techniques yield measures of sensory capacity which are purported to be independent of the observer's response criterion (see Green & Swets, 1966). Thus, Experiment 1 used a yes-no signal detection rating scale procedure to obtain receiver-operating characteristic (ROC) curves from which the signal detection measure of sensitivity P(A) was extracted. Similarly, Experiments 2 and 3 used a criterion-free forced-choice procedure (Blackwell, 1953; Green & Swets, 1966) to measure sensory capacity. These signal detection measures indicated that the critical duration was briefer in the fovea than at 7° eccentricity. Thus, the foveal-peripheral differences in temporal integration obtained in this study were independent of the observer's response criterion.

That the observer's response criterion can indeed differ across retinal loci can be seen by inspecting the false alarm rates and B values at each retinal locus. Although there was no relationship between the magnitude of the false alarm rates (and B values) and the time course of temporal integration in this study, the subject's response criterion is an extraneous variable which can influence threshold estimates, and therefore should be controlled or monitored.

Do signal detectability measures which are purported to be independent of the observer's response criterion yield different estimates of temporal integration from the frequency-of-seeing measures obtained with the more classical psychophysical methods? Experiment 1 indicates that response frequency and P(A) yielded highly comparable measures of integration at each retinal locus regardless of the false alarm rate. Thus, although some studies have shown criterion to have an effect on the time course of integration (Bruder, 1971; Bruder & Kietzman, 1973; Levine & Kietzman, 1972), no differences were found in this study.

Prior foveal-peripheral investigations of temporal integration used either an equal-performance or an equal-energy stimulus paradigm. Could contradictory findings have been due to this difference? For example, Van den Brink and Bouman (1954) used an equal-energy stimulus paradigm and found no loci differences in integration while Dannheim and Drance (1971) used an equal-performance stimulus paradigm and found a foveal-peripheral difference in integration. The present study shows that foveal-peripheral differences were obtained with both stimulus paradigms (see Table 2).

While a good number of electrophysiological investigations of visual temporal integration have been performed (see p. 2), no study, to this author's knowledge, has directly compared temporal integration at two or more retinal loci. The question arises as to what might be the physiologic basis for the differences in integration found in this paper. It is well known that the photoreceptors in the fovea consist almost entirely of cones, and that the proportion of rods to cones increases as the distance from the fovea increases (Osterberg, 1935). Several investigations have suggested that rod and cone responses may have different time courses of recovery (Brown & Watanabe, 1962; Brown, Watanabe, & Murakami, 1965; Kaneko & Yamada, 1972; Tomita, 1970; Whitten & Brown, 1973). Thus, Brown and Watanabe and Brown, Watanabe, and Murakami have provided evidence which shows that early receptor potentials from the predominately rod retina of the night monkey decay much more slowly than early receptor potentials from the macaque monkey whose retina consists of both rods and cones.

A more direct investigation of the time course fo recovery in rods and cones has been performed by recording intracellularly from single photoreceptors in the same organism (Fain & Dowling, 1973). They recorded from both the rods and cones in the retina of the mudpuppy, Necturus maculosus. Their recordings confirm the fact that rod and cone responses differ greatly in their time course of recovery after brief flashes of light in the dark adapted state. Although rod and cone responses resembled one another in many respects (rise times and latencies at all intensities were highly comparable), they did differ strikingly in their time course of recovery. Rod responses returned to their baseline much more slowly than cone resonses regardless of whether the two were compared at the same amplitude of response or at the same intensity.

Thus, several studies have shown that the decay of the rod receptor potential is consistently much slower than that of the cone receptor potential. The rapid recovery of the cone response enables the cones to respond to a subsequent stimulus as if a previous stimulus had not occurred. Thus, in the present two-pulse study of integration, at the longer intervals of darkness, the cones may respond to the first and second light pulses as separate events, and a failure to summate the excitation caused by the two light pulses may result in a below threshold level of responding. However, the rods may not respond to the first and second light pulses as separate events; instead, the excitation caused by the second pulse may summate with the excitation remaining from the first pulse resulting in a threshold level of responding. The longer critical duration of the peripheral retina may have as its physiologic basis the property of a subsequent stimulus being able to add on to the "excitatory remainder" of a previous stimulus.

While caution must be exercised in making inferences from electrophysiological findings on a cellular level to the behavior of an organism, it is highly possible that the different time courses of receptor potentials may determine some of the major functional differences between rods and cones, especially those involved in the dimension of time (Brown, 1974). Thus, these electrophysiological results support the findings of this study. Moreover, those investigations which did not find a foveal-peripheral difference in integration must also find a physiologic basis for their results.

What functional utility might there be of greater temporal integrative capacity in the peripheral retina than in the fovea? Perhaps the fovea of the human eye is primarily a spatial analyzer (Alpern, 1972) while the function of the peripheral retina is primarily to detect stimuli. Detection in the periphery could initiate fixation reflexes which result in the object of interest being projected onto the fovea where its fine detail can be better analyzed. The integration of stimulus energy over time enhances the ability to detect because the more stimulus energy received, the greater is the probablity of detection. Furthermore, detection has survival value since the failure of an organism to detect peripheral stimulation may result in the loss of possibly important information.

APPENDIX I

Light Calibration

The measurement of the glow modulator's light output was accomplished with a Pritchard photometer (Photo Research Corp.) which was checked for accuracy using a 100 footlambert standard of luminance (Gamma Scientific 220-1). A relative calibration was performed before each day's testing so as to maintain a constant "common" level of intensity throughout the study. To accomplish this, the photometer was focused onto the opal diffusing glass of the target which was filled with the light from the glow modulator tube. The voltage reading from the photometer, as displayed on the oscilloscope, was kept at a constant "common" level (approximately 2% error) by adding or eliminating filters to compensate for any change in the output of the glow tube.

APPENDIX II

Filter Calibration

The percentage of light transmitted by the filters employed in this study was measured in the optical system using photomultipliers 1 and 2 (see Figure 7). With the glow modulator tube being pulsed at 15 msec "on"/ 1 sec "off," the difference in voltage measured by the two photomultipliers was read on the oscilloscope using a high-gain differential plug-in unit (Tektronix, Type D). Each photomultiplier was also wired into its own resistance box (Shallcross) which was pre-set at 100 kilo-ohms. Preceding each filter calibration, the voltage difference between the photomultipliers was "nulled" by reducing the resistance of photomultiplier 2 so that its voltage equalled that of photomultiplier 1. The filter to be calibrated was then placed in the light path using one of the filter holders located between photomultipliers 1 and 2. The voltage difference that resulted from the reduced light input and voltage at photomultiplier 2 was then "nulled" by reducing the resistance of photomultiplier 1. The obtained resistance reading (R) when corrected for the input impedance of the oscilloscope's preamplifier gave the percent transmission of the filter:

$$\frac{(10^{-5}) \quad + \quad (0.0125) \quad (10^{-5})}{(1/R)\ (10^{-5}) \quad + \quad (0.0125)\ (10^{-5})} = \text{Percent Transmission}$$

APPENDIX III

Tables 5 (O:BB) and 6 (O:RP) list the frequency (f) of use of each response category and estimates of hit, P(S/s), and false alarm, P(S/n), proportions in the fovea and at 7° eccentricity (Experiment 1).

Table 5

Frequency of Use of Each Response Category and Estimates of Hit, P(S/s), and False Alarm, P(S/n), Proportions in the Fovea and at 7° Eccentricity for O:BB (Experiment 1)

Total Stimulus Duration (msec)		Fovea						7° Eccentricity					
		Yes			No			Yes			No		
		3	2	1	1	2	3	3	2	1	1	2	3
3	f	20	26	42	28	7	5	27	16	33	33	13	6
	P(S/s)	.156	.359	.688	.906	.961.	1.0	.211	.336	.594	.852	.953	1.0
12	f	19	18	33	37	12	10	25	18	27	32	17	9
	P(S/s)	.147	.287	.543	.752	.845	1.0	.195	.336	.547	.797	.930	1.0
22	f	13	12	41	41	11	10	32	18	33	32	8	5
	P(S/s)	.101	.195	.516	.836	.922	1.0	.250	.391	.648	.898	.961	1.0
42	f	17	9	34	44	77	17	22	15	40	31	12	8
	P(S/s)	.133	.203	.469	.812	.867	1.0	.172	.289	.602	.844	.938	1.0
62	f	5	16	41	38	16	12	25	13	30	36	10	14
	P(S/s)	.039	.164	.484	.781	.906	1.0	.195	.297	.531	.812	.891	1.0
82	f	4	6	35	41	20	22	15	20	41	29	19	4
	P(S/s)	.031	.078	.352	.672	.828	1.0	.117	.273	.594	.820	.969	1.0
102	f	8	10	33	45	14	18	11	21	34	42	13	7
	P(S/s)	.062	.141	.398	.750	.859	1.0	.086	.250	.516	.844	.945	1.0
1	f	2	5	27	53	20	20	6	7	39	44	17	15
	P(S/s)	.016	.055	.268	.685	.842	1.0	.047	.102	.406	.750	.883	1.0
Blanks	f	2	6	39	92	46	71	4	12	65	100	44	31
	P(S/n)	.008	.031	.184	.543	.723	1.0	.016	.062	.316	.707	.879	1.0

Table 6

Frequency (f) of Use of Each Response Category and Estimates of Hit, P(S/s), and False Alarm, P(S/n), Proportions in the Fovea and at 7° Eccentricity for O:RP (Experiment 1)

Total Stimulus Duration (msec)		Fovea						7° Eccentricity					
		Yes			No			Yes			No		
		3	2	1	1	2	3	3	2	1	1	2	3
3	f	1	7	52	40	12	0	3	8	43	50	9	0
	P(S/s)	.009	.071	.536	.893	1.0	1.0	.027	.097	.478	.920	1.0	1.0
6	f	4	5	45	47	10	1	4	5	37	57	9	0
	P(S/s)	.036	.080	.482	.902	.991	1.0	.036	.080	.411	.920	1.0	1.0
12	f	1	5	37	59	11	0	5	18	39	41	8	0
	P(S/s)	.009	.053	.381	.903	1.0	1.0	.045	.207	.559	.928	1.0	1.0
22	f	1	5	46	55	6	0	3	13	34	54	8	0
	P(S/s)	.009	.053	.460	.947	1.0	1.0	.027	.143	.446	.929	1.0	1.0
52	f	0	6	44	54	8	0	2	14	40	49	7	8
	P(S/s)	.000	.054	.446	.929	1.0	1.0	.018	.143	.500	.937	1.0	1.0
82	f	0	3	31	63	14	0	2	8	30	56	8	0
	P(S/s)	.000	.027	.306	.874	1.0	1.0	.018	.088	.434	.929	1.0	1.0
102	f	1	6	31	66	8	0	1	9	45	46	11	0
	P(S/s)	.009	.062	.339	.929	1.0	1.0	.009	.089	.491	.902	1.0	1.0
122	f	0	6	34	64	8	0	0	7	36	55	14	0
	P(S/s)	.000	.054	.357	.929	1.0	1.0	.000	.062	.384	.875	1.0	1.0
142	f	0	1	34	60	15	0	0	4	28	67	13	0
	P(S/s)	.000	.009	.318	.864	1.0	1.0	.000	.036	.286	.884	1.0	1.0
1	f	0	0	24	77	11	0	0	1	25	70	16	00
	P(S/s)	.000	.000	.214	.902	1.0	1.0	.000	.009	.232	.857	1.0	1.0
Blanks	f	0	1	51	245	57	0	1	2	46	271	32	0
	P(S/n)	.000	.003	.147	.839	1.0	1.0	.003	.008	.139	.909	1.0	1.0

Reference Note

1. Berenhaus, I. J. Personal communication, February, 1979.

References

Adrian, E. D., & Mathews, R. The action of light on the eye. Part II. The processes involved in retinal excitation. *Journal of Physiology*, 1927, *64*, 279-301.

Alpern, M. Eye movements. In D. Jameson & L. M. Hurvich (Eds.), *Handbook of Sensory Physiology* (Vol. VII/4). New York: Springer-Verlag, 1972.

Alpern, M., & Faris, J. J. Luminance-duration relationship in the electric response of the human retina. *Journal of the Optical Society of America*, 1956, *46*, 845-850.

Baker, F. H., Sanseverino, E. R., Lamarre, Y., & Poggio, G. F. Excitatory responses of geniculate neurons of the cat. *Journal of Neurophysiology*, 1969, *32*, 916-929.

Barlow, H. B. Retinal noise and absolute threshold. *Journal of the Optical Society of America*, 1956, *46*, 634-639.

Barlow, H. B. Temporal and spatial summation in human vision at different background intensities. *Journal of Physiology*, 1958, *141*, 337-350.

Bartlett, N. R. Thresholds as dependent on some energy relations and characteristics of the subject. In C. H. Graham (Ed.), *Vision and visual perception*. New York: John Wiley & Sons, Inc., 1965.

Bartley, S. H. Relation of intensity and duration of brief retinal stimulation by light to the electric response of the optic cortex of the rabbit. *American Journal of Physiology*, 1934, *108*, 397-408.

Battersby, W. S., & Defabaugh, G. L. Neural limitations of visual excitability: After-effects of subliminal stimulation. Vision Research, 1969, 9, 757-768.

Baumgardt, E., & Hillman, B. Duration and size as determinants of peripheral retinal response. Journal of the Optical Society of America, 1961, 51, 340-344.

Beams, J. W. The eye as an integrator of short light flashes. Journal of the Optical Society of America, 1935, 25, 48.

Biersdorf, W. R. Critical duration in visual brightness discrimination for retinal areas of various sizes. Journal of the Optical Society of America, 1955, 45, 920-925.

Biersdorf, W. R. Luminance-duration relationships in the light-adapted electroretinogram. Journal of the Optical Society of America, 1958, 48, 412-417.

Blackwell, H. R. Brightness discrimination data for the specification of quantity of illumination. Illuminating Engineering, 1952, 47, 602-609.

Blackwell, H. R. Psychophysical thresholds: Experimental studies of methods of measurement, Ann Arbor, Michigan: The University of Michigan Press, The Engineering Research Institute, No. 36, 1953.

Blake, R., & Fox, R. The psychophysical inquiry into binocular summation. Perception & Psychophysics, 1973, 14, 161-185.

Blondel, A., & Rey, J. The perception of lights of short duration at their range limits. Transactions of Illuminating Engineering Society, 1912, vii, 625-662.

Bouman, M. A., & Van den Brink, G. On the integrate capacity in time and space of the human peripheral retina. Journal of the Optical Society of America, 1952, 42, 617-620.

Boynton, R. M. The psychophysics of vision. In R. N. Haber (Ed.), Contemporary theory and research in visual perception. New York: Holt, Rinehart and Winston, Inc., 1968.

Boynton, R. M. Discrimination of homogeneous double pulses of light. In D. Jameson & L. M. Hurvich (Eds.), Handbook of Sensory Physiology (Vol. VII/4). New York: Springer-Verlag, 1972.

Brindley, G. S. The Bunsen-Roscoe law for the human eye at very short durations. Journal of Physiology (Lond.), 1952, 118, 135-139.

Brown, K. T. Physiology of the retina. In V. B. Mountcastle (Ed.), Medical Physiology (VI). St. Louis: C. V. Mosby Co., 1974.

Brown, J. L., & Black, J. E. Critical duration for resolution of acuity targets. Vision Research, 1976, 16, 309-315.

Brown, K. T., & Watanabe, K. Isolation and identification of a receptor potential from the pure cone fovea of the monkey retina. Nature, 1962, 196, 547-550.

Brown, K. T., Watanabe, K., & Murakami, M. The early and late receptor potentials of monkey cones and rods. Cold Spring Harbor Symposium of Quantitative Biology, 1965, 30, 457-480.

Bruder, G. E. Temporal integration for three response measures. (Doctoral dissertation, City University of New York, 1971). Ann Arbor, Mich: University Microfilms, 1972, No. 72-5802.

Bruder, G. E., & Kietzman, M. L. Visual temporal integration for threshold, signal detectability, and reaction time measures. Perception & Psychophysics, 1973, 13, 293-300.

Bruder, G. E., Sutton, S., Babkoff, H., Gurland, B. I., Yozawitz, A., & Fleiss, J. L. Auditory signal detectability and facilitation of simple reaction time in psychiatric patients and non-patients. Psychological Medicine, 1975, 5, 260-272.

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

Clark, W. C., & Blackwell, H. R. Relations between visibility thresholds for single and double-pulses. Project Michigan Report 214-3435, 1959.

Cohn, T. E., & Lasley, D. J. Binocular vision: Two possible central interactions between signals from two eyes. Science, 1976, 192, 561-563.

Collins, P. J., Kietzman, M. L. Sutton, S., & Shapiro, E. Visual temporal integration in psychiatric patients. In L. Wynne, R. Cromwell, & S. Matthysse (Eds.), Nature of schizophrenia: New findings and future strategies. New York: Wiley, 1978.

Cornsweet, T. N. *Visual perception*. New York: Academic Press, 1971.

Corso, J. F. A theoretico-historical review of the threshold concept. *Psychological Bulletin*, 1963, *60*, 356-370.

Dannheim, F., & Drance, S. M. Studies of temporal summation of central retinal areas in normal people of all ages. *Ophthalmological Research*, 1971, *2*, 295-303.

Davy, E. The intensity-time relation for multiple flashes of light in the peripheral retina. *Journal of the Optical Society of America*, 1952, *42*, 937-941.

Dawson, W. ., & Harrison, J. M. Bloch's law for brief flashes of large angular subtense. *Perceptual & Motor Skills*, 1973, *36*, 1055-1061.

Egan, J. P., & Clarke, F. R. Psychophysics and signal detection. In J. B. Sidowski (Ed.), *Experimental methods and instrumentation in psychology*. New York: McGraw Hill, 1966.

Engen, T. Psychophysics. I. Discrimination and detection. In J. W. Kling & L. A. Riggs (Eds.), *Woodworth & Schlosberg's experimental psychology* (3rd ed.). New York: Holt, Rinehart and Winston, Inc., 1972.

Eriksen, C. W. Temporal luminance summation effects in backward and forward masking. *Perception & Psychophysics*, 1966, *1*, 87-92.

Eriksen, C. W., Hamlin, R. M., & Breitmeyer, R. G. Temporal factors in visual perception as related to aging. Perception & Psychophysics, 1970, 7, 354-356.

Fain, G. L., & Dowling, J. E. Intracellular recordings from single rods and cones in the mudpuppy retina. Science, 1973, 180, 1178-1181.

Galanter, E. Contemporary psychophysics. In R. Brown, E. Galanter, E. H. Hess, & G. Mandler (Eds.), New directions in psychology. New York: Holt, Rinehart and Winston, 1962.

Gilmer, T. E. The integrating power of the eye for short flashes of light. Journal of the Optical Society of America, 1937, 27, 386-388.

Graham, C. H. Some fundamental data. In C. H. Graham (Ed.), Vision and visual perception. New York: John Wiley & Sons, Inc., 1965.

Graham, C. H., & Kemp, E. H. Brightness discrimination as a function of the duration of the increment in intensity. Journal of General Physiology, 1938, 21, 635-650.

Graham, C. H., & Margaria, R. Area and the intensity-time relation in the peripheral retina. American Journal of Physiology, 1935, 113, 299-305.

Granit, R., & Davis, W. A. Comparative studies on the peripheral and central retina. IV Temporal summation of the subliminal visual stimuli and the time course of the excitatory aftereffect. American Journal of Physiology, 1931, 48, 644-653.

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

Grice, G. R. Dependence of empirical laws upon the source of experimental variation. *Psychological Bulletin*, 1966, *66*, 488-498.

Grossberg, M. The latency of response in relation to Bloch's law at threshold. *Perception & Psychophysics*, 1968, *4*, 229-232.

Grossberg, M. Frequencies and latencies in detecting two-flash stimuli. *Perception & Psychophysics*, 1970, *7*, 377-380.

Hartline, H. K. Intensity and duration in the excitation of single photoreceptor units. *Journal of Cellular and Comparative Physiology*, 1934, *5*, 229-247.

Herrick, R. M. Increment thresholds for two identical flashes. *Journal of the Optical Society of America*, 1972, *62*, 104-110.

Herrick, R. M. Foveal increment thresholds for multiple flashes. *Journal of the Optical Society of America*, 1973, *63*, 870-878. (a)

Herrick, R. M. Increment thresholds for multiple identical flashes in the peripheral retina. *Journal of the Optical Society of America,* 1973, *63*, 1261-1265. (b)

Herrick, R. M. Foveal light detection thresholds with two temporally spaced flashes: A review. *Perception & Psychophysics*, 1974, *15*, 361-367.

Hood, D. C., & Grover, B. G. Temporal summation of light by a vertebrate visual receptor. Science, 184, 1974, 1003-1005.

Ikeda, M. Temporal summation of positive and negative flashes in the visual system. Journal of the Optical Society of America, 1965, 55, 1527-1534.

Johnson, E., & Bartlett, N. Effect of stimulus duration on electrical response of the human retina. Journal of the Optical Society of America, 1956, 46, 167-170.

Kahneman, D., & Norman, J. The time-intensity relation in visual perception as a function of observer's task. Journal of Experimental Psychology, 1964, 68, 215-220.

Kaneko, A., & Yamade, M. S-Potentials in the dark-adapted retina of the carp. Journal of Physiology, 1972, 227, 261-273.

Karn, H. W. Area and the intensity-time relation in the fovea. Journal of General Psychology, 1936, 14, 360-369.

Keller, M. The relation between the critical duration and intensity in brightness discrimination. Journal of Experimental Psychology, 1941, 28, 407-418.

Kietzman, M. L. Response variables in suprathreshold studies of stimulus reciprocity. Paper presented at the American Psychological Association, San Fransisco, August, 1968.

Kietzman, M. L., & Gillam, B. J. Visual temporal integration and simple reaction time. Perception & Psychophysics, 1972, 11, 333-340.

Levick, W. R., & Zacks, J. L. Response of cat retinal ganglion cells to brief flashes of light. Journal of Physiology, 1970, 206, 677-700.

Levine, R. R., & Kietzman, M. L. Simple visual reaction time measurement of temporal integration: The interaction between sensory and criterion factors. Paper presented at the meeting of the Eastern Psychological Association, Boston, April, 1972.

Levitt, H. Transformed up-down methods in psychoacoustics. Journal of the Acoustical Society of America, 1971, 49, 467-477.

Long, G. E. The effect of duration of onset and cessation of light flash on the intensity-time relation in the peripheral retina. Journal of the Optical Society of America, 1951, 41, 743-747.

McNicol, D. A primer of signal detection theory. London: George Allen & Unwin LTD, 1972.

Matin, L. Use of the glow modulator tube for visual research. American Journal of Psychology, 1964, 77, 650-651.

Meijer, J. G., Van der Wildt, G. J., & Van den Brink, G. Twin-flash response as a function of flash diameter. Vision Research, 1978, 18, 1111-1116.

Nilsson, T. H. Two-pulse difference thresholds and their implications about sensory processes which limit visual temporal acuity. Unpublished masters thesis, University of Alberta, 1968.

Nolan, G. F. On the functional relation between luminous energy target size and duration for foveal stimuli. *Journal of the Optical Society of America*, 1957, *47*, 394-397.

Osterberg, G. Topography of the layer of rods and cones in the human retina. *Acta Ophthalmologica*, 1935, *6*, 1-102.

Piéron, H. *The sensations: Their functions, processes, and mechanisms*. Paris: Editions Gallimard, 1945. Translated by M. H. Pirenne & B. C. Abbott. New Haven: Yale University Press, 1952.

Pirenne, M. H. Binocular and uniocular thresholds of vision. *Nature*, 1943, *152*, 698-699.

Pirenne, M. H. *Vision and the eye* (2nd ed.). London: Associated Book Publishers, 1967.

Pulling, N. H. Visual reciprocity failure for short exposures. Unpublished Ph. D. thesis, Harvard University, 1951.

Raab, D., & Febrer, E. Supplementary report: The effect of stimulus duration and luminance on visual reaction time. *Journal of Experimental Psychology*, 1962, *64*, 326-327.

Rashbass, C. The visibility of transient changes in luminance. *Journal of Physiology* (Lond.), 1970, *210*, 165-186.

Ronchi, L. Absolute threshold before and after correction of oblique-ray astigmatism. *Journal of the Optical Society of America*, 1971, *61*, 1705-1709.

Ronchi, L. Wavelength dependence of the luminance-time relationship at absolute threshold. Further experimental evidence. *Pubblicazioni Dell' Istituto Nazionali Di Ottica*. Serie II, N. 1592, 1974, *6*, 945-956.

Ronchi, L., & Novakova, O. Luminance-time relation at various eccentricities: individual differences. *Journal of the Optical Society of America*, 1971, *61*, 115-118.

Rouse, R. O. Color and the intensity-time relation. *Journal of the Optical Society of America*, 1952, *42*, 626-630.

Saunders, R. McD. The critical duration of temporal summation in the human central fovea. *Vision Research*, 1975, *15*, 699-703.

Sperling, H. G., & Jolliffe, C. L. Intensity-time relationship at threshold for spectral stimuli in human vision. *Journal of the Optical Society of America*, 1965, *55*, 191-199.

Stenson, H. H. A signal detection analysis of temporal summation and masking in the visual system. Doctoral Dissertation, University of Illinois, 1965.

Swets, J. A. Is there a sensory threshold? *Science*, 1961, *134*, 168-177.

Swets, J. A. (Ed.). *Signal detection and recognition by human observers.* New York: Wiley, 1964.

Swets, J. A. The relative operating characteristic in psychology. *Science*, 1973, *182*, 990-1000.

Swets, J. A., Tanner, W. P. Jr., & Birdsall, T. G. Decision processes in perception. Psychological Review, 1961, 68, 301-340.

Tanner, W. P. Jr., & Swets, J. A. A decision-making theory of visual detection. Psychological Review, 1954, 61, 401-409.

Tayal, O. P. Absolute and difference limen in visual perception as a function of the duration of stimulus pulse. Perception & Psychophysics, 1978, 24, 40-48.

Thorn, F., & Boynton, R. M. Human binocular summation at absolute threshold. Vision Research, 1974, 14, 445-458.

Tittarelli, R., & Marriott, F. H. C. Temporal summation in foveal vision. Vision Research, 1970, 10, 1477-1481.

Tomita, T. Electrical activity of vertebrate photoreceptors. Quarterly Review of Biophysics, 1970, 3, 179-222.

Uetsuki, T., & Ikeda, M. Study of temporal visual response by the summation index. Journal of the Optical Society of America, 1970, 60, 377-381.

Van den Brink, G., & Bouman, M. A. Variation of integrative actions in the retinal system: An adaptational phenomenon. Journal of the Optical Society of America, 1954, 44, 616-620.

Wasserman, G. S., & Kong, K. L. Temporal summation in a photoreceptor: Dependence on response magnitude. Vision Research, 1975, 15, 1297-1299.

Wicke, J. D., Donchin, E., & Lindsley, D. B. Visual evoked potentials as a function of flash luminance and duration. *Science*, 1964, *146*, 83-85.

Whitten, D. N., & Brown, K. T. The time courses of late receptor potentials from monkey cones and rods. *Vision Research*, 1973, *13*, 107-135.

Wilson, M. E. Spatial and temporal summation in impaired regions of the visual field. *Journal of Physiology* (Lond.), 1967, *189*, 189-208.

Young, R. S. L., & Cole, R. E. Luminance-duration threshold relationship under monocular and binocular viewing conditions. *Journal of the Optical Society of America*, 1973, *63*, 1014-1015.

Zacks, J. L. Responses of cat retinal ganglion cells to brief light flashes. Unpublished masters thesis, University of California, Berkeley, 1967.

Zacks, J. L. Temporal summation phenomena at threshold: Their relation to visual mechanisms. *Science*, 1970, *170*, 197-199.