

72-5802

BRUDER, Gerard E., 1942-
THE TEMPORAL INTEGRATION OF LUMINOUS ENERGY FOR
RESPONSE FREQUENCY, RESPONSE LATENCY, AND
SIGNAL DETECTABILITY.

The City University of New York, Ph.D., 1971
Psychology, experimental

University Microfilms, A XEROX Company, Ann Arbor, Michigan

**THE TEMPORAL INTEGRATION OF LUMINOUS ENERGY FOR RESPONSE
FREQUENCY, RESPONSE LATENCY, AND SIGNAL DETECTABILITY**

by

GERARD E. BRUDER

**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.**

1971

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.

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Abstract

THE TEMPORAL INTEGRATION OF LUMINOUS ENERGY FOR RESPONSE
FREQUENCY, RESPONSE LATENCY, AND SIGNAL DETECTABILITY

by

Gerard E. Bruder

Adviser: Professor Mitchell L. Kietzman

Psychophysical studies of temporal integration have demonstrated a reciprocal relation between the luminance and duration needed to obtain a constant threshold response (referred to as Bloch's law) and the longest duration producing reciprocity has been called the critical duration. Most threshold studies of temporal integration have been concerned with the influence of a variety of stimulus variables on the luminance-duration relation. The findings of some physiological and behavioral studies indicate that temporal integration may also be influenced by response variables--e.g. the type of response measure. In particular, some studies have presented evidence suggesting differences in the luminance-duration relations for psychophysical threshold measures and simple reaction time (RT).

This study further investigated the influence of the response measure on temporal integration. A new stimulus paradigm was used which allowed the measurement and comparison of the characteristics of temporal integration for three response measures: (1) the frequency of detection responses; (2) the latency of the detection responses;

(3) the signal detectability as measured using confidence ratings. All three response measures were obtained for the same \underline{O} s, on the same trials, in a task involving the detection of a light pulse. The stimulus manipulations consisted of varying the luminous energy of the light pulse in two different ways: (1) by varying the luminance with duration fixed at 1 msec.; (2) by varying the duration with luminance fixed. The luminance-varied and duration-varied conditions spanned the same luminous energy levels, which yielded from 20-95% detection responses. A Maxwellian view optical system presented orange (581 nm) light pulses of 50' visual angle to the \underline{O} 's dark-adapted fovea. The \underline{O} was instructed that a light pulse would be presented on only 75% of the trials. The other 25% of the trials were blanks. The \underline{O} 's task was to lift his finger from a key as fast as possible when he saw the light flash. He also rated the confidence in his detection response. Each of two \underline{O} s received a total of 9,600 trials--360 trials per stimulus condition and 2,400 blank trials.

The characteristics of temporal integration evident in the response frequency data agreed with those found in previous threshold studies using similar stimulus conditions. The response frequency showed luminance-duration reciprocity up to a critical duration in the region of 45-65 msec. This was followed by a period of partial integration lasting up to as long as 150-200 msec. after stimulus onset.

Overall, the signal detectability measure showed the same characteristics of temporal integration as found for the response frequency measure. The receiver operating characteristic (ROC) curves obeyed Bloch's law, in that, equal-energy stimuli shorter than about 50 msec. yielded almost identical ROC curves. The ROC curves were asymmetrical in form, with slopes of less than 1.0 on double-probability paper.

Luminance-duration reciprocity and partial integration were demonstrated in the RT data. However, the critical duration demonstrated in the median RTs--about

25-30 msec.-- was shorter than the critical durations for the response frequency and signal detectability. The duration up to which partial integration was in evidence in the median RTs--65-95 msec.--was likewise shorter. Moreover, luminance-duration reciprocity was also demonstrated in the RT semi-interquartile ranges up to an even longer critical duration than obtained for the median RT.

Thus, although the luminance-duration relations for the response frequency, signal detectability and median RT measures were similar in form, shorter characteristics of temporal integration were found for the median RT measure.

ACKNOWLEDGMENTS

I would first like to thank my sponsor, Mitchell Kietzman, who is most responsible for the completion of this study. In addition to introducing me to the problem investigated in this study, he supplied the apparatus, financial assistance, and valuable advice. A number of others also assisted me in this work: Eleanor Shapiro and Stuart Steinhauer assisted in the testing; Walter Chalupa served as an observer; Ray Simon and Reinhold Brenner assisted with the apparatus; Jennie Gilliland and Naomi Stolper did the typing.

I also benefitted from the advice and criticism of Harvey Babkoff, William Battersby, Crawford Clark, Patrick Collins, Ruth Rutschmann, and Samuel Sutton.

I would also like to thank my wife, Helen, and my family for being both helpful and understanding.

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CHAPTER I

General Problem and Purpose of This Investigation

Psychophysics has been described as the study of the relations between stimulus manipulations and their effects on an observer's responses (e.g. Boynton, 1968; Graham, 1958). In establishing these stimulus-response relations, it has been traditional to stress the control, manipulation, and measurement of the stimulus with much less attention given to the response. A frequently used procedure in visual psychophysics limits the observer (O) to a simple "yes" vs. "no" response and measures the luminance necessary to obtain 50% "yes" responses (threshold) to each of the stimulus conditions. Note that this procedure calls for the presentation of the results in terms of the stimulus luminance necessary to produce a constant response. Usually no effort is made to record other aspects of the O's responses, e.g. the latency of his responses. Nor has much attention been directed to comparing the results found using threshold measures to those which may be found using other response measures, e.g. signal detectability measures (see Green & Swets, 1966).

From the earliest psychophysical studies of the temporal integration of luminous energy, threshold measures (both absolute and difference thresholds) have predominantly served as the response index. These studies have established that increases in the duration of the stimulus allow for an equivalent decrease in the luminance

needed to reach threshold. This reciprocal relation between the luminance and duration of a visual stimulus for a constant threshold response (referred to as Bloch's law) holds for only relatively short durations and the longest duration producing reciprocity is called the critical duration. Increases in duration beyond this critical duration may have only a partial effect (referred to as partial integration) or may have no effect at all on the response measure. Most studies of temporal integration using threshold measures have looked at the influence of a variety of stimulus variables on the luminance-duration relation. It has been shown that the critical duration is highly dependent on a number of stimulus variables including--background luminance (Barlow, 1958; Biersdorf, 1955), stimulus area (Graham & Margaria, 1935; Karn, 1936), and wavelength (Sperling & Jolliffe, 1965). Psychophysical studies have, until recently, shown little or no interest in the influence of response variables--e.g. the type of response measure--on the luminance-duration relation (Kahneman & Norman, 1964; Kietzman, 1968).

Electrophysiological studies of temporal integration have used a number of different response measures--e.g. response frequency, amplitude, latency. Some of the earliest electrophysiological studies (Adrian & Matthews, 1927; Bartley, 1934; Hartline, 1934) used latency measures of temporal integration. In his classic study, Hartline reported both the frequency and latency of responses of single optic nerve fibres of the Limulus to stimuli of varying luminances and durations. His data are suggestive of a shorter critical duration for the latency than for the frequency measures. Recent studies recording responses from ganglion cells of cats (Levick & Zacks, 1970; Zacks, 1967a) and from cells in the lateral geniculate of cats (Baker, Sanseverino, Lamarre, & Poggio, 1969) give similar evidence of shorter critical

durations for their latency than for their frequency measures. In man, recordings of electroretinograms (Alpern & Farris, 1956; Biersdorf, 1958; Johnson & Bartlett, 1956) and cortical evoked potentials from the scalp (Wicke, Donchin, & Lindsley, 1964) have shown differences in luminance-duration relation for their amplitude and latency measures.

In recent behavioral studies there have also been some suggestions of a difference in the luminance-duration relation for response latency--i.e. simple reaction time (RT)--and psychophysical threshold measures (Grossberg, 1968, 1970; Raab & Fehrer, 1962). Grossberg studied this problem directly by measuring both the frequency and latency of an O's "yes" responses in a detection task and concluded that the frequency of detection responses showed reciprocity in accordance with Bloch's law while the median RT did not. However, an analysis of Grossberg's RT data for threshold level stimuli shorter than about 20 msec. revealed less deviation from Bloch's law than implied in his general conclusion. Moreover, studies using suprathreshold stimuli (Kaswan & Young, 1965; Kietzman & Gillam, in press; Lewis, 1964; Pease, 1971) have demonstrated luminance-duration reciprocity for RT at very short durations. Thus, the question still remains as to whether or not Bloch's law holds for RTs to very short duration threshold level stimuli. If Bloch's law can be shown to apply to RTs to threshold level stimuli, the next question is how the critical duration for RT compares with the critical duration for response frequency or threshold measures. Raab and Fehrer (1962) suggest that the critical duration for RT is shorter than that for threshold measures. Although very short critical durations have generally been reported in RT studies of temporal integration (e.g. Kaswan & Young, 1965; Kietzman & Gillam, in press; Pease, 1971), these critical durations

were obtained at suprathreshold levels. More information is needed on how the critical duration for RTs to threshold level stimuli compares with the critical duration for threshold measures to these same stimuli.

How do the luminance-duration relations for RT and threshold measures compare at stimulus durations longer than the critical duration? Kietzman & Gillam (in press) have indicated that the critical duration for RT is followed by a period of partial integration during which reciprocity fails and yet increases in stimulus duration are still effective in reducing RT. Partial integration is evident not only in their data, but also in the data of other RT studies of temporal integration (e.g. Grossberg, 1968, 1970; Raab & Fehrer, 1962; Pease, 1971). Although partial integration has similarly been found using threshold measures (e.g. Graham & Margaria, 1935; Sperling & Jolliffe, 1965), it is possible that there are differences in the periods over which partial integration may be demonstrated for RT and threshold measures.

The criterion that the O adopts in deciding to respond has been shown to influence both thresholds (Barlow, 1956; Swets, Tanner, & Birdsall, 1961), and RTs (Greenbaum, 1963; Grice, 1968; Murray, 1970). What effect does the criterion have on threshold and RT measures of temporal integration? Do signal detectability measures (see Green & Swets, 1966) that are believed to be independent of the criterion yield different estimates of temporal integration than the threshold and RT measures? Although a few studies have used signal detectability measures to study temporal integration (Clark & Blackwell, 1959; Kietzman, 1968; Stenson, 1965), more information on the role of the criterion and response measure in temporal integration investigations is needed to answer the above questions.

Previous studies, taken together, suggest that the characteristics of temporal integration may differ for different response measures. The major purpose of the present study was, therefore, to measure and compare the characteristics of temporal integration for threshold, RT, and signal detectability measures obtained by the same Os, in the same task, and under identical stimulus conditions. Specifically, three response measures were recorded to light pulses: (1) the frequency of detection responses; (2) the latency of these responses; (3) the O's confidence in these responses. The confidence ratings were used to obtain receiver operating characteristic (ROC) curves and signal detectability measures. The stimulus manipulations employed allowed the comparison across these response measures, not only of luminance-duration reciprocity and its termination--the critical duration, but also of the period of partial integration.

CHAPTER II

Related Literature

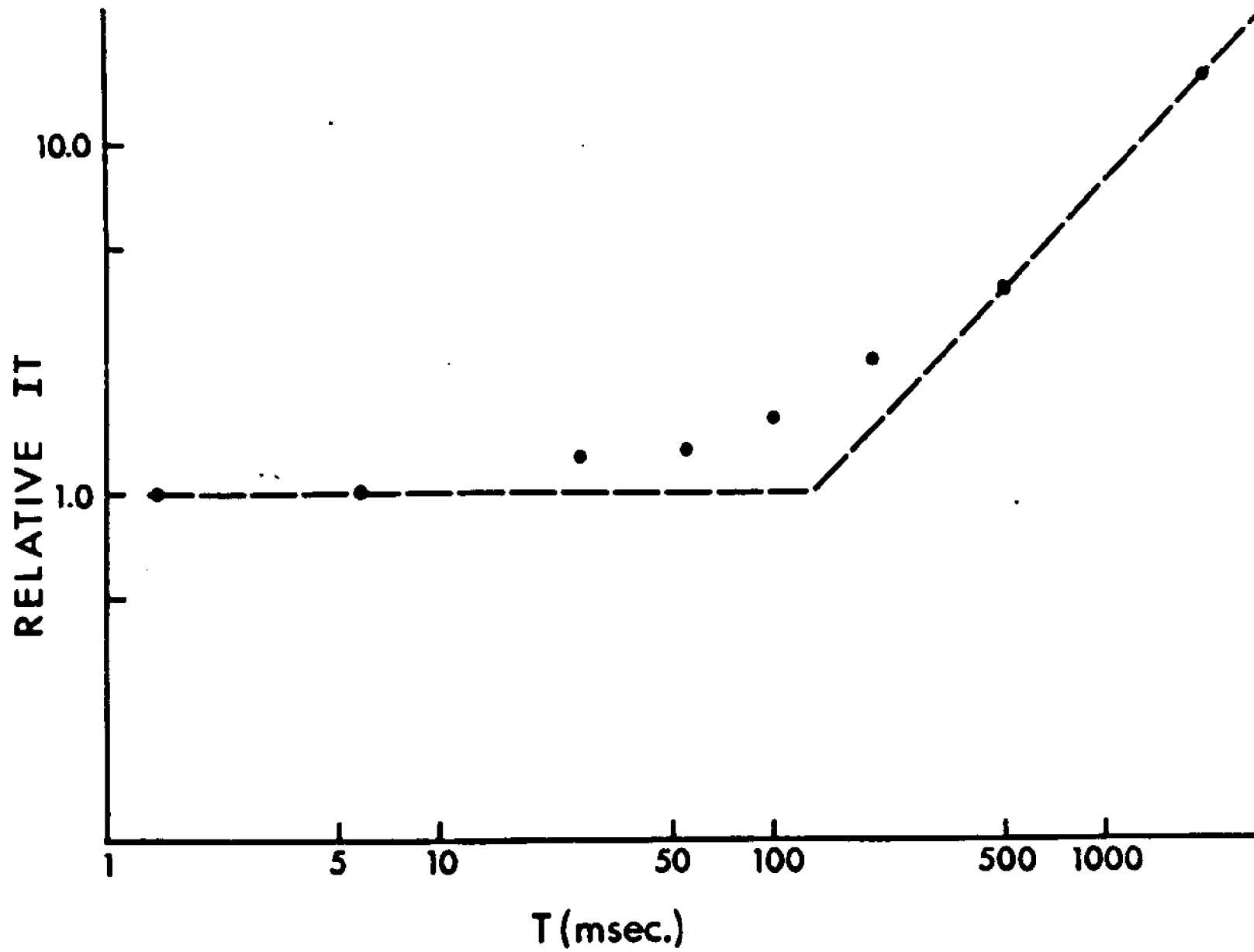
The next three sections of this study review the relevant studies of temporal integration, which have used threshold, RT, or signal detection measures.

Threshold studies of temporal integration

The form of the luminance-duration relation found in most threshold studies may be described rather generally (e.g. see Bartlett, 1965; Graham, 1965). The present account outlines the characteristics of temporal integration that have been observed using threshold as well as other response measures (see Kietzman & Gillam [in press] for a parallel account for RT measures of temporal integration).

The most frequently used procedure in threshold studies of temporal integration involves measuring the luminance (I) necessary to obtain a constant threshold response at each of a number of stimulus durations (T). The results 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 IT vs. T function obtained by Sperling and Jolliffe (1965) using stimulus conditions--i.e. a 45', orange (580nm) light pulse presented to a dark adapted fovea--that are almost identical to those used in the present study. The form of this function is representative of those shown in most threshold studies of temporal integration. Note that at short durations the points fall along a straight line of zero slope indicating that the IT product at threshold was

Fig. 1. IT vs. T function from Sperling and Jolliffe (1965).



constant in accordance with Bloch's law ($IT=C$). This is the region of luminance-duration reciprocity or complete integration. At very long durations, the points tend to fall on a line of unit slope indicating that luminance alone determined the threshold ($I=C$). This is the region of no integration. Although there may be a fairly abrupt transition from complete to no integration under some conditions (e.g. Graham & Margaria, 1935; Karn, 1936), a more gradual transition is evident in the functions shown in most threshold studies. In the latter case, the duration at which the first deviation from complete integration occurs--i.e., the critical duration--is followed by a period of partial integration.¹ The period of partial integration lasts up to a duration at which the function adopts a unit slope--referred to as the utilization time (after Piéron, 1952). In summary, there are five characteristics of temporal integration which may be observed in the IT vs. T functions of most threshold studies: (1) complete integration or luminance-duration reciprocity; (2) a critical duration; (3) partial integration; (4) a utilization time; (5) no integration.

These characteristics of temporal integration are also evident in the findings of threshold studies that have used double-pulse stimulus manipulations, in which the effects of varying the dark interval between two light pulses are of interest (e.g. Battersby & Defabough, 1969; Bouman & van den Brink, 1952; Davy, 1952; Grossberg, 1970; Ikeda, 1965; van den Brink & Bouman, 1954).

¹ Some investigators have used the intersection of the lines of zero slope ($IT=C$) and unit slope ($I=C$) as an estimate of the critical duration. Note that this procedure ignores the period of partial integration. When there is a period of partial integration (as in Figure 1), the intersection of the lines of zero and unit slope comes at a considerably longer duration than the point of initial deviation from complete integration.

Although the results of most threshold studies are in general agreement with those outlined 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 extent of partial integration--may differ greatly depending on the stimulus conditions employed in these studies. It has been shown that the critical duration may be shortened below the frequently cited 100 msec. figure by using large stimuli (Graham & Margaria, 1935; Karn, 1936), or high background illumination (Barlow, 1958; Biersdorf, 1955). Barlow's data illustrate how stimulus area and background illumination may affect not only the critical duration, but also partial integration and the utilization time. Using a small stimulus (7.1') with no background illumination, integration was complete up to a critical duration of 100 msec. and almost complete up to the longest duration--1 sec. In contrast, using a large stimulus (5.9°) with high background illumination, complete integration ended at a critical duration of 30 msec. and there was little partial integration beyond this point.

The influence of stimulus conditions on temporal integration has proven to be complex. This may be illustrated by the conflicting reports on the influence of stimulus area. Barlow (1958) and Biersdorf (1955) show much longer critical durations for large area stimuli than one would expect based on findings of Graham and Margaria (1935) and Karn (1936). Moreover, some studies have not found an influence of stimulus area on temporal integration (Baumgardt & Hillmann, 1961; Defabaugh, 1967; Granit & Davis, 1931). These conflicting findings may be due to complex interactions between stimulus area and other stimulus variables which may differ in these studies--e.g. wavelength. An interaction between stimulus area and wavelength has actually been demonstrated by Sperling and Jolliffe (1965). Although Bouman and van den Brink

(1952) and Rouse (1952) had indicated that wavelength did not affect temporal integration, Sperling and Jolliffe showed this to be the case only for the very small stimuli used in these studies. Specifically, Sperling and Jolliffe found shorter critical durations and utilization times for longer wavelengths when using a 45' stimulus, but not with a 4.5' stimulus. It is also possible that the conflicting findings as to the influence of stimulus conditions on temporal integration may stem from differences in the response conditions--e.g. response criteria--in these studies. This possibility is difficult to assess due to the lack of information on the influence of response conditions in temporal integration studies.

The rather complex influence of stimulus conditions on the characteristics of temporal integration in threshold studies suggests the necessity for making any comparison across response measures under the same stimulus conditions. Any difference in the stimulus conditions under which the responses of interest are recorded may have effects which will be confounded with those of the response measures.

Reaction time studies of temporal integration

The general preference for threshold measures in visual psychophysics is reflected in the limited use of response latency in the psychophysical studies of temporal integration. Why latency measures have not proven to be more popular is unclear considering the early demonstrations by Cattell (1886, 1902) of the possible value of RT in the psychophysical context, and also considering the successful use of latency measures in electrophysiological studies of temporal integration (e.g. Adrian & Matthews, 1927; Bartley, 1934; Hartline, 1934). Perhaps the reports that duration had only a slight effect on RT, and only over very short durations (e.g. Woodworth & Schlosberg,

1954, p. 25), discouraged investigators from using RT to study temporal integration.

There has, however, been a recent trend to record response latency in behavioral studies of temporal processes in vision. Raab and his associates (Raab & Fehrer, 1962; Raab, Fehrer, & Hershenson, 1961) confirmed the previous reports of the extremely limited range of durations affecting RT. In fact, at Raab and Fehrer's higher luminance levels (300 & 3000 ft-L), RT was independent of duration even for stimuli as short as 0.5 msec. At their lowest, but still suprathreshold, luminance level (0.3 ft-L) increasing the duration from 2-20 msec. did produce a substantial reduction in the RT. Most interestingly, their data show greater RT changes as the luminance and duration--and therefore the luminous energy--was reduced toward the threshold. This is reminiscent of the general finding in visual and auditory RT studies of larger changes in RT as the threshold is approached (e.g., Steinman, 1944; Woodworth & Schlosberg, 1954, p. 20-24). Much larger effects of duration on RT may, therefore, be demonstrated at near threshold levels than has been shown by Raab and his associates and other investigators using suprathreshold levels. Kietzman (1968) and Kietzman and Gillam (in press) have argued for the value of using low luminous energy levels in RT studies of temporal integration and have presented data supporting this position.

Nonetheless, Raab and Fehrer did conclude that at the suprathreshold levels they employed the critical durations for RT were very brief and far shorter than those usually seen for threshold measures. Indeed, Raab and Fehrer's data show that the constant RT for constant luminous energy relation required by Bloch's law did not hold for any of the equal-energy comparisons available in their data.

Grossberg (1968) extended Raab and Fehrer's study to include lower threshold

and suprathreshold luminous energy levels and recorded both the frequency and latency of the detection responses. Grossberg concluded, in accordance with Raab and Fehrer's findings, that Bloch's law failed for the median RT over the same durations where it held for the response frequency. Thus, RT deviated from Bloch's law even at low threshold or near threshold levels of luminance energy. However, Grossberg's indication that, "... latencies were not everywhere consistent with the law" (p. 231) seems to imply that there were times when RT did obey Bloch's law. A comparison of his median RTs for equal-energy stimuli detected less than 100% of the times showed that this was indeed the case. For example, although the median RT for a stimulus of about 60 msec. was much longer than that for an equal-energy stimulus of about 6 msec. there was little or no difference in the median RTs for equal-energy stimuli of approximately 6 and 0.6 msec. In general, the deviations from the constant RT for equal-energy relation are less evident at very short durations (e.g. below 20 msec.) than at longer durations. It is noteworthy that for threshold level stimuli shorter than about 20 msec. the major deviation from Bloch's law in the RT vs. Energy functions for O:HH (Grossberg's Figure 5) comes at a point where there is a reversal in his RT vs. Energy function. At this point, increasing the luminous energy actually led to an increase in the median RT. One wonders whether this reversal may be a reflection of the large variability of RT at threshold (Grossberg's semi-interquartile ranges for these conditions were from 30-50 msec.) and the small number of trials per point (between 15 & 30) used by Grossberg. If this were the case, it would be difficult to assess the extent to which these points deviated from Bloch's law. The data for the other O:JS did not show this reversal, and most importantly, his RT vs. Energy functions for these very short threshold stimuli overlapped in accordance with Bloch's law. Thus, the median RTs for very short threshold stimuli may show

less deviance from Bloch's law than was suggested by Grossberg in his general conclusions. Furthermore, Grossberg did indicate that the semi-interquartile ranges of RTs to low energy stimuli were consistent with Bloch's law.

Luminance-duration reciprocity has been demonstrated for the RTs to very short suprathreshold stimuli (Kaswan & Young, 1965; Kietzman & Gillam, in press; Lewis, 1964; Pease, 1971). Lewis (1964) has obtained evidence that the distributions of RTs to equal-energy stimuli obey Bloch's law. Thus, Lewis found that equal-energy pulses of 2 and msec. yielded RT distributions that did not differ significantly. Kaswan and Young (1965), and more recently Kietzman and Gillam (in press), have used a new paradigm to demonstrate luminance-duration reciprocity for RT. The results of both studies show that at very short durations increasing the luminous energy via duration may be just as effective in reducing RT as equivalent increases in luminous energy via luminance. In Kietzman and Gillam's data, the RT vs Energy function obtained by varying the duration overlapped the function obtained by varying the luminance up to a critical duration of about 11 msec. Kaswan and Young show similar results for their lowest energy stimuli, which suggest a critical duration in the region of 16 msec. The findings of RT studies using double-pulse stimulus manipulations (Kietzman & Gillam, in press; Pease, 1971), also give evidence of Bloch's law. Results presented by Pease actually suggest that Bloch's law is applicable for RTs up to a critical duration as long as 30-50 msec.

Kietzman (1968) has also indicated that the reason some investigators have concluded that there was little temporal integration for RT was because they concentrated their attention on luminance-duration reciprocity and ignored the possibility of partial integration for RT. He stated, "Our experiments suggest that in the measurement of simple,

visual reaction time the more demonstrable effects are for partial rather than for complete reciprocity. This seems to be true because the critical duration for reaction time is very brief, especially at higher energy levels." Kietzman (1968) and Kietzman and Gillam (in press) have actually found partial integration for RT up to at least 50 msec. after stimulus onset. Inspection of Grossberg's (1968, 1970) and Raab and Fehrer's (1962) data also revealed durations over which Bloch's law did not hold, and yet, considerable partial integration was present.

The above findings suggest that the question raised by Grossberg--whether Bloch's law holds for response frequency, but not for RT--may not have been the most valuable question to ask. Rather, it may be more worthwhile to inquire as to the possible differences in the periods over which luminance-duration reciprocity and partial integration may be demonstrated for RT and response frequency. For example, are the critical duration and utilization time for RT shorter than those seen for response frequency?

Signal detection studies of temporal integration

What is the influence of decision or criterion factors in threshold studies of temporal integration? Boynton (1968, p.11) has presented an excellent description of the role of the criterion in a visual detection 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.

The criterion that an O adopts in deciding he has "seen" a stimulus has been shown

to have a great effect on response frequency or percent "seen" psychometric functions and thresholds (e.g., Barlow, 1956, Swets, Tanner & Birdsall, 1961). Barlow showed that an O by lowering his criterion from "seen" to "possibly seen" could lower his threshold by 25%. If the O's criterion should vary for different stimulus conditions--e.g., for different durations or luminances--then the influence of the O's criterion may be confounded with those of the stimulus conditions.

Some psychophysical measures are, however, believed to be less influenced by O's criterion. Signal detection theorists have employed a number of procedures which attempt to provide indices of sensitivity that are independent of the O's criterion (Green & Swets, 1966). Briefly, the Yes-No, forced-choice, and rating procedures yield measures such as--detectability (d'), percent correct, or the proportion of area under ROC curves. The independence of these signal detection measures from criterion effects combined with the influence of the criterion on response frequency or threshold measures may lead to differences in the findings of temporal integration studies using signal detection and threshold measures.

It should also be noted that the O's criterion may affect his RTs. A number of investigators (e.g., Greenbaum, 1963; Grice, 1968; John, 1967; Murray, 1970; Zeidman, 1966) have pointed to the influence of the criterion on RT and have presented supporting data. Greenbaum demonstrated criterion influences on the distribution of RTs which are analogous to those on percent "seen" psychometric functions. Inducing the O to adopt a more lax criterion produced a shift in the distribution of RTs toward shorter latencies. The median RT was therefore shorter the more lax the criterion of the O. Interestingly enough, Greenbaum has even speculated as to the effects that the criterion in the RT situation may have on

neural integration mechanisms.

To the extent that the criterion may affect the nature of temporal integration seen for RT, as well as response frequency, then measures less influenced by the criterion--e.g., signal detection measures--may show somewhat different estimates of temporal integration. This possibility is difficult to evaluate due to the scarcity of temporal integration studies using signal detection measures. Of the existing studies, one has used the rating procedure (Stenson, 1965), while the others have employed forced-choice tasks (Clark & Blackwell, 1959; Kietzman, 1966, 1968). The results of these studies generally agree in showing very short critical durations--ranging from 6-30 msec.--for their suprathreshold stimuli. However, Clark and Blackwell did show longer critical durations closer to 100 msec. using zero background luminance, which parallels the demonstrations in threshold studies of longer critical durations at lower luminance levels (Barlow, 1958; Biersdorf, 1955). Again, this underscores the importance of the stimulus conditions in determining the critical duration and suggests the difficulties of comparing the critical durations for signal detection as opposed to response frequency or RT measures obtained in different studies using different stimulus conditions.

CHAPTER III

Paradigm for Determining the Characteristics of Temporal Integration

In order to compare the characteristics of temporal integration for response frequency, RT, and signal detectability measures, the present study used stimulus manipulations that would allow the determination of all the characteristics of temporal integration for each of these response measures. Although it is common practice in temporal integration studies using response frequency or threshold measures to obtain IT vs. T functions, it may be less appropriate when using other response measures (e.g., RT). A new paradigm used for measuring temporal integration for RT (Kaswan & Young, 1965; Kietzman & Gillam, in press) may be applied equally well for estimating the characteristics of temporal integration for other response measures, e.g. response frequency and signal detectability.

The stimulus manipulations involved in this paradigm consist of varying the luminous energy of a light pulse in two different ways: (1) by varying the luminance with duration fixed at some brief value that is presumably completely integrated; (2) by varying the duration with luminance fixed. Each duration-varied condition is paired with a luminance-varied condition of equivalent luminous energy.

Each response measured to these stimulus manipulations may then be plotted as a function of the luminous energy of the luminance-varied and duration-varied conditions, and the characteristics of temporal integration can be determined for each response measure. For example, if there is luminance-duration reciprocity

for the median RT then identical median RT vs. Luminous energy functions should be obtained whether varying the luminous energy via luminance or duration. The luminance-varied and duration-varied functions should overlap at durations shorter than the critical duration, beyond which the function for the duration-varied conditions should show poorer performance (i.e. slower RTs) than the function for the luminance-varied conditions. The critical duration may be followed by a period of partial integration in which increasing the luminous energy via duration is only partially as effective in reducing RT as increasing the luminous energy via luminance. At longer durations the utilization time may be reached, beyond which increasing the luminous energy via duration no longer reduces the RT. The response frequency and signal detectability could similarly be plotted as a function of the luminous energy and a determination made of the characteristics of temporal integration for these response measures.

CHAPTER IV

Method

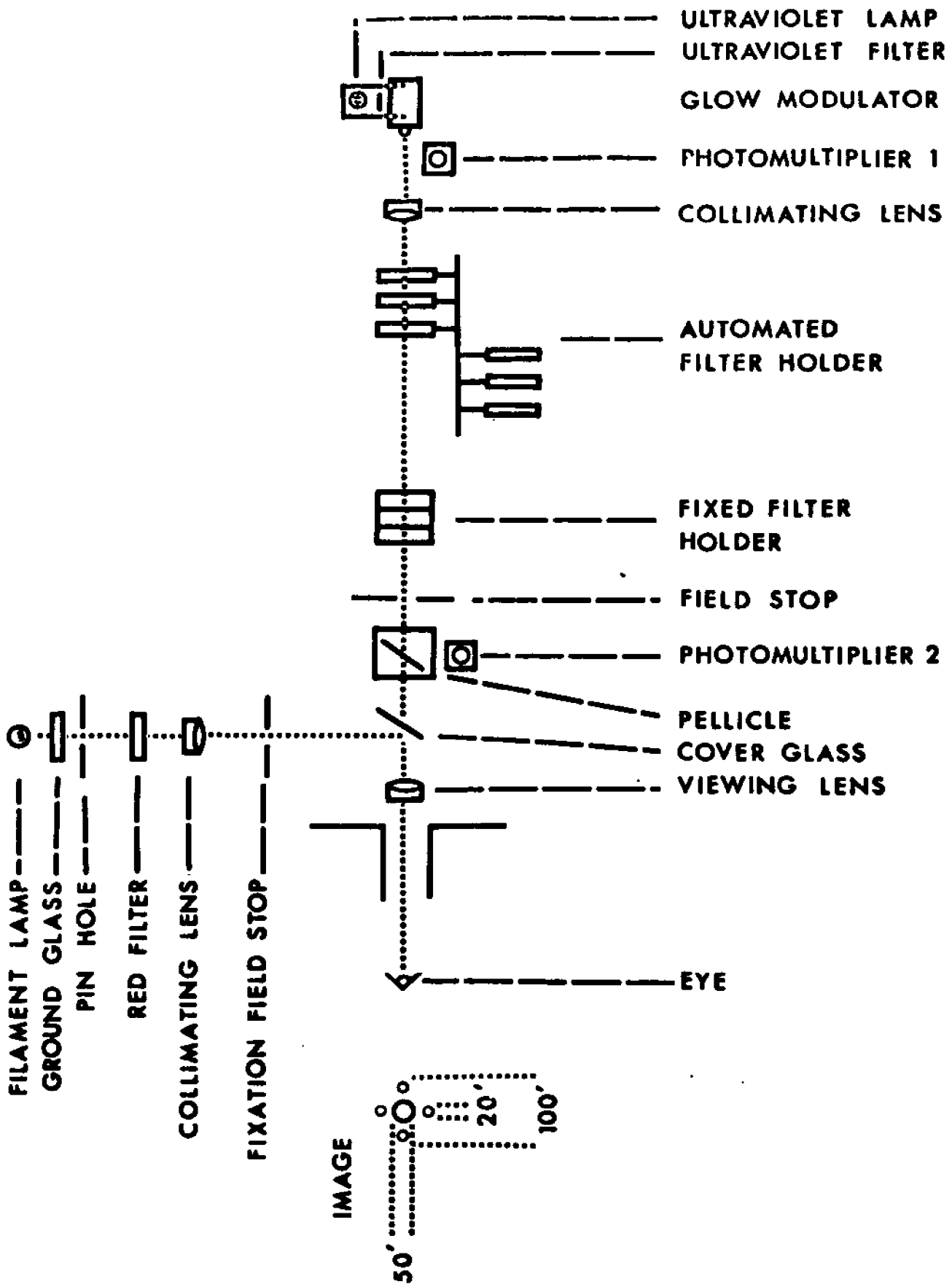
Observers

There were two Os. O: W.C., a male undergraduate college student, was paid for his services. He was informed only of the information required for his task and was not aware of the specific stimulus conditions or the purpose of the study. O: G.B., the author, was of necessity aware of both. Before the Os participated in the main experiment, they received extensive practice in their task during preliminary testing.

Apparatus

Optical System. The two-channel monocular Maxwellian view optical system used to present the light pulses and the fixation lights is outlined in Figure 2. 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 activated through timing and gating circuits. To provide short and stable "ionization times" of less than 10 μ sec., the glow modulator was irradiated by an argon ultraviolet lamp (General Electric AR-4). The light from this lamp was passed through an ultraviolet filter (Corning 9863) to prevent visible radiation from reaching the O's eye. 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

Fig. 2. Two-channel Maxwellian view optical system.



filtered (Kodak Wratten 106) to approximate the C.I.E photopic-luminous-efficiency curve. The light from the glow modulator, 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 combinations of these filters into the light path. Using the possible combinations of these six filters, the percentage of light transmitted could be varied in small steps, over a wide range. Additional metallic filters, as well as neutral density gelatine filters (Kodak Wratten), were mounted in a fixed filter holder, which also held a narrow band interference filter (Schott) with maximum transmission at 581 nm and half-value width of 10 nm. The latter filter was used throughout this study to obtain light of more uniform spectral composition and also to take advantage of a peak in the output of the glow modulator in this region (see the emission spectrum of glow modulators in Riggs, 1965). The filtered light was reduced in size using a field stop with a 2.52 mm aperture. This light, after passing through a pellicle beamsplitter (National Photocolor Corp.) and a cover glass, was focused by the viewing lens on the O's eye producing a retinal image of 50' visual angle. An adjustable bite-board was used to position the O's eye so that the image of the glow modulator's crater was focused on the O's cornea and passed completely through the center of his pupil. The second Maxwellian view channel, having a tungsten filament lamp (General Electric 55) as its source, provided the fixation lights. The image produced by the fixation lights appeared as four dim red dots surrounding the light pulses (see Figure 2).

The procedures used in calibrating the light from the glow modulator and the

percent transmission of the filters are presented in Appendixes I and II.

Correction for glow-modulator rise time. A glow modulator source was used to produce rectangular light pulses with very short rise and decay times. In our laboratory (see Kietzman and Gillam, in press), the rise and decay time of glow modulator pulses were found to be approximately $20\mu\text{sec.}$ and $2\mu\text{sec.}$ respectively. However, there still may be a slight loss of luminous energy during the "ionization time" ($<10\mu\text{sec.}$) and the rise time ($\approx 20\mu\text{sec.}$), and the magnitude of this loss would be greater the higher the luminance of the light pulse. In order to compensate for this loss of luminous energy during the "ionization time" and rise time, $30\mu\text{sec.}$ were added to the duration of each stimulus condition.

Heat-up of the glow modulator. It is known that the light output of glow modulator tubes may increase as the pulse duration increases (e.g., Lewis, 1964; Nilsson, 1968). Oscilloscope tracings of the light pulses used in this study did show a slight increase in voltage with increasing duration. The magnitude of this increase was found to be about 3% at 211 msec. after stimulus onset--i.e., the longest duration used in the main experiment (see Appendix III). Since the increase in glow modulator output with increasing duration was small, no correction was used for this factor.

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 indeterminacy of 1 part in 10,000. The timer delivered a pulse of the desired duration to a gating device which in turn activated the glow modulator for that duration.

Response recording apparatus. The O made his detection responses by lifting his finger from a telegraph key. The latency of these responses was measured on an

electronic counter which read in tenths of milliseconds and had an accuracy of $.01\% \pm 1$ count. The frequency and latency of the detection responses was recorded on a CMC printer which was located in a room outside the laboratory. The O signaled his confidence in his detection responses by pressing one of three switches located immediately to the left of the telegraph key which in turn activated a corresponding light on the experimenter's panel.

Procedure

During testing the O was seated in a light-tight booth and positioned using a bite-board. Each trial began with a warning click that signaled the O to fixate in the center of the four fixation dots. On 75% of the trials, the warning click was followed by a light pulse after a 2 sec. fixed foreperiod (signal trials). On the other 25% of the trials, no light pulse was presented (blank trials). The O was aware that the signal would be presented on only 75% of the trials. The O's task was to lift his finger from a telegraph key as fast as possible upon seeing the light flash. He was encouraged to lift his finger even when very uncertain of seeing the light flash. However, if he did not see the light flash he was to keep his finger on the key until a second click sounded 4 sec. after the warning click. Following the second click, the O rated the confidence in his response by pressing one of three switches which represented: (1) low, (2) moderate, and (3) high confidence. On trials when he lifted his finger from the telegraph key, he rated the confidence in his judgment that the light did flash. If he did not lift his finger, then he rated the confidence in his judgment that the light didn't flash. On trials when the light pulse was actually present, a tone was sounded immediately after the O's confidence

rating. The O thus received feedback on the accuracy of his detection responses. He was also instructed to stress both accuracy and speed in making his detection responses. The length of each trial was approximately 5 or 6 sec. depending on the time taken to make the confidence rating and the interval between light pulses was approximately 8 - 10sec.

Preliminary testing. The O was given an extensive period of testing prior to the main experiment. The purpose of this was twofold: (1) to give the O practice in his task; (2) to provide pilot data to be used to select the stimulus conditions for the main experiment. The O's task and the procedure followed on each trial were as described above. During the first few days of training, a random double staircase technique was used to obtain a rough estimate of the O's threshold. Subsequently, an Up-Down-Transformed-Response (UDTR) procedure was employed to estimate the 29.3% and 70.7% points on the psychometric function (Wetherill & Levitt, 1965; Levitt & Treisman, 1969).² The luminance needed to obtain 29.3% and 70.7% responses was determined for a number of stimulus durations ranging from 1 to 300 msec. There were from 2-4 separate sessions for each of the stimulus durations.

²The UDTR procedure, like the random double staircase procedure, involves changing the stimulus level from trial to trial by a fixed amount (i.e. the step size) in a direction that depends on the prior response of the O and the "stepping rule". For example, in order to estimate the 70.7% point, the luminance was reduced by a step (approximately 0.1 log unit) only after two consecutive "yes" (i.e. seen) responses. However, the luminance was increased by a step after each "no" response. This "stepping rule" will converge on a luminance where the probability of a "yes" response is 0.707. The "stepping rule" used to estimate the 29.3% point is exactly the reverse. Levitt and Treisman (1969) provide control charts which allow both the 29.3% and 70.7% "stepping rules" to be followed randomly from trial to trial.

During a 30-40 min. session consisting of about 96 trials (25% blanks), an average of 8 "runs" were obtained at each response level. The midpoints of every other "run" were averaged to obtain the estimates for the 29.3% and 70.7% levels.

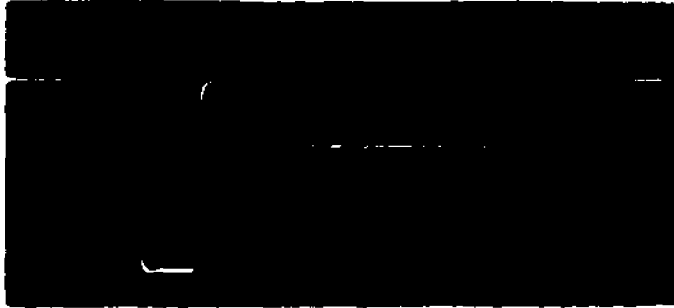
Main experiment. The O's task during this part of the study remained the same as in the preliminary testing. The major difference in the procedure was the stimulus manipulations. Basically, the luminous energy of the light pulses was manipulated and its effects on the response measures recorded. The luminous energy was varied in two different ways: (1) by varying the luminance with duration fixed; (2) by varying the duration with luminance fixed. Using the method of constant stimuli, the luminance or duration was varied over five luminous energy levels (E1-E5) yielding from 20-95% detection responses. These stimulus manipulations are illustrated in Figure 3 which shows oscilloscope tracings of some of the luminance-varied conditions and duration-varied conditions at four of the luminous energy levels used for O:WC. The retinal illuminance, duration, and luminous energy of all of the stimulus conditions used for O:WC and O:GB are listed in Tables 1 and 2. In the luminance-varied conditions, the retinal illuminance of 1 msec. pulses was varied over five levels of luminous energy. In the duration-varied conditions, the retinal illuminance was fixed and the duration varied over the same levels of luminous energy used for the luminance-varied conditions. Three sets of duration-varied conditions (I, II, & III) spanned the same luminous energy range, but each set used progressively longer durations. Some additional oscilloscope tracings of O:WC's luminance-varied condition and duration-varied conditions (I, II, & III) at E5 are shown in Figure 4.

The measuring of multiple response indices on the same trials (in this study--RT,

Fig. 3 Oscilloscope tracings of \underline{Q} :WC's luminance-varied and duration-varied-1 conditions (E1-E4).

LUMINANCE DURATION
VARIED VARIED I

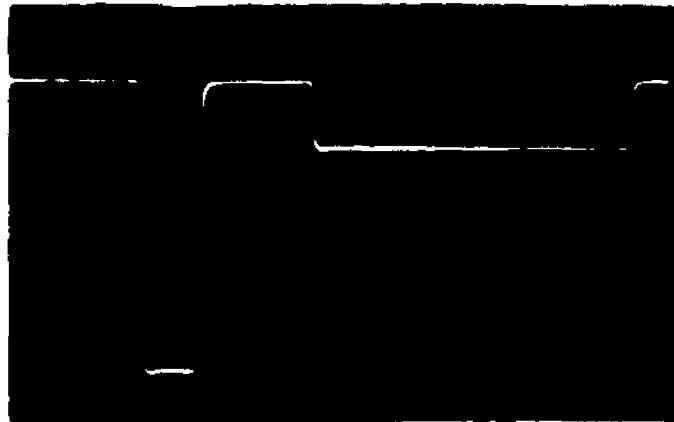
E1



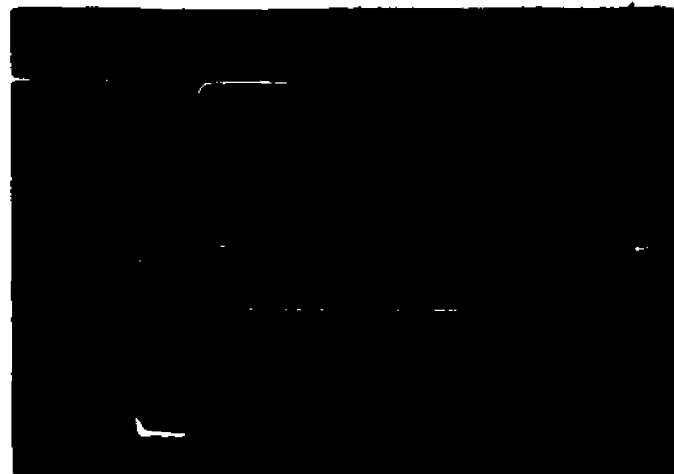
E2



E3



E4



.5 VOLTS I

1 MSEC

TABLE 1

Stimulus Conditions for $\underline{O}:WC$

Conditions	Retinal illuminance ^a (trolands)	Duration (msec.)	Luminous energy (trolands·msec.)
Luminance varied			
E1	15.04	1.00	15.04
E2	18.68	"	18.68
E3	23.55	"	23.55
E4	28.84	"	28.84
E5	40.83	"	40.83
Duration varied I			
E1	4.82	3.39	16.34
E2	"	4.21	20.29
E3	"	5.31	25.59
E4	"	6.50	31.33
E5	"	9.21	44.39
Duration varied II			
E1	0.621	24.2	15.03
E2	"	30.1	18.69
E3	"	38.0	23.54
E4	"	46.5	28.81
E5	"	65.8	40.86
Duration varied III			
E1	0.239	61	14.93
E2	"	76	18.62
E3	"	96	23.49
E4	"	118	28.88
E5	"	166	41.07

^aSee Appendixes I and IV for the procedures used in obtaining the retinal illuminance values.

TABLE 2

Stimulus Conditions for \underline{O} :GB

Conditions	Retinal illuminance ^a (trolands)	Duration (msec.)	Luminous energy (trolands·msec.)
Luminance varied			
E1	6.82	1.00	6.82
E2	9.10	"	9.10
E3	11.56	"	11.56
E4	16.36	"	16.36
E5	22.55	"	22.55
Duration varied I			
E1	0.775	8.8	6.82
E2	"	11.8	9.07
E3	"	14.9	11.55
E4	"	20.1	15.58
E5	"	27.7	21.47
Duration varied II			
E1	0.228	30.0	6.84
E2	"	40.0	9.12
E3	"	50.8	11.58
E4	"	68.4	15.60
E5	"	94.4	21.50
Duration varied III			
E1	0.102	67	6.83
E2	"	90	9.18
E3	"	114	11.63
E4	"	153	15.61
E5	"	211	21.52

^aSee Appendixes I and IV for the procedures used in obtaining the retinal illuminance values.

Fig. 4. Oscilloscope tracings of O:WC's luminance-varied condition and duration-varied-I, -II, and -III conditions (E5). Note that different luminance levels (and therefore different luminous energies) were used in obtaining the oscilloscope tracings separated by dashed lines.

E5

LUMINANCE
VARIED

DURATION
VARIED I



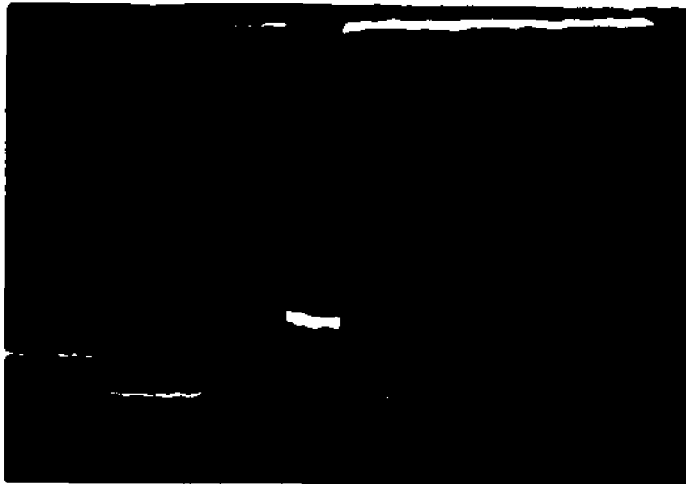
1 VOLT I

1 MSEC

E5

DURATION
VARIED I

DURATION
VARIED II



1 VOLT I

10 MSEC

E5

DURATION
VARIED II

DURATION
VARIED III



1 VOLT I

20 MSEC

response frequency, signal detectability) presents special procedural difficulties. Procedures which are good for one measure may not be ideal for other response measures. One problem was whether to vary the luminous energy within a block of trials or between blocks. Although the between block design has most often been used in signal detection studies (with some exceptions--Emmerich, 1968; Blocker, 1965; Tucker, Evans & Jeffress, 1967), there is evidence that the between block design may not be a preferred procedure for studying energy effects on RT. For example, Thrane (1960) has shown that differences in RT obtained by varying intensity are smaller using the between block design as compared to the within block design. Thrane attributed the reduction of intensity effects on RT to differences in preparatory set across blocks. Moreover, Lewis (1964) has indicated that such between block differences in set may interfere with demonstrating Bloch's law for RT. Thus, when using a RT measure of temporal integration, it may be desirable to vary the luminous energy within blocks and thereby avoid possible between block differences in preparatory set. However, what is the effect of using a within block design on the ROC curves and the proportion of area under these curves? Emmerich (1968) presented data which may help answer this question. He compared the rating ROC curves obtained using within block versus between block procedures. The rating ROC curves found when intensities were randomized within block proved to be highly similar to the ROC curves found when the intensities were presented in separate blocks. The areas under the ROC curves for the within block and between block procedures were of similar magnitude. Thus, the ROC curves and signal detectability measures obtained using the within block design may not differ from those obtained using the between block design. It therefore seemed justified to use the within block

design when varying the luminous energy of the stimuli in the present study and thereby avoid the problems of using the between block design in the case of RT.

On each day of testing during the main experiment there were four separate blocks of 100 trials--one for the luminance-varied conditions and one for each set of duration-varied conditions (I, II, & III). Within each of these blocks, the stimuli at the five luminous energy levels (E1-E5) and the blanks were randomized with the restriction that there be three trials at each luminous energy level and five blanks within each sub-block of 20 trials. There were then 15 trials at each of the five luminous energy levels and 25 blanks within each block of 100 trials. The order of the luminance-varied and duration-varied (I, II, and III) blocks on each day was randomly selected from the 24 possible orders. To counterbalance order effects, each of the possible orders were used once during the course of 24 days of testing. Each O received a total of 9,600 trials--360 trials per stimulus condition and 2,400 blanks.

A typical day of testing included two 1 hour sessions which proceeded as follows: (1) O was dark adapted for at least 5 min; (2) the first block of 100 trials were presented with 1 min. rests after every 25 trials; (3) a 5 min. rest was given at the end of the block; (4) the second block of 100 trials with rests were presented. At the end of the session, the O was given a 15-20 min. rest outside his booth. This was followed by a second session during which the last two blocks were presented as outlined above.

Treatment of data: Preliminary testing

The estimates of the luminous energy needed to obtain 29.3% and 70.7%

responses for pulse durations of 1-300 msec. are presented in the form of IT vs. T functions (Figure 5). Dashed lines with slopes of zero ($IT=C$) and unity ($I=C$) were passed through the data points for the 1 and 200 msec. durations respectively. Brackets representing ± 1 standard deviation are included around each data point.

Treatment of data: Main experiment

Each response measure was plotted as a function of the log luminous energy of the luminance-varied and duration-varied conditions (e.g. Figure 6). To aid in interpreting the results in these figures, the durations of the duration-varied conditions are listed below their respective luminous energy levels. The data points for the luminance-varied conditions were fitted with straight lines using the method of least squares, and brackets representing 95% confidence limits were included around these data points. Confidence limits for all the conditions are given in Appendix V.

The response frequency, signal detectability, and response latency measures used in the main experiment are described in the following sections.

Response frequency. The percentage of trials on which the O responded "yes" (i.e., lifted his finger from the key) in the presence of each of the stimulus conditions was plotted as a function of the log luminous energy of these conditions. The data were plotted on normal probability paper so as to yield linear luminance-varied psychometric functions.

Signal detectability. The use of confidence ratings in addition to the "yes-no" response provided six response categories ranging from Yes-3 (highly confident) to No-3 (highly confident). The frequency of use of the six response categories on

signal and blank trials yielded the data for estimating the hit rates, $P(S/s)$, and false alarm rates, $P(S/n)$, which are plotted in the form of ROC curves (see Green & Swets, 1966, p. 41-43). The proportion of area under the ROC curves, $P(A)$, was used as the measure of signal detectability. In addition to being a distribution-free measure, $P(A)$ has the advantage of being equivalent to the proportion of correct responses, $P(C)$, in two-alternative forced-choice tasks (see Green & Swets, 1966, p. 404-405). The formula used to adjust the $P(C)$ for chance³ was used to adjust the $P(A)$ so as to facilitate the comparison of the results found using this measure and the response frequency measure. The adjusted $P(A)$, i.e. $P(A)'$, was plotted on normal probability paper as a function of the log luminous energy of the stimulus conditions.

Response latency. Both the medians and semi-interquartile ranges of RTs to each of the stimulus conditions were plotted as a function of the log luminous energy. Cumulative frequency distributions of the RTs are also given and the Kolmogorov-Smirnov test was used to determine the significance of differences between the RT distributions for the luminance-varied and duration-varied conditions.

³ In a two-alternative forced choice task the formula is:

$$P(C)' = \frac{P(C) - .50}{.50}$$

CHAPTER V

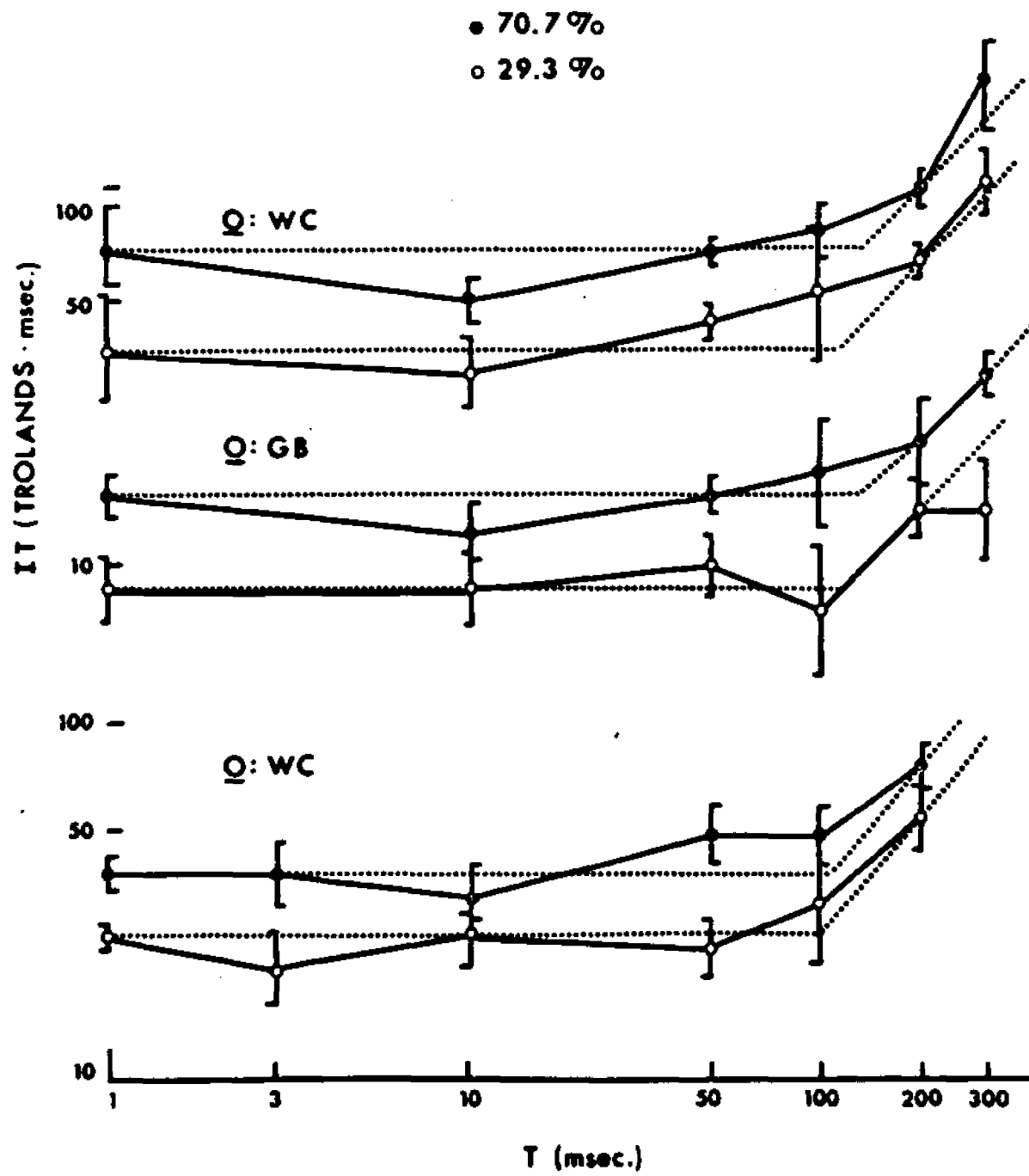
Results

Preliminary testing

The IT vs. T functions obtained for \underline{O} :WC and \underline{O} :GB at the 29.3% and 70.7% response levels are given in Figure 5. A later replication of the IT vs. T functions for \underline{O} :WC is also shown in the lower portion of Figure 5. Despite some variability, these functions provided initial estimates of the characteristics of temporal integration for response frequency which aided in the selection of the stimulus values for the main experiment. Over the durations from about 50 to 200 msec., the functions for both \underline{O} s show a transition from luminance-duration reciprocity (dashed line with zero slope) to no integration (dashed line with unit slope). Although the initial departures from reciprocity that occurred in the region of 50-100 msec. suggest a critical duration in this region, it is difficult to estimate the exact value of the critical duration given the variability of the data points. A larger departure from reciprocity was evident by 200 msec. Beyond this duration, the functions show slopes of about unity (except \underline{O} :GB's function at 29.3%), and therefore, they give evidence of no integration beyond 200 msec.

Note that \underline{O} :WC required consistently more luminous energy at the 29.3% and 70.7% response levels than \underline{O} :GB. This may have resulted, at least in part, from the stricter criterion adopted by \underline{O} :WC during the UDTR testing. While the

Fig. 5. IT vs. T functions for $\bar{O}:WC$ and $\bar{O}:GB$ at the 29.3% and 70.7% response levels. A replication of the functions for $\bar{O}:WC$ is shown in the lower portion of the figure.

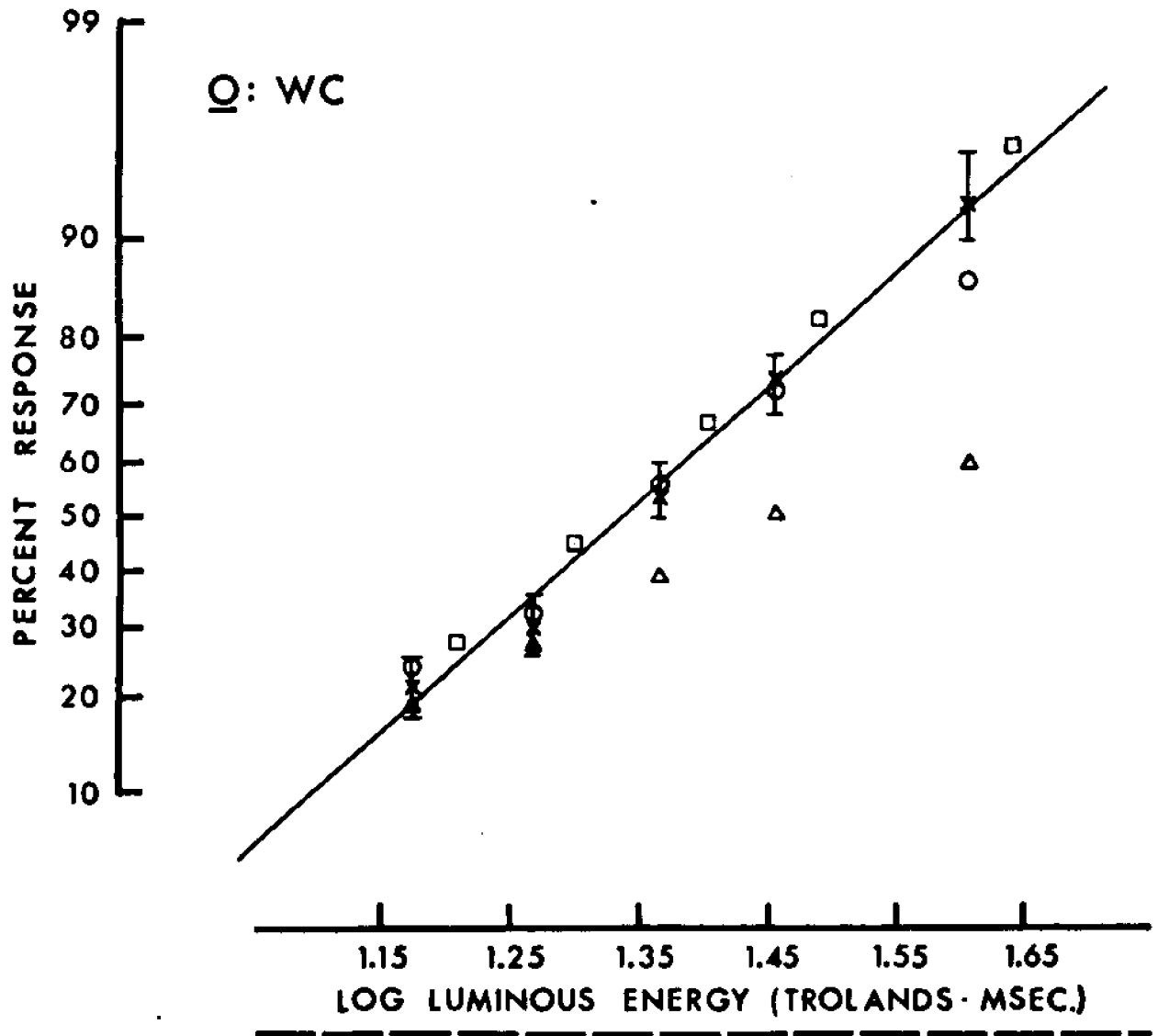


false alarm proportions for O:GB ranged from .05 to .17 for the different durations, O:WC showed false alarm proportions of only .00 to .02. There was also some suggestion in the data for O:GB of a relation between the false alarm proportions and the stimulus duration. His false alarm proportions increased from .05 to .17 as the duration was increased from 1 to 100 msec., and then decreased at still longer durations. These criterion differences, both across Os and stimulus conditions, underscored the need for using a signal detectability measure in the main experiment to control for the criterion.

Main Experiment

Response frequency. The characteristics of integration for the response frequency data obtained in this portion of the study correspond closely with those suggested in the preliminary testing. The psychometric functions for the percentage of "yes" responses given by O:WC and O:GB to the luminance-varied and duration-varied conditions are shown in Figures 6 and 7. Plotting the percent response on a probability axis yielded fairly linear psychometric functions at least for the luminance-varied conditions and shorter duration-varied conditions. The straight line fitted to the data points for the 1 msec. luminance-varied conditions represents the psychometric function obtained by varying the luminous energy of pulses which were presumably short enough to be completely integrated. The data points for the duration-varied-I conditions ranging from 3.39-9.21 msec. for O:WC and 8.8-27.7 msec. for O:GB fell along the luminance-varied function, demonstrating luminance-duration reciprocity at these short durations. The duration-varied-II conditions also showed reciprocity up to a critical duration in the region of 46.5-65.8 msec. for O:WC and 50.8-68.4 msec.

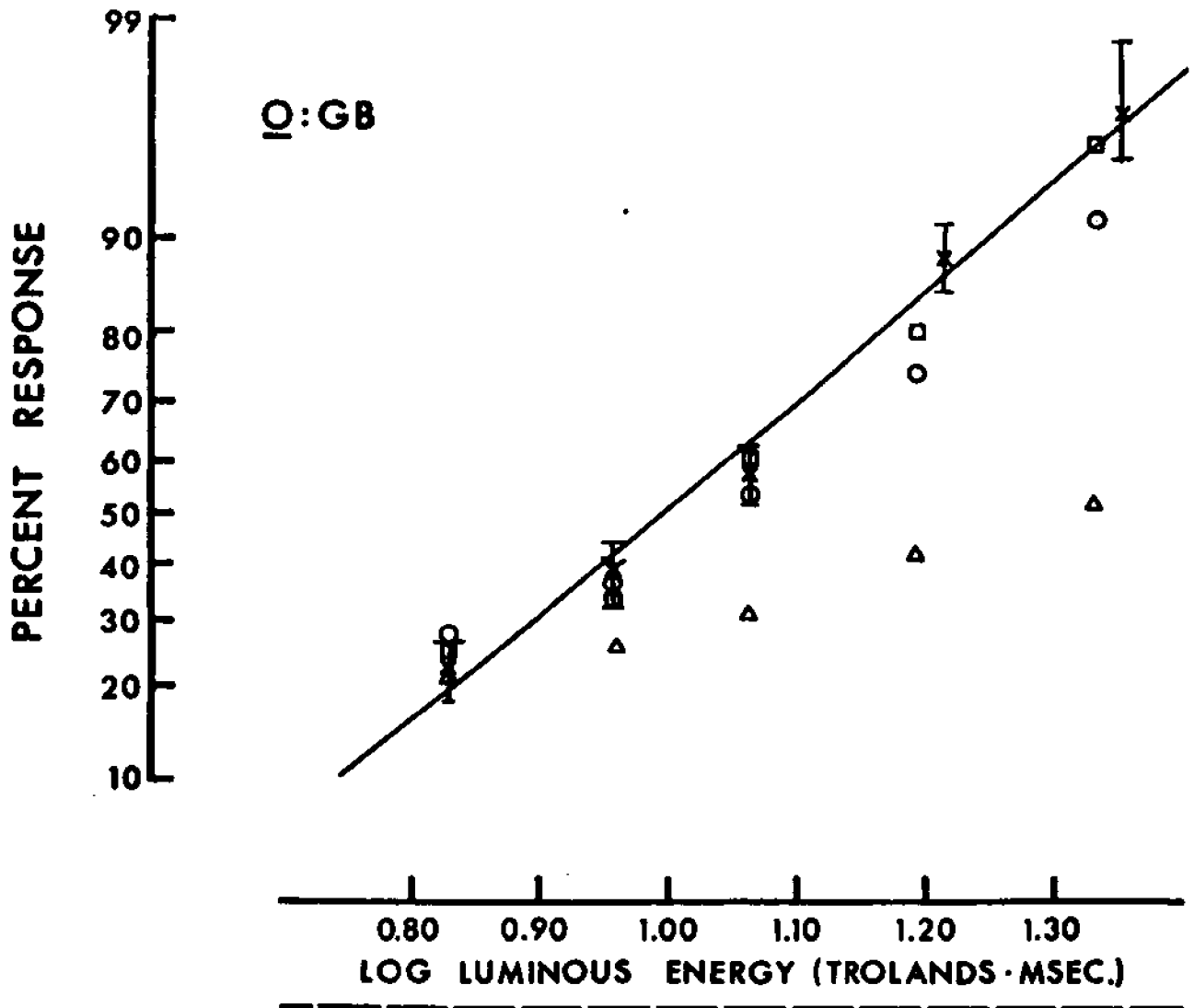
Fig. 6. The percent response psychometric functions obtained by O:WC for the 1 msec. luminance-varied conditions (x), and the duration-varied I (□), - II (o), and -III (Δ) conditions.



DURATIONS (MSEC.)

□	□	□	□	□
3.39	4.21	5.31	6.50	9.21
○	○	○	○	○
24.2	30.1	38.0	46.5	65.8
△	△	△	△	△
61	76	96	118	166

Fig. 7. The percent response psychometric functions obtained by O:GB for the 1 msec. luminance-varied conditions (x), and the duration-varied-I (□), -II (○), and -III (△) conditions.



DURATIONS (MSEC.)

□	□	□	□	□
8.8	11.8	14.9	20.1	27.7
○	○	○	○	○
30.0	40.0	50.8	68.4	94.4
△	△	△	△	△
67	90	114	153	211

for \underline{O} :GB. Notice that the shorter duration-varied-III conditions (61 and 76 msec. for \underline{O} :WC and 67 msec. for \underline{O} :GB) showed higher percent responses than would be expected if these durations were beyond the critical duration. The critical duration suggested by the duration-varied-III conditions--in the region of 76-96 msec. for \underline{O} :WC and 67-90 msec. for \underline{O} :GB--is longer than that suggested by the duration-varied-II conditions. However, the longer estimate of the critical duration for the duration-varied-III conditions may have resulted from a laxer criterion adopted by the \underline{O} s during the blocks containing the duration-varied-III conditions. Evidence to this effect is presented in the signal detectability results section. The more gradual rate of increase of the \underline{O} s' psychometric functions for the duration-varied-III conditions as compared to their luminance-varied functions indicates that integration was only partial at these longer durations. Thus, increases in luminous energy via duration were only partially as effective in increasing the percent response as equivalent increases in luminance. The functions for the duration-varied-III conditions show partial integration out to the longest duration used in the main experiment.

Signal detectability. The characteristics of integration evident in the signal detectability data for the \underline{O} s' duration-varied-I and duration-varied-II conditions were almost identical to those seen for the response frequency. Luminance-duration reciprocity was demonstrated in the signal detectability data of both \underline{O} s up to a critical duration in the region of 40-60 msec. Unlike the response frequency measure which did not allow for the \underline{O} s' criteria, the signal detectability measure took into consideration the laxer criterion adopted for the duration-varied-III conditions. The \underline{O} s' signal detectability data for even the shortest duration-varied-III

conditions showed the departures from reciprocity to be expected given a critical duration in the region of 40-60 msec. Like the response frequency measure, partial integration was found in the \underline{O} 's' signal detectability data out to the longest duration-varied-III conditions.

Tables 3 and 4 summarize the data used to plot the ROC curves and to obtain the signal detectability measures. These tables give the frequency with which each \underline{O} 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 condition, the frequencies in the six response categories were cumulated from left to right (i.e., from Yes-3 to No-3) and then divided by the number of stimulus presentations. The false alarm proportions (see bottom of Tables 3 and 4) were calculated in a similar manner, but using the frequencies of responses in the six categories that occurred on blank trials. Note that there are separate estimates of the false alarm rates for blanks from the luminance-varied, duration-varied-I, duration-varied-II, and duration-varied-III blocks. However, the five luminous energy levels (E1-E5) that were randomized within each of these blocks share a "common" estimate of the false alarm rates obtained within the block. Hit and false alarm estimates for response categories that were used very infrequently or not at all (e.g. response categories No-1 and No-2 for \underline{O} :WC) add little or no information and therefore were not plotted in the ROC curves. This reduced the number of points plotted in the ROC curves, especially for \underline{O} :WC.

Figures 8-12 show the ROC curves obtained by \underline{O} :WC and \underline{O} :GB for the luminance-varied and duration-varied conditions at luminous energy levels E1-E5.

TABLE 3

Frequency (f) of Use of Each Response Category and Estimates of Hit, P(S/s), and False Alarm, P(S/n), Proportions for O:WC

		Luminance varied						Duration varied I						Duration varied II						Duration varied III					
		Yes			No			Yes			No			Yes			No			Yes			No		
		3	2	1	1	2	3	3	2	1	1	2	3	3	2	1	1	2	3	3	2	1	1	2	3
E1	f	0	3	75	1	1	278	4	6	94	1	3	255	1	3	83	0	7	265	0	1	69	0	9	281
	P(S/s)	0	.008	.218	.221	.223	1.0	.011	.028	.286	.259	.298	1.0	.003	.011	.242	.242	.262	1.0	0	.003	.194	.194	.219	1.0
E2	f	0	14	99	3	3	239	3	26	128	2	1	200	2	8	112	1	3	236	2	5	96	2	8	249
	P(S/s)	0	.039	.316	.324	.332	1.0	.008	.080	.436	.436	.442	1.0	.006	.028	.337	.340	.348	1.0	.006	.019	.284	.290	.312	1.0
E3	f	11	41	147	1	1	156	21	68	156	1	3	107	7	32	159	1	2	153	2	6	137	1	3	214
	P(S/s)	.031	.146	.557	.560	.563	1.0	.059	.250	.688	.691	.699	1.0	.020	.110	.559	.562	.568	1.0	.006	.022	.399	.402	.410	1.0
E4	f	22	71	170	2	1	93	59	101	137	0	0	64	19	67	176	0	2	98	9	19	151	0	4	176
	P(S/s)	.061	.259	.732	.738	.741	1.0	.163	.443	.823	.823	.823	1.0	.052	.238	.724	.724	.729	1.0	.025	.078	.499	.499	.510	1.0
E5	f	125	118	91	1	2	23	201	78	64	0	0	16	99	93	121	0	2	42	10	38	171	1	4	137
	P(S/s)	.347	.675	.928	.930	.936	1.0	.560	.777	.955	.955	.955	1.0	.277	.538	.877	.877	.882	1.0	.028	.133	.607	.609	.620	1.0
Blanks	f	0	0	40	0	6	550	1	0	38	0	3	557	1	0	42	1	3	554	1	0	53	2	14	529
	P(S/n)	0	0	.067	.067	.077	1.0	.002	.002	.065	.065	.070	1.0	.002	.002	.072	.073	.078	1.0	.002	.002	.090	.093	.117	1.0

TABLE 4

Frequency (f) of Use of Each Response Category and Estimates of Hit, P(S/s),
and False Alarm, P(S/n), Proportions for O:GB

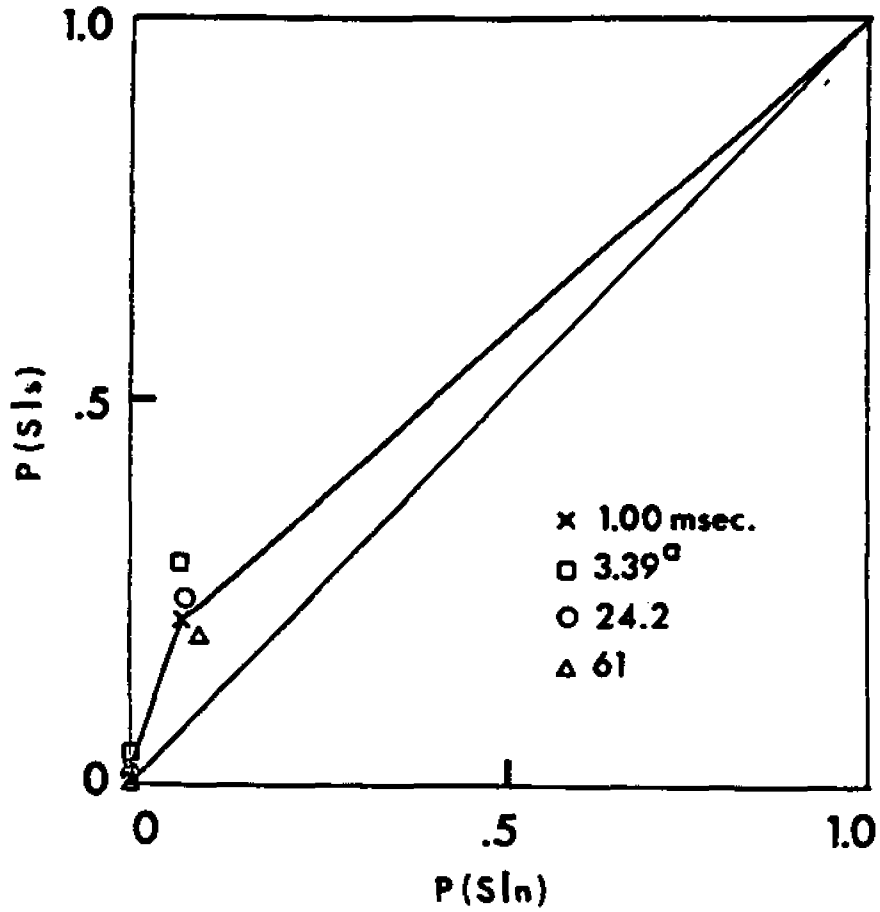
	Luminance varied						Duration varied I						Duration varied II						Duration varied III						
	Yes			No			Yes			No			Yes			No			Yes			No			
	3	2	1	1	2	3	3	2	1	1	2	3	3	2	1	1	2	3	3	2	1	1	2	3	
E1	f	4	11	66	67	72	141	7	10	74	71	70	135	8	7	81	71	56	139	2	7	68	71	66	145
	P(S/s)	.011	.042	.224	.410	.609	1.0	.019	.046	.248	.441	.632	1.0	.022	.041	.265	.461	.616	1.0	.006	.025	.214	.412	.596	1.0
E2	f	15	19	105	63	50	109	17	19	90	68	77	87	22	15	95	64	64	104	4	8	81	66	69	134
	P(S/s)	.042	.094	.385	.560	.698	1.0	.047	.100	.352	.542	.757	1.0	.060	.102	.363	.538	.714	1.0	.011	.033	.257	.439	.630	1.0
E3	f	61	30	117	64	39	50	49	27	137	57	35	51	56	25	109	68	41	61	12	14	85	70	56	121
	P(S/s)	.169	.252	.576	.753	.861	1.0	.138	.213	.598	.758	.857	1.0	.156	.225	.528	.717	.830	1.0	.034	.073	.310	.506	.662	1.0
E4	f	178	62	76	20	12	10	147	52	90	22	19	29	117	40	108	34	38	21	13	17	120	68	56	87
	P(S/s)	.497	.670	.883	.938	.972	1.0	.409	.554	.805	.866	.919	1.0	.327	.438	.740	.835	.941	1.0	.036	.083	.416	.604	.759	1.0
E5	f	305	21	22	6	1	1	310	18	18	9	2	3	241	39	48	19	5	6	18	31	137	59	52	62
	P(S/s)	.857	.916	.978	.994	.997	1.0	.861	.911	.961	.986	.992	1.0	.673	.782	.916	.969	.983	1.0	.050	.136	.518	.682	.827	1.0
Blanks	f	1	0	34	98	114	353	3	5	39	93	103	357	1	3	41	88	120	342	1	0	64	87	152	298
	P(S/n)	.002	.002	.058	.222	.412	1.0	.005	.013	.078	.233	.405	1.0	.002	.007	.076	.224	.425	1.0	.002	.002	.108	.252	.505	1.0

Fig. 8. ROC curves obtained by O:WC and O:GB for each of the luminance-varied conditions (x) and duration-varied-I (\square), -II (\circ), and -III (Δ) conditions at E1.

^aThis duration-varied-I condition had about 8% greater luminous energy than the O's other conditions at E1 (see Appendix IV).

E1

Q: WC



Q: GB

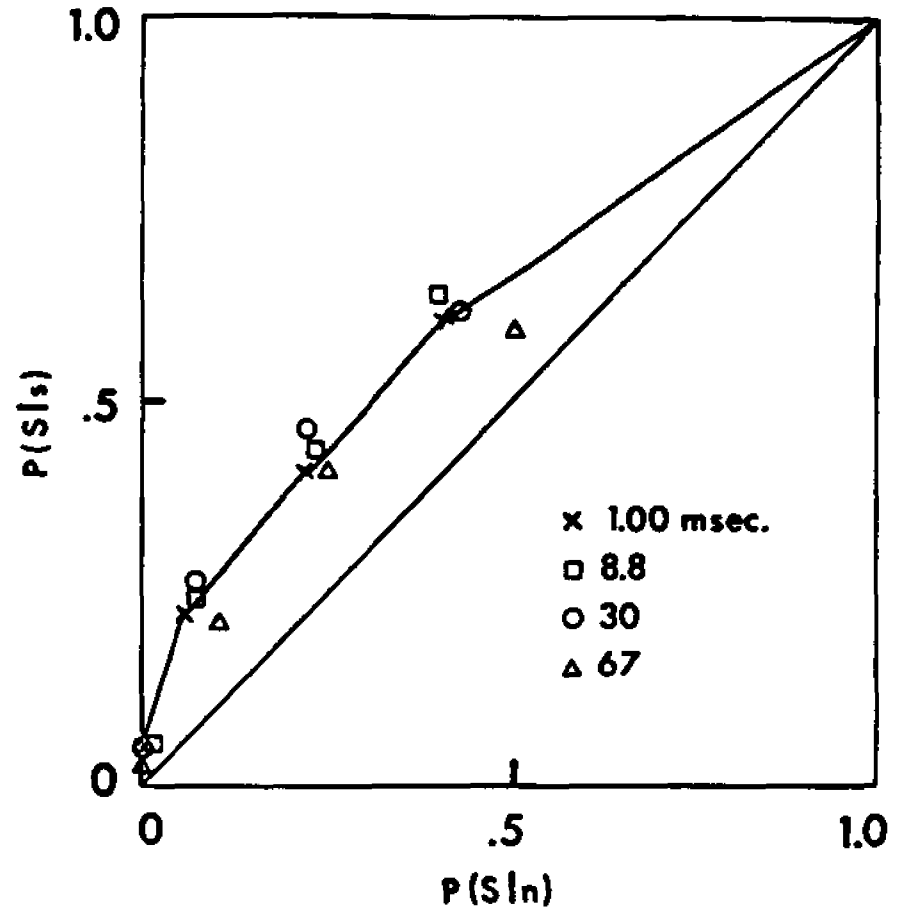
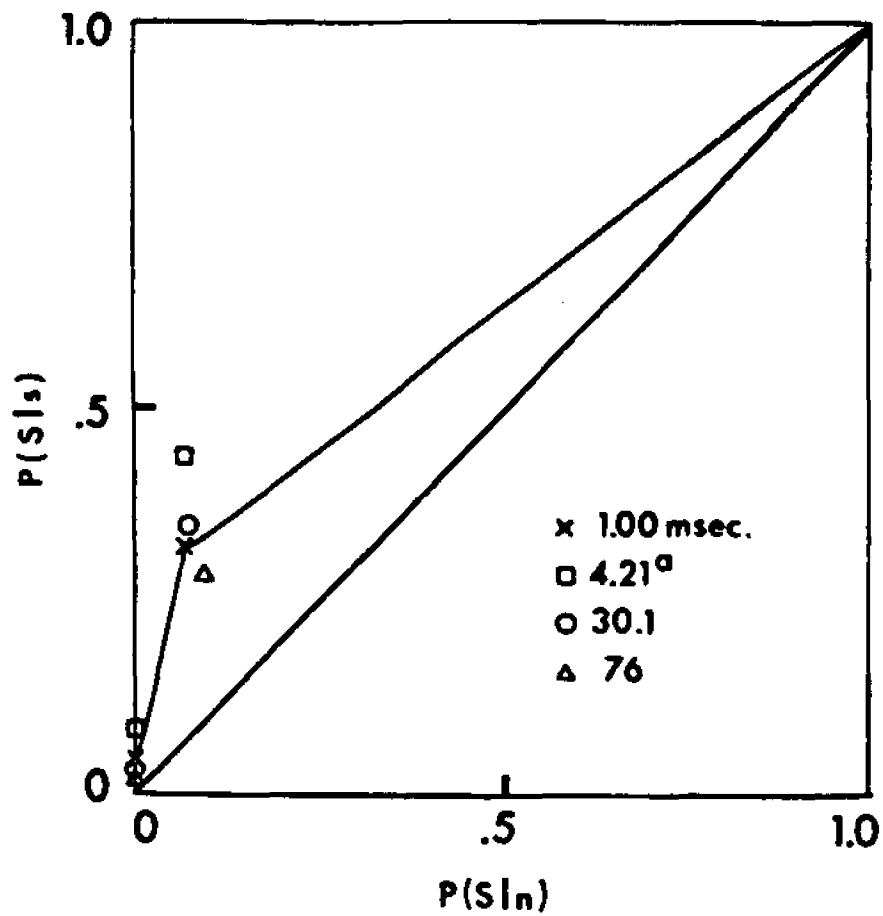


Fig. 9. ROC curves obtained by \underline{Q} :WC and \underline{Q} :GB for each of the luminance-varied (x) and duration-varied-I (■), -II (○), and -III (△) conditions at E2.

^aThis duration-varied-I condition had about 8% greater luminous energy than the \underline{Q} 's other conditions at E2 (see Appendix IV).

E2

\underline{Q} : WC



\underline{Q} : GB

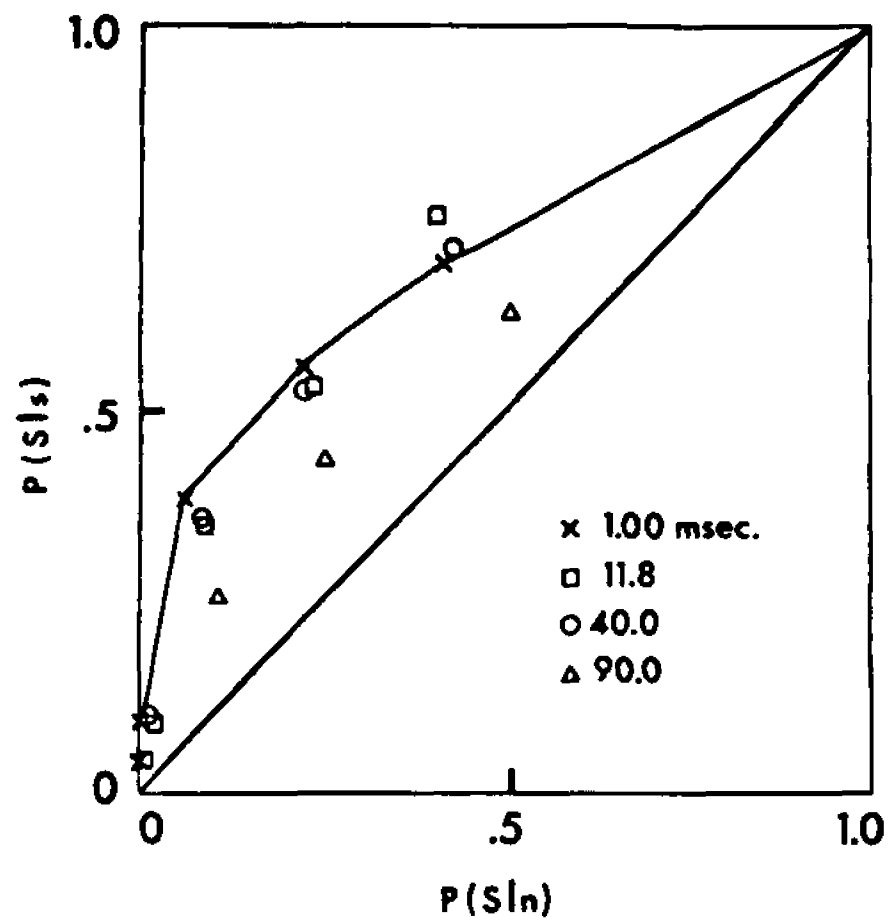
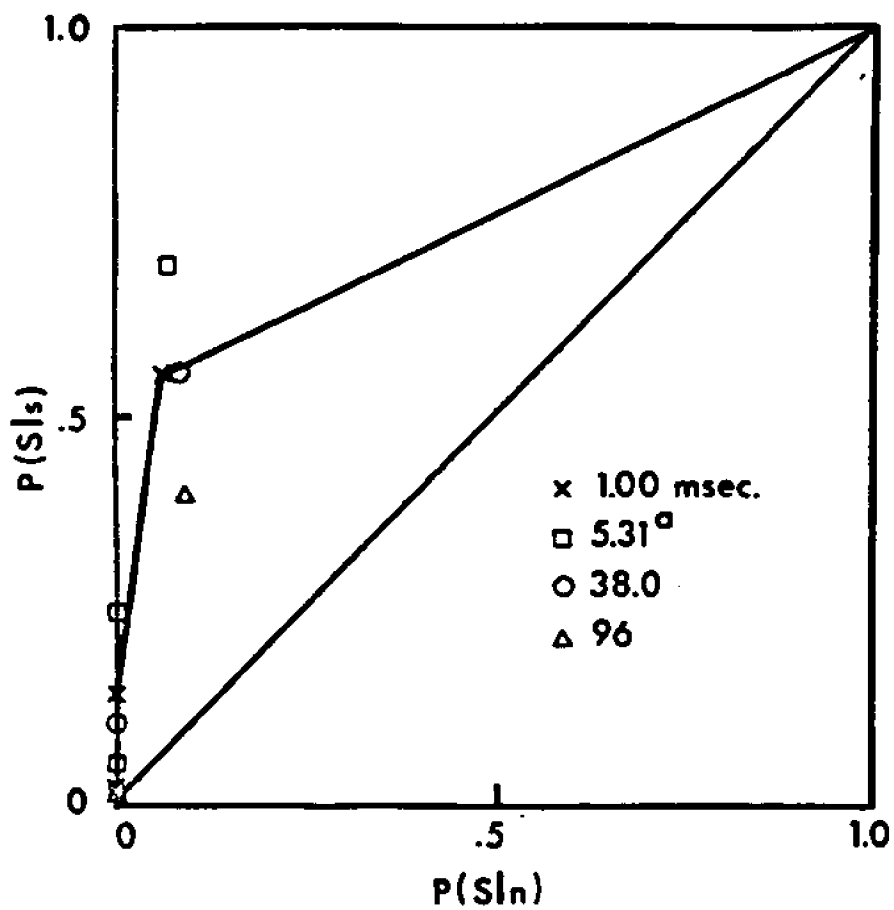


Fig. 10. ROC curves obtained by O:WC and O:GB for each of the luminance-varied (x) and duration-varied-I (\square), -II (\circ), and -III (\triangle) conditions at E3.

^aThis duration-varied-I condition had about 8% greater luminous energy than the O's other conditions at E3 (see Appendix IV).

E3

Q: WC



Q: GB

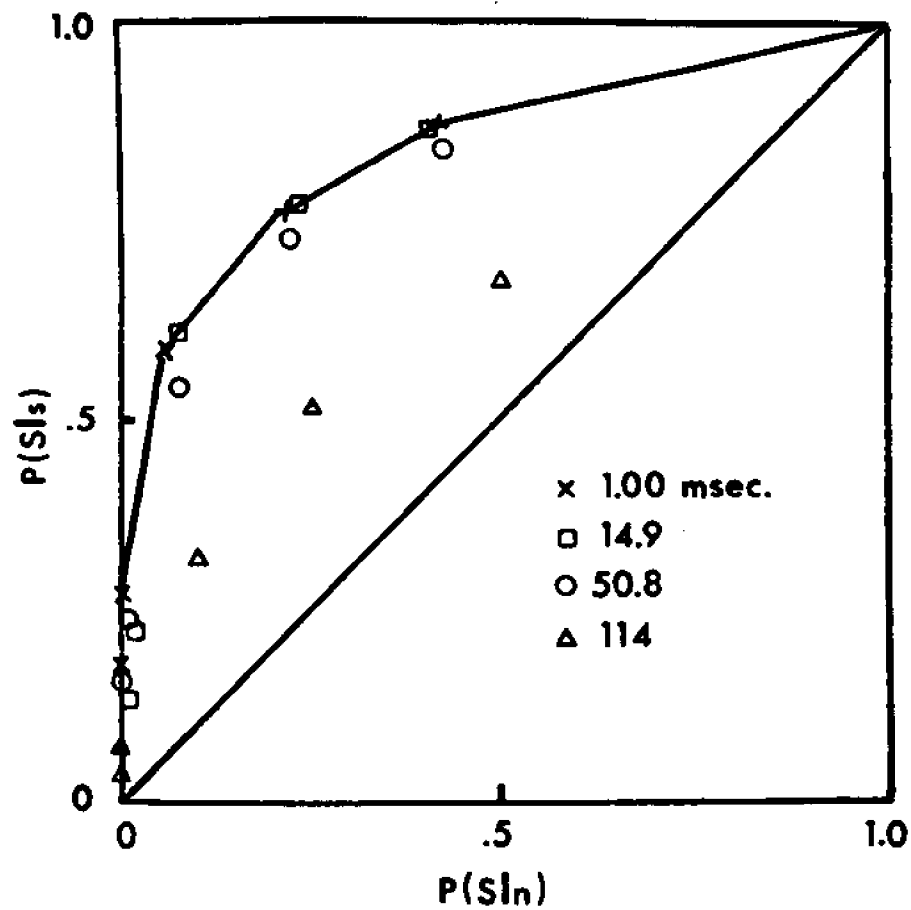


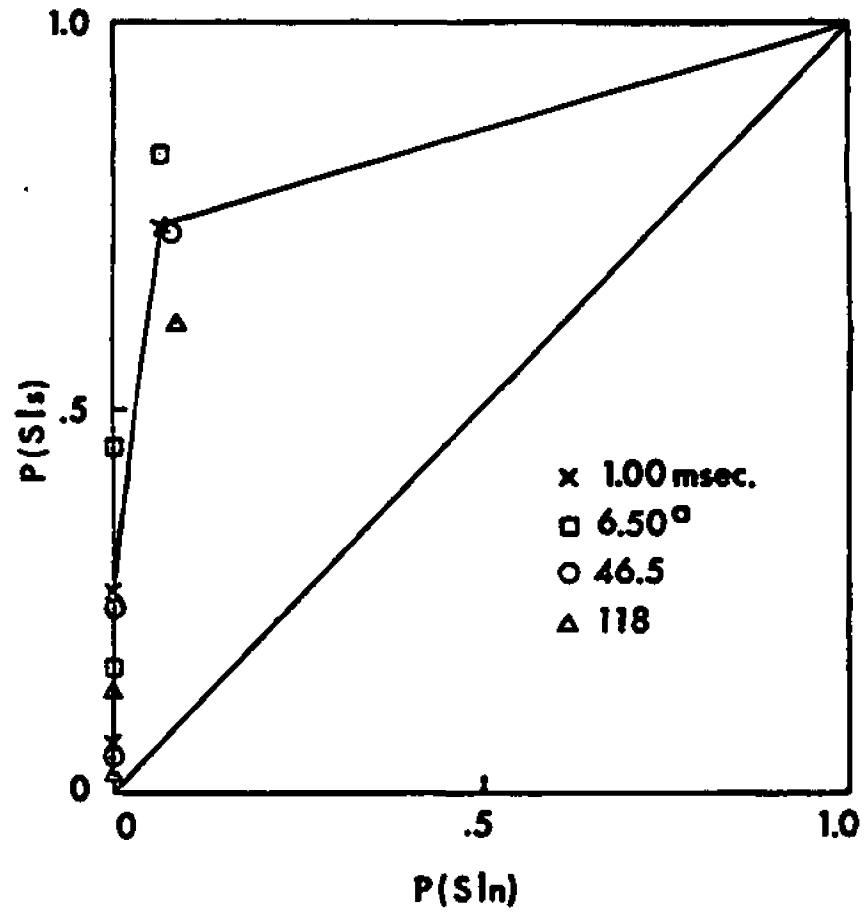
Fig. 11. ROC curves obtained by O:WC and O:GB for each of the luminance-varied (x) and duration-varied-I (\square), -II (\circ), and -III (\triangle) conditions at E4.

^aThis duration-varied-I condition had about 8% greater luminous energy than the O's other conditions at E4 (see Appendix IV).

^bThis luminance-varied condition had about 5% greater luminous energy than the O's other conditions at E4 (see Appendix IV).

E4

Q: WC



Q: GB

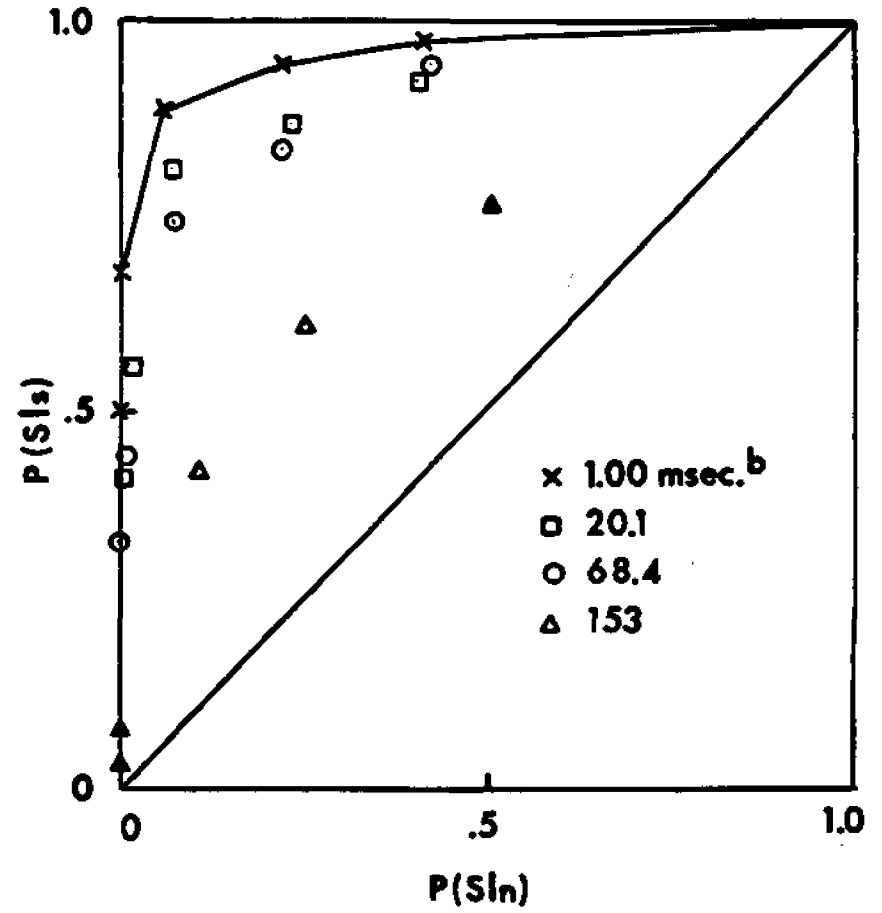


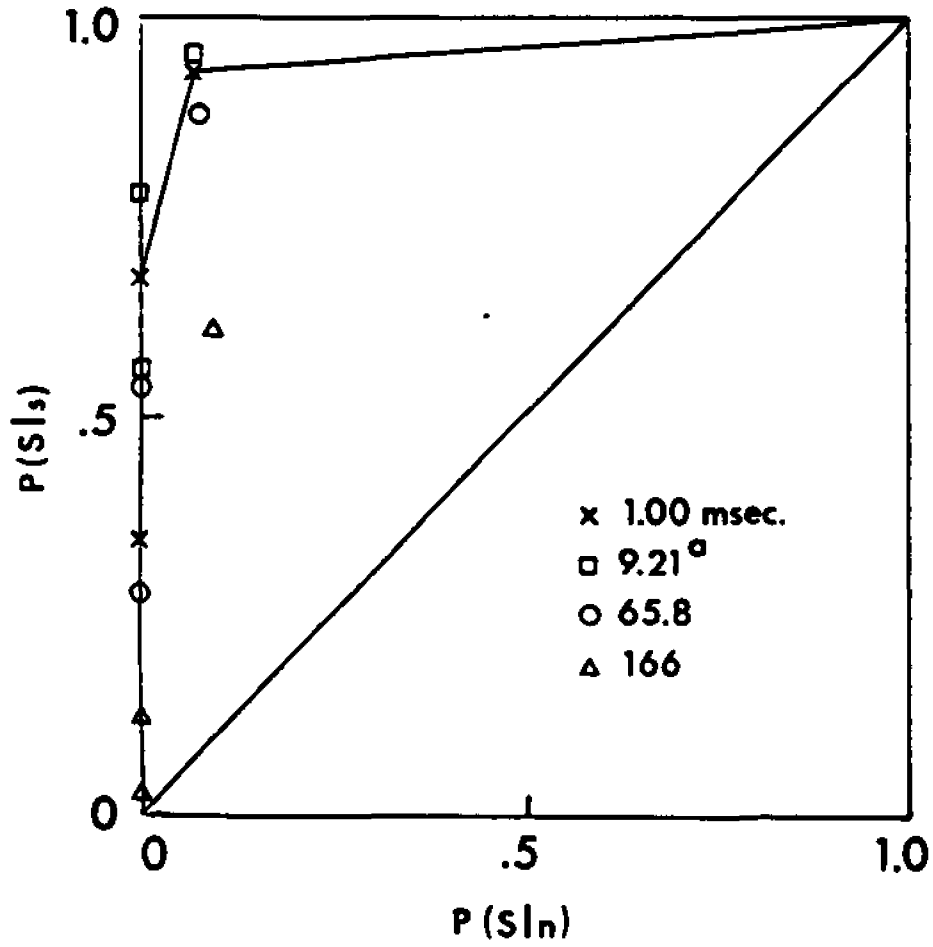
Fig. 12. ROC curves obtained by \underline{O} :WC and \underline{O} :GB for each of the luminance-varied (x) and duration-varied-I (\square), -II (o), and -III (Δ) conditions at E5.

^aThis duration-varied-I condition had about 8% greater luminous energy than the \underline{O} 's other conditions at E5 (see Appendix IV).

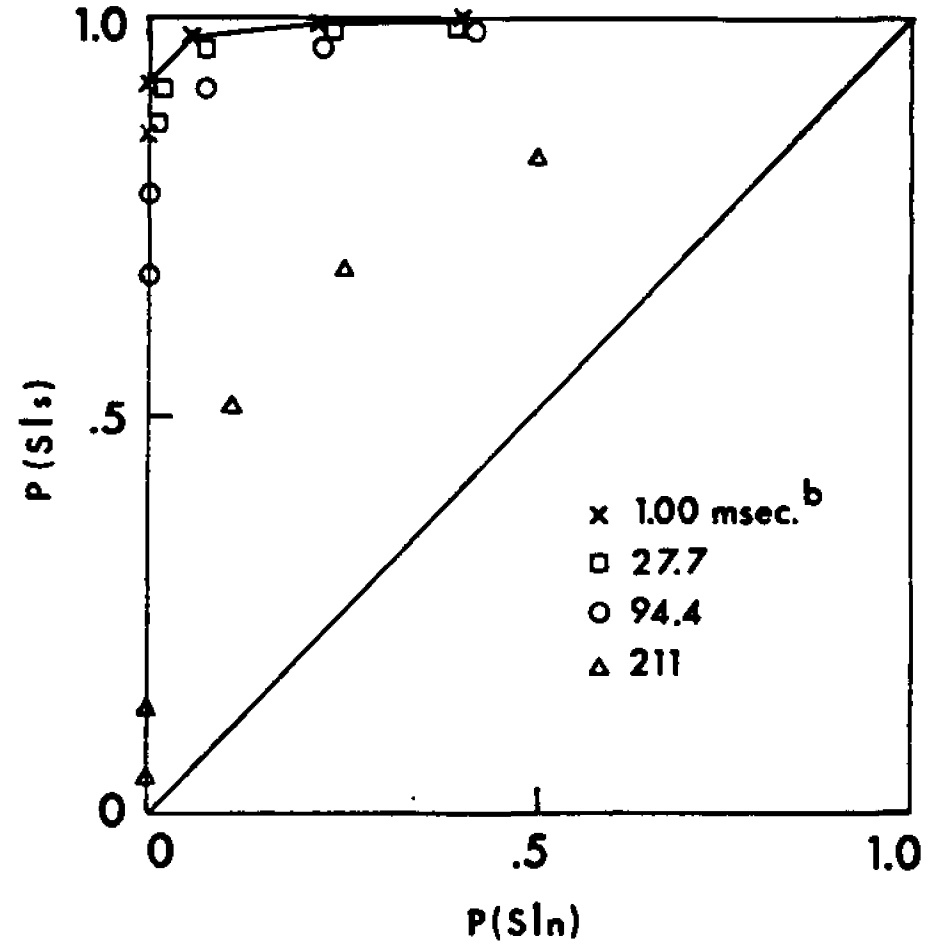
^bThis luminance-varied condition had about 5% greater luminous energy than the \underline{O} 's other conditions at E5 (see Appendix IV).

E5

Q: WC



Q: GB

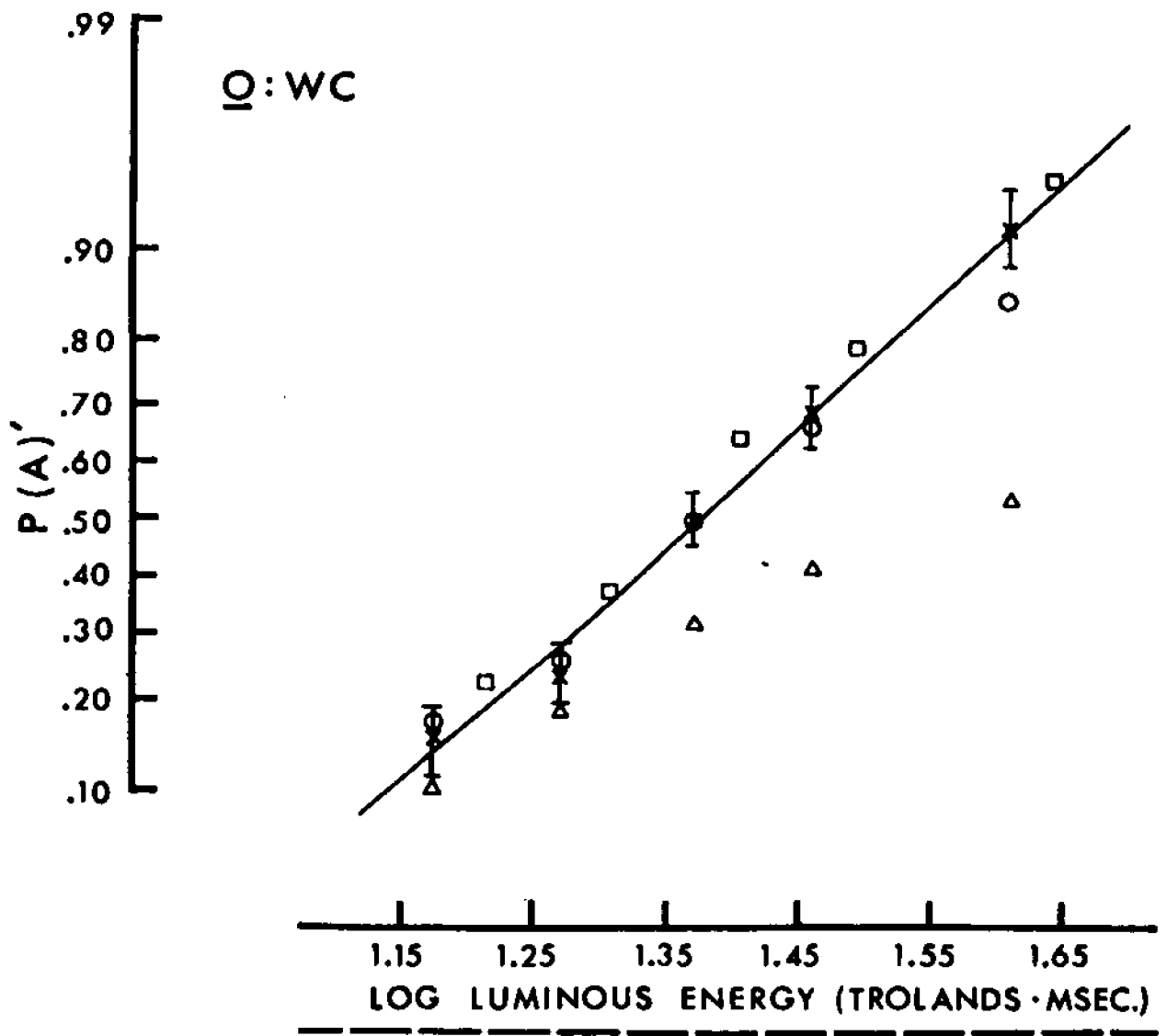


Increasing the luminous energy from E1-E5 led to an increase in the distance of the points on the ROC curves from the chance diagonal (straight line running from lower left origin to upper right origin). This was reflected in an increase in the proportion of area under the ROC curves.⁴ However, equal-energy luminance-varied and duration-varied conditions shorter than about 50 msec. show highly similar ROC curves with approximately equal proportion of area under the curves. In the ROC curves for O:WC, the data points for the 24.2-46.5 msec. duration-varied-II conditions overlapped the ROC curves for the equal-energy luminance-varied pairs. The data points for longer duration-varied-II and -III conditions ranging from 61-166 msec. fell below the ROC curves for the equal-energy luminance-varied pairs. Similarly, the ROC curves obtained by O:GB for equal-energy luminance-varied and duration-varied conditions of 40 msec. or less were almost identical. O:GB's ROC curves for duration-varied conditions of 50.8 msec or longer fell below the ROC curves for shorter equal-energy conditions. Thus, the ROC curves for both Os obeyed Bloch's law when the stimulus duration was less than about 50 msec. At longer durations, the ROC curves show partial rather than complete integration.

Figures 13 and 14 show the psychometric functions obtained for O:WC and O:GB when using the adjusted proportion of area under the ROC, i.e. $P(A)'$, as the signal detectability measure. The $P(A)'$ psychometric functions obtained for the

⁴To compute the proportion of area under each ROC curve, the points on each ROC, the lower left origin, and the upper right origin were connected by straight lines (e.g. as shown for the ROC curves for the luminance-varied conditions in Figures 8-12). The ROC was then divided into trapezoids and its area determined using the trapezoidal rule.

Fig. 13. The P(A)' psychometric functions obtained by O:WC for the 1 msec. luminance-varied conditions (x), and the duration-varied-I (\square), -II (o), and -III (\triangle) conditions.

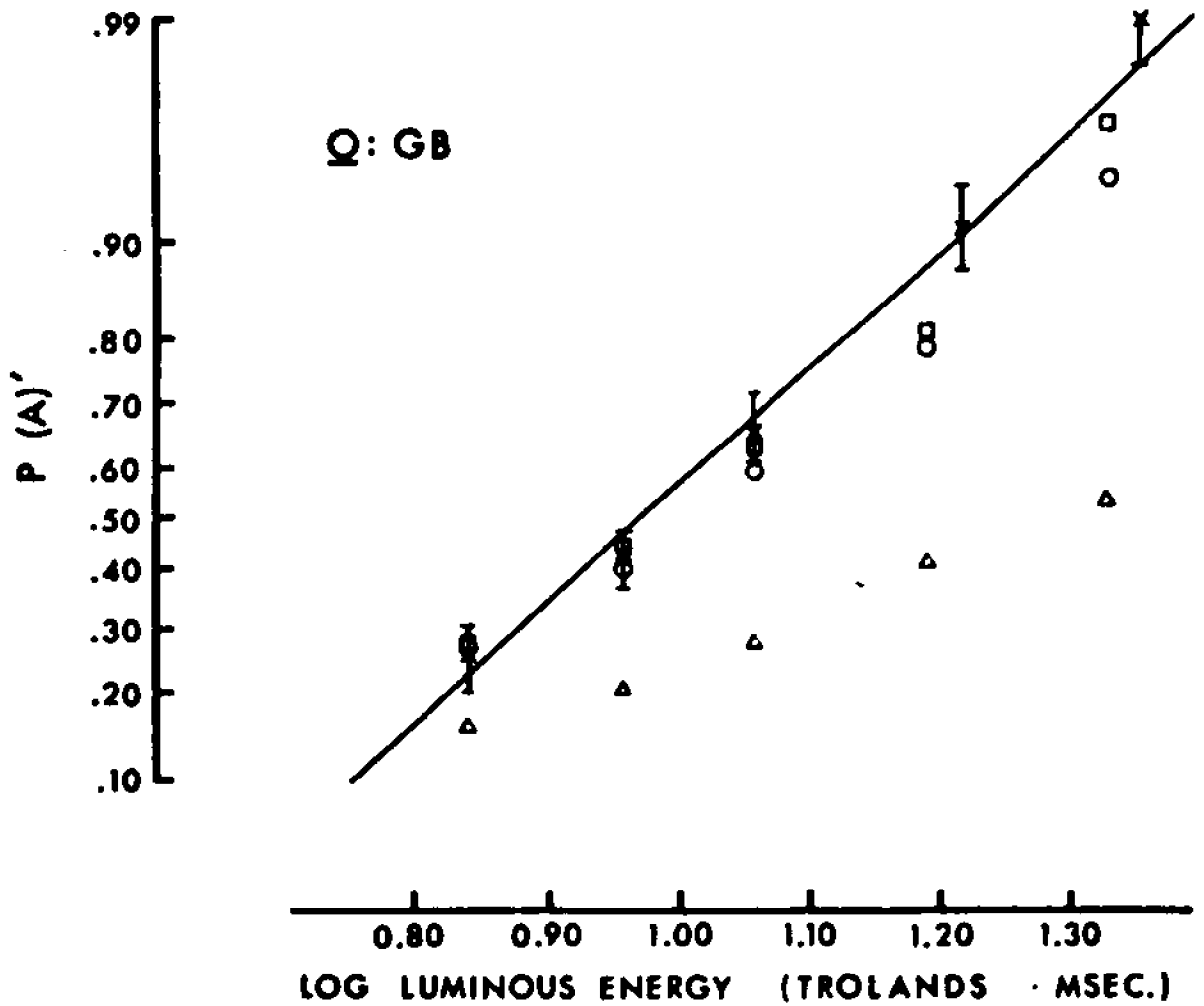


1.15 1.25 1.35 1.45 1.55 1.65
 LOG LUMINOUS ENERGY (TROLANDS · MSEC.)

DURATIONS (MSEC.)

□	□	□	□	□
3.39	4.21	5.31	6.50	9.21
○	○	○	○	○
24.2	30.1	38.0	46.5	65.8
△	△	△	△	△
61	76	96	118	166

Fig. 14. The $P(A)$ ' psychometric functions obtained by O:GB for the 1 msec. luminance-varied conditions (x), and the duration-varied-I (\square), -II (\circ), and -III (Δ) conditions.



DURATIONS (MSEC.)

□	□	□	□	□
8.8	11.8	14.9	20.1	27.7
○	○	○	○	○
30.0	40.0	50.8	68.4	94.4
△	△	△	△	△
67	90	114	153	211

luminance-varied conditions⁵ are very similar to those seen for the response frequency measure. Likewise, the functions for the duration-varied-I and -II conditions demonstrate luminance-duration reciprocity up to about the same critical durations as found for the response frequency measure, i.e. in the region of 46.5-65.8 msec. for O:WC and 40.0-50.8 msec. for O:GB. Note that the P(A)' for even the shortest duration-varied-III conditions (61 msec. for O:WC and 67 msec. for O:GB) fell below the luminance-varied function as would be expected if these durations were beyond the critical duration. Thus, the P(A)' measure revealed differences between these equal-energy luminance-varied and duration-varied-III conditions that were obscured in the response frequency data due to criterion differences. The P(A)' measure, unlike the response frequency measure, allowed for the laxer criterion and resulting higher false alarm rates for the duration-varied-III conditions (see Tables 3 and 4) and thereby yielded functions for the duration-varied-III conditions that suggest less integration than the corresponding response frequency functions. However, the duration-varied-III function for the P(A)' measure had the same form as was found for the response frequency measure, and similarly, demonstrated partial integration out to the longest duration used in the main experiment.

Although very similar characteristics of temporal integration are suggested in the ROC curves for the two Os, the larger number of points on O:GB's ROC curves

⁵The extremely high value of P(A)' obtained by O:GB at the highest luminous energy level was not included in the least-square fit of the luminance-varied conditions. The dropping of such extreme proportions is common practice when fitting psychometric functions (e.g. see Guilford, 1954, p. 130-131).

give a more detailed picture of the form of the ROC curves. Generally, the luminance-varied and duration-varied conditions showed ROC curves of similar form. The ROC curves were not symmetrical about the negative diagonal of the ROC graph. When these asymmetrical ROC curves were plotted on double probability paper and fitted by eye with straight lines (e.g., as shown in Figure 15 for the luminance-varied conditions) they all showed slopes (m) of less than unity. Moreover, the slopes of the ROC curves tended to decrease slightly the higher the luminous energy.

Response latency. The characteristics of integration obtained for RT are not unlike those seen for the response frequency and signal detectability measures. The major difference is in the shorter critical duration and utilization time found for the Os' median RTs. Thus, luminance-duration reciprocity was demonstrated in the median RTs of both Os up to a critical duration of about 25-30 msec. This was followed by a period of partial integration lasting up to a utilization time in the region of 65-95 msec. Moreover, luminance-duration reciprocity was also obtained for the RT semi-interquartile ranges over an even longer period than for the median RTs.

Cumulative frequency distributions of the RTs to the luminance-varied and duration-varied conditions at the five levels of luminous energy are given in Figure 16 (O:WC) and Figure 17 (O:GB). These frequency distributions show the proportions of RTs to each stimulus condition that were shorter than values of t on the abscissa. For both Os, increasing the luminous energy via luminance led not only to a decrease in the median RT (i.e. the value of t at which $P = .50$), but also to a decrease in the variability of RTs (i.e. steeper RT distributions). The frequency distributions obtained for both Os' duration-varied-I conditions demonstrated similar decreases in RT medians

Fig. 15. O:GB's ROC curves for the luminance-varied conditions (E1-E5) plotted on double-probability paper. The slopes (m) of the straight lines fitted to the data points are also shown.

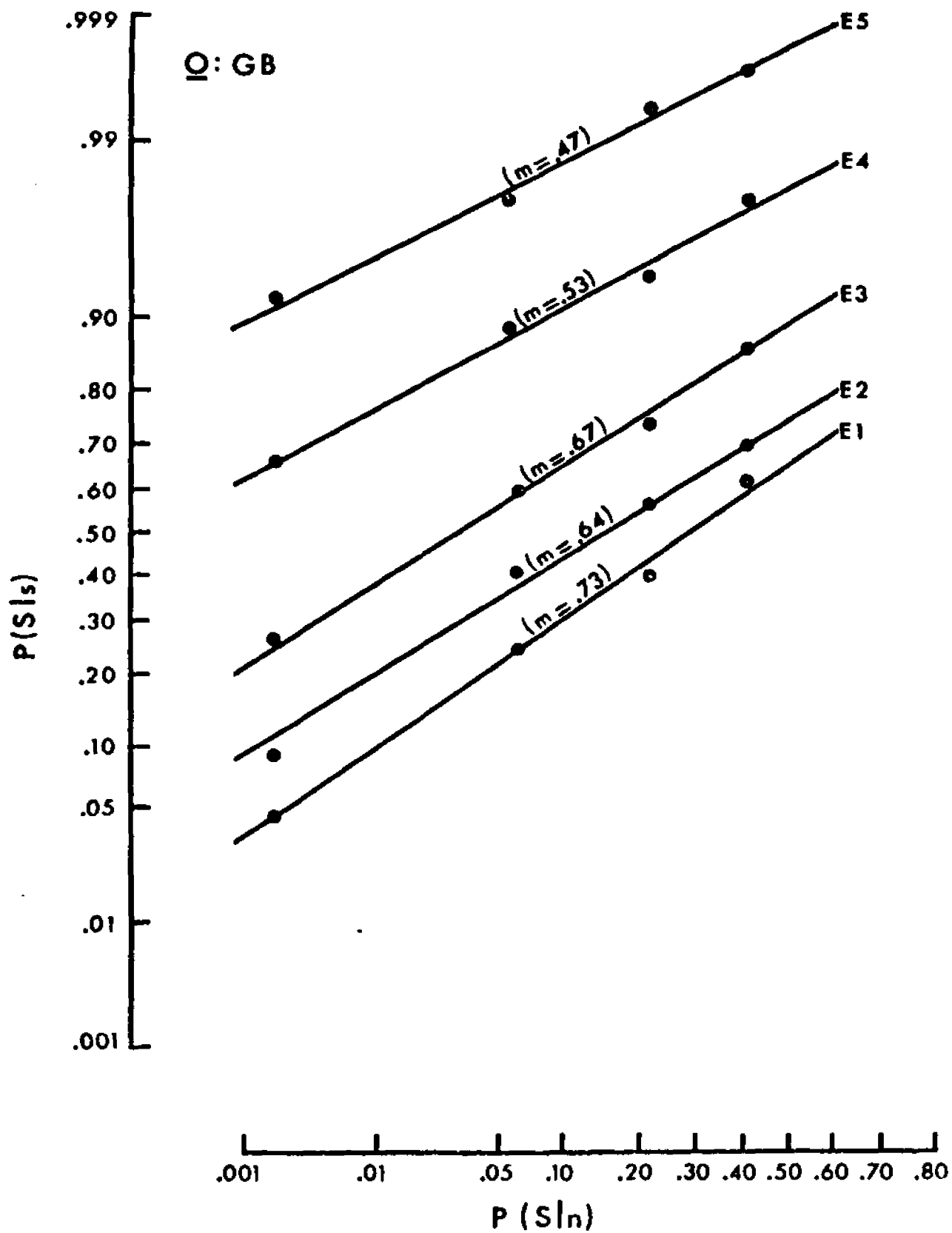


Fig. 16. The cumulative frequency distributions of RTs, i.e. the proportions of RTs shorter than values of t on the abscissa, for each of \bar{O} :WC's luminance-varied (x) and duration-varied-I (a), -II (o), and -III (Δ) conditions at E1-E5.

^aThese duration-varied-I conditions had about 8% greater luminous energy than the \bar{O} 's other conditions at the same energy level.

Q:WC

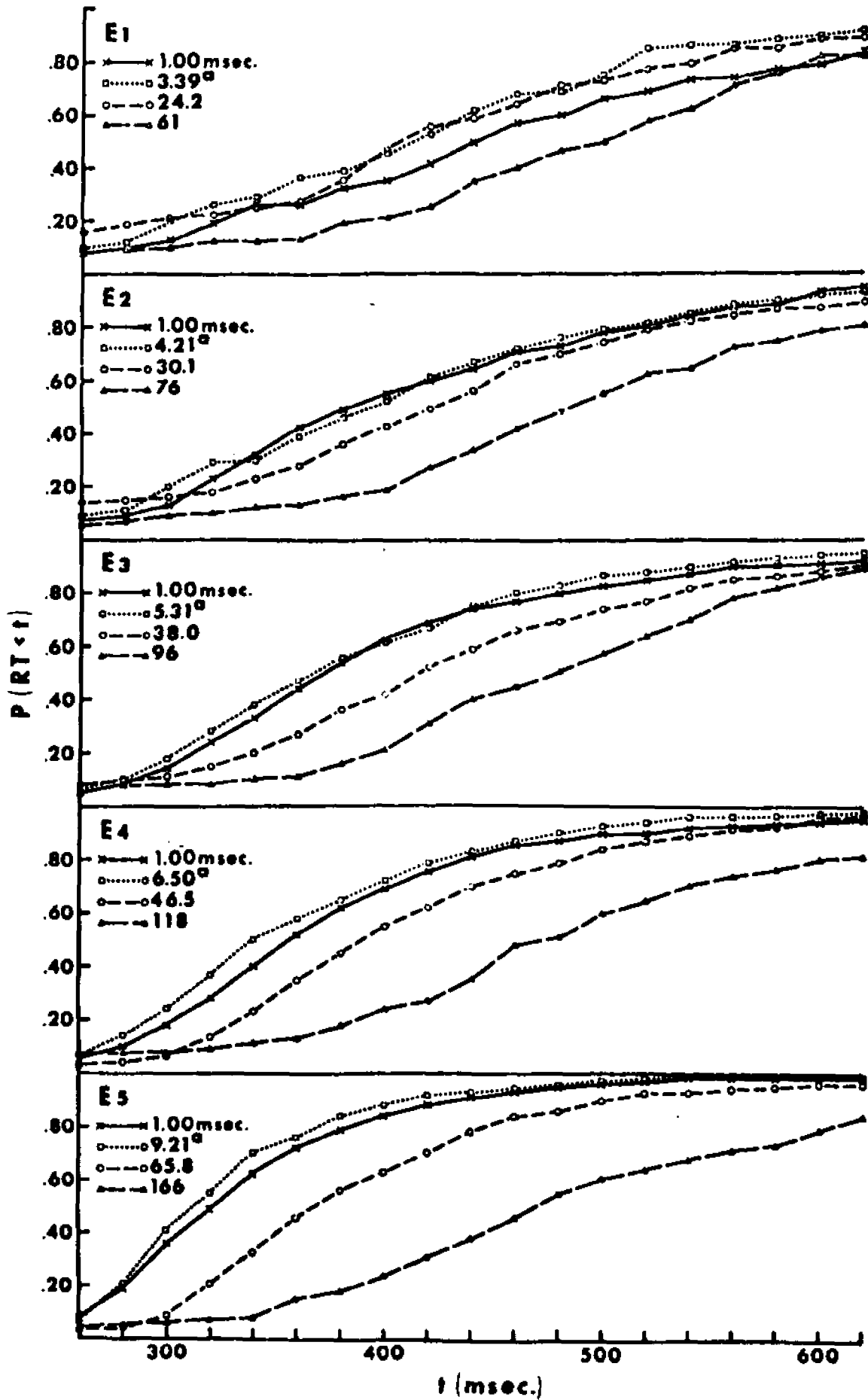
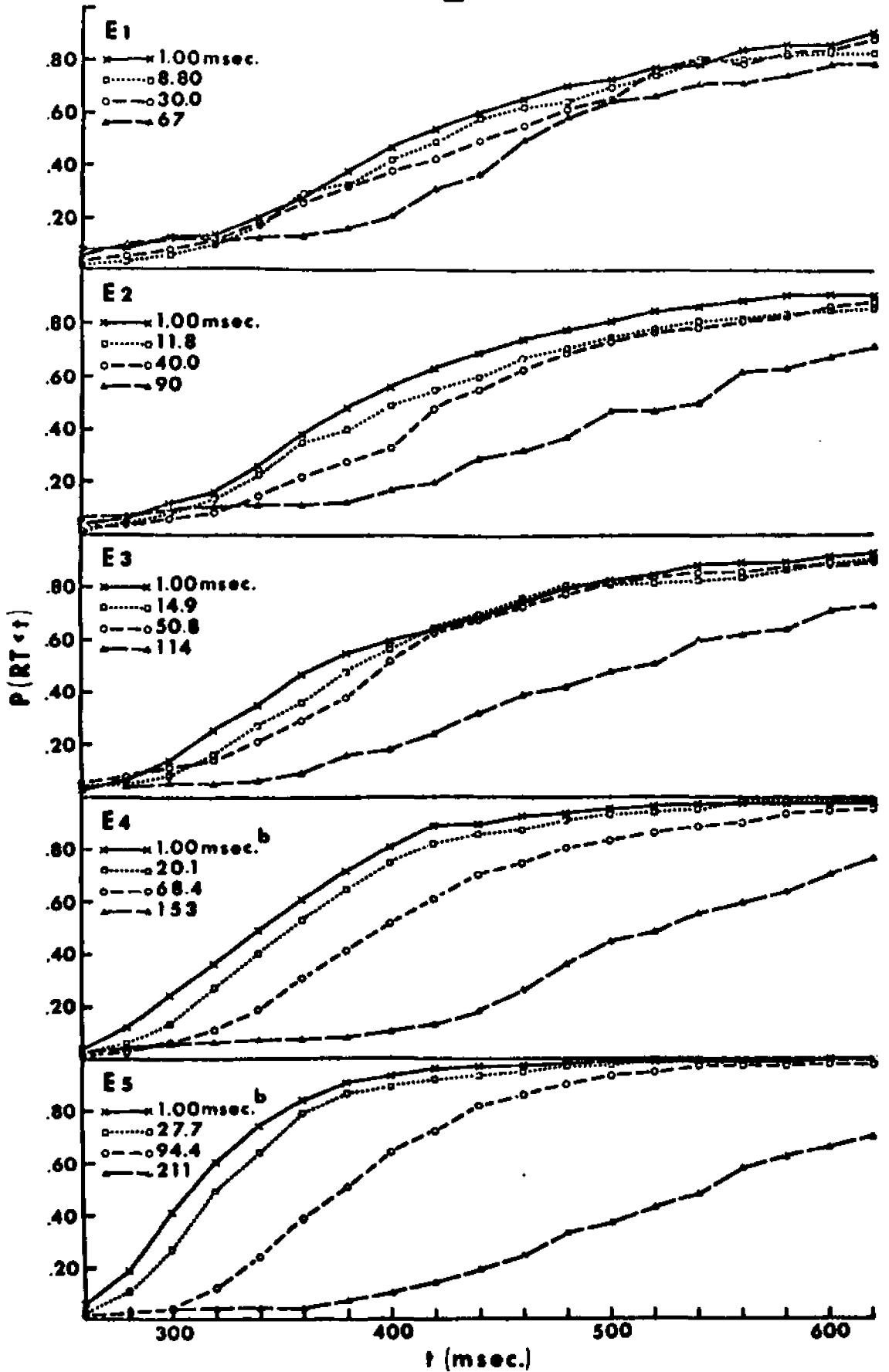


Fig. 17. The cumulative frequency distributions of RTs, i.e. the proportions of RTs shorter than values of t on the abscissa, for each of O:GB's luminance-varied (x) and duration-varied-I (■), -II (○), and -III (△) conditions at E1-E5.

^bThese luminance-varied conditions had about 5% greater luminous energy than the O's other conditions at the same energy level.

Q:GB



and variabilities with increasing luminous energy as seen for the luminance-varied conditions. Increases in luminous energy via duration were effective in reducing RT medians and variabilities up to a duration of about 65 - 95 msec. after stimulus onset. Further increases in duration did not appreciably affect the RT frequency distributions.

The \underline{O}_s ' cumulative frequency distributions for very short duration-varied conditions and their luminance-varied pairs were found to obey Bloch's law. Thus, the results of Kolmogorov-Smirnov tests showed that the \underline{O}_s ' frequency distributions for duration-varied conditions of 30 msec. or less and their equal-energy luminance-varied pairs did not differ significantly. Table 5 gives the maximum differences between the proportions on the frequency distributions for the luminance-varied and duration-varied conditions at each luminous energy level, and also, the maximum differences that must be exceeded to reach significance at $\alpha = .05$ (values in parenthesis). The data for both \underline{O}_s show differences in the frequency distributions for equal-energy luminance-varied and duration-varied conditions of 30 msec. or less, but in all cases these differences were not significant. However, the duration-varied conditions of 38 msec. for $\underline{O}:WC$ and 40 msec. for $\underline{O}:GB$ did yield frequency distributions that were significantly different from their equal-energy luminance-varied pairs. This indicates that the RT frequency distributions obeyed Bloch's law up to durations as long as 30 msec. The RT medians and variances(semi-interquartile ranges) should, therefore, also obey Bloch's law at these very short durations. The next sections show that this was indeed the case.

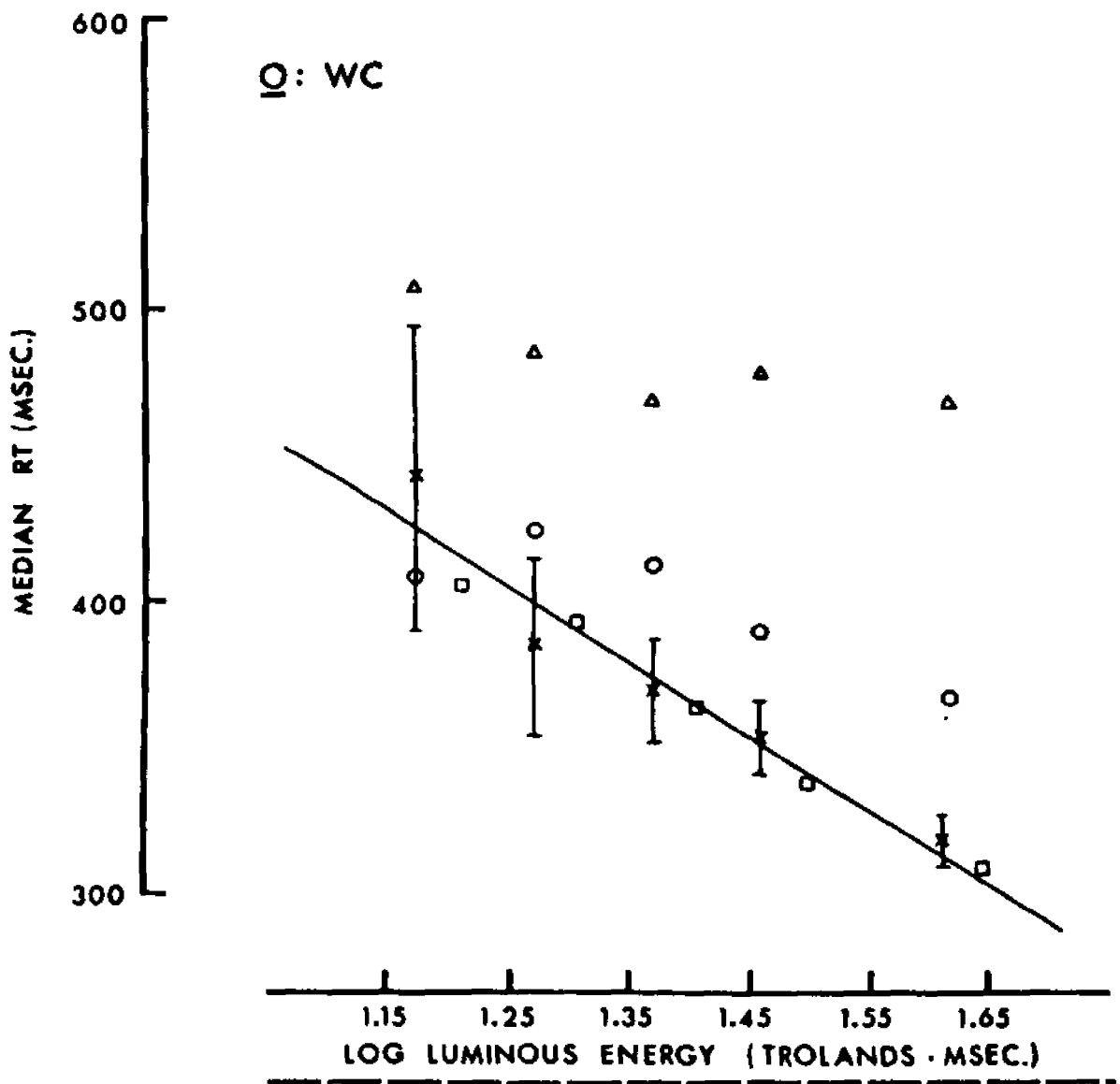
The median RT vs. log luminous energy functions obtained for $\underline{O}:WC$ (Figure 18) and $\underline{O}:GB$ (Figure 19) show that increasing the luminous energy via luminance

TABLE 5

Maximum Differences (D) Between the Cumulative RT Distribution for Each Duration-varied Condition and Its Luminance-varied Pair and Values of D Needed for Significance at $\alpha = .05$

Duration varied I	<u>O:WC</u>		Duration varied I	<u>O:GB</u>	
	D	D $\alpha = .05$		D	D $\alpha = .05$
3.39 msec.	.159	(.206)	8.8 msec.	.093	(.210)
4.21	.063	(.168)	11.8	.096	(.167)
5.31	.057	(.131)	14.9	.093	(.132)
6.50	.103	(.116)	20.1	.105	(.111)
9.21	.080	(.105)	27.7	.145	(.104)
Duration varied II			Duration varied II		
24.2 msec	.136	(.213)	30.0 msec.	.117	(.206)
30.1	.147	(.180)	40.0	.230	(.166)
38.0	.207	(.137)	50.8	.181	(.137)
46.5	.171	(.120)	68.4	.307	(.114)
65.8	.282	(.108)	94.4	.506	(.105)
Duration varied III			Duration varied III		
61 msec.	.176	(.226)	67 msec.	.260	(.218)
76	.355	(.185)	90	.437	(.183)
96	.418	(.150)	114	.417	(.161)
118	.479	(.132)	153	.746	(.135)
166	.602	(.120)	211	.838	(.124)

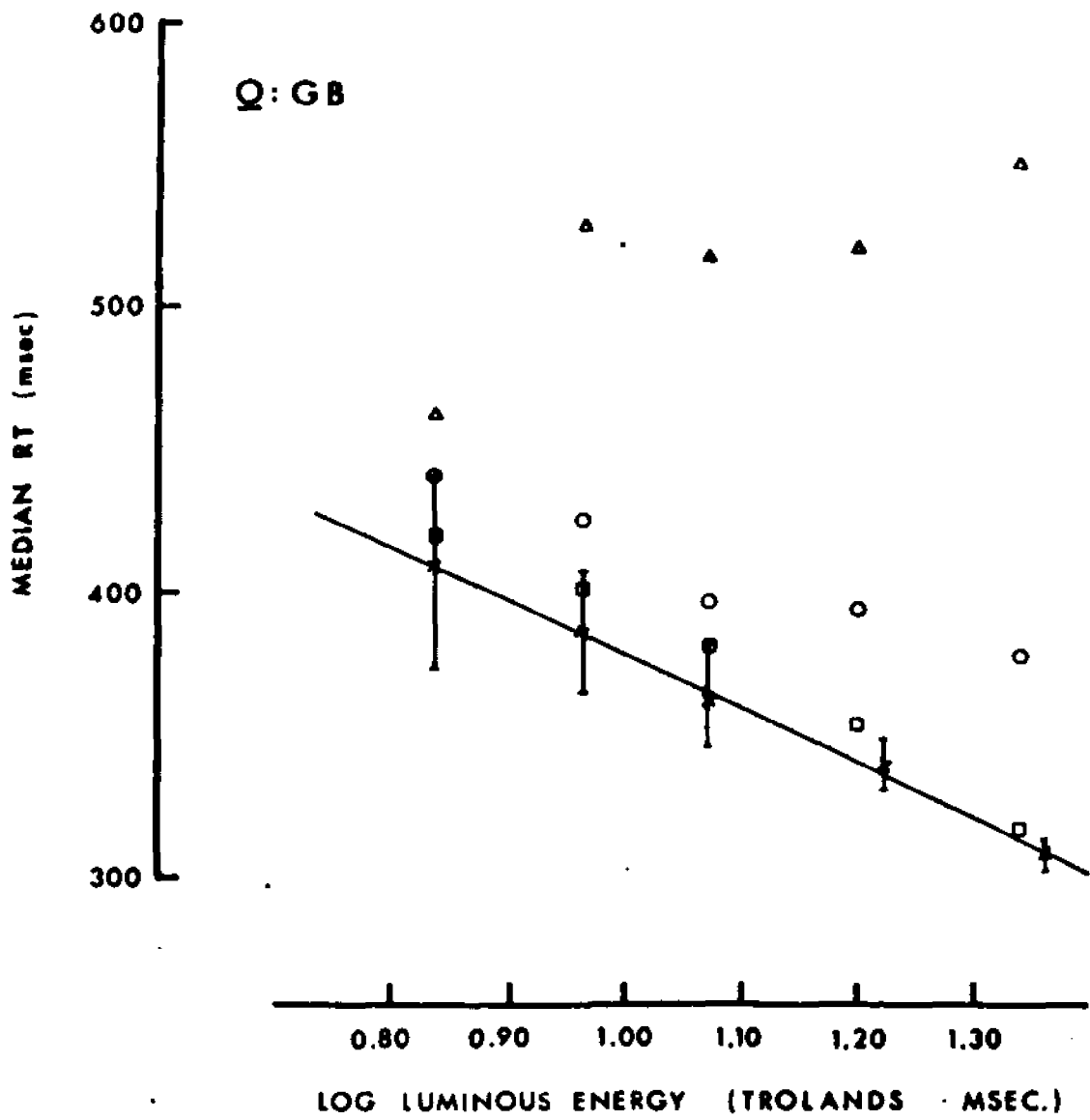
Fig. 18. The median RT vs. log luminous energy functions obtained by O:WC for the 1 msec. luminance-varied conditions (x), and the duration-varied-I ($\bar{\square}$), -II (o), and -III (Δ) conditions.



DURATIONS (MSEC.)

□	□	□	□	□
3.39	4.21	5.31	6.50	9.21
○	○	○	○	○
24.2	30.1	38.0	46.5	65.8
△	△	△	△	△
61	76	96	118	166

Fig. 19. The median RT vs. log luminous energy functions obtained by O:GB for the 1 msec. luminance-varied conditions (x), and the duration-varied-I (a), -II (o), and -III (Δ) conditions.



DURATIONS (MSEC.)

□	□	□	□	□
8.8	11.8	14.9	20.1	27.7
○	○	○	○	○
30.0	40.0	50.8	68.4	94.4
△	△	△	△	△
67	90	114	153	211

resulted in a monotonic decrease in the median RT. The median RTs obtained by O:WC for the duration-varied-I conditions (3.39-9.21 msec.) overlapped his luminance-varied function, demonstrating luminance-duration reciprocity at these very short durations. The first departure from reciprocity occurred in his duration-varied-II conditions at 30.1 msec. At this point, the functions for the duration-varied-II and luminance-varied conditions separated with longer median RTs evident for the duration-varied-II conditions. This suggests that the critical duration for median RT was in the interval from 24.3 to 30.1 msec. Somewhat longer duration-varied-I conditions were used for O:GB to determine in more detail the nature of the integration between 9 and 30 msec. All of his duration-varied-I conditions (8.8-27.7 msec.) yielded longer median RTs than would be expected if there were complete reciprocity at these durations. However, the deviations of the points for the duration-varied-I conditions from the luminance-varied function were small, and in general, did not exceed the 95% confidence limits. Also, the median RT functions for the duration-varied-I conditions and the luminance-varied conditions showed very similar slopes, indicating that increasing the luminous energy via duration was just as effective in reducing the median RT as increasing luminous energy via luminance. Larger departures from the luminance-varied function were evident for O:GB's duration-varied-II conditions starting at the shortest duration--30 msec.

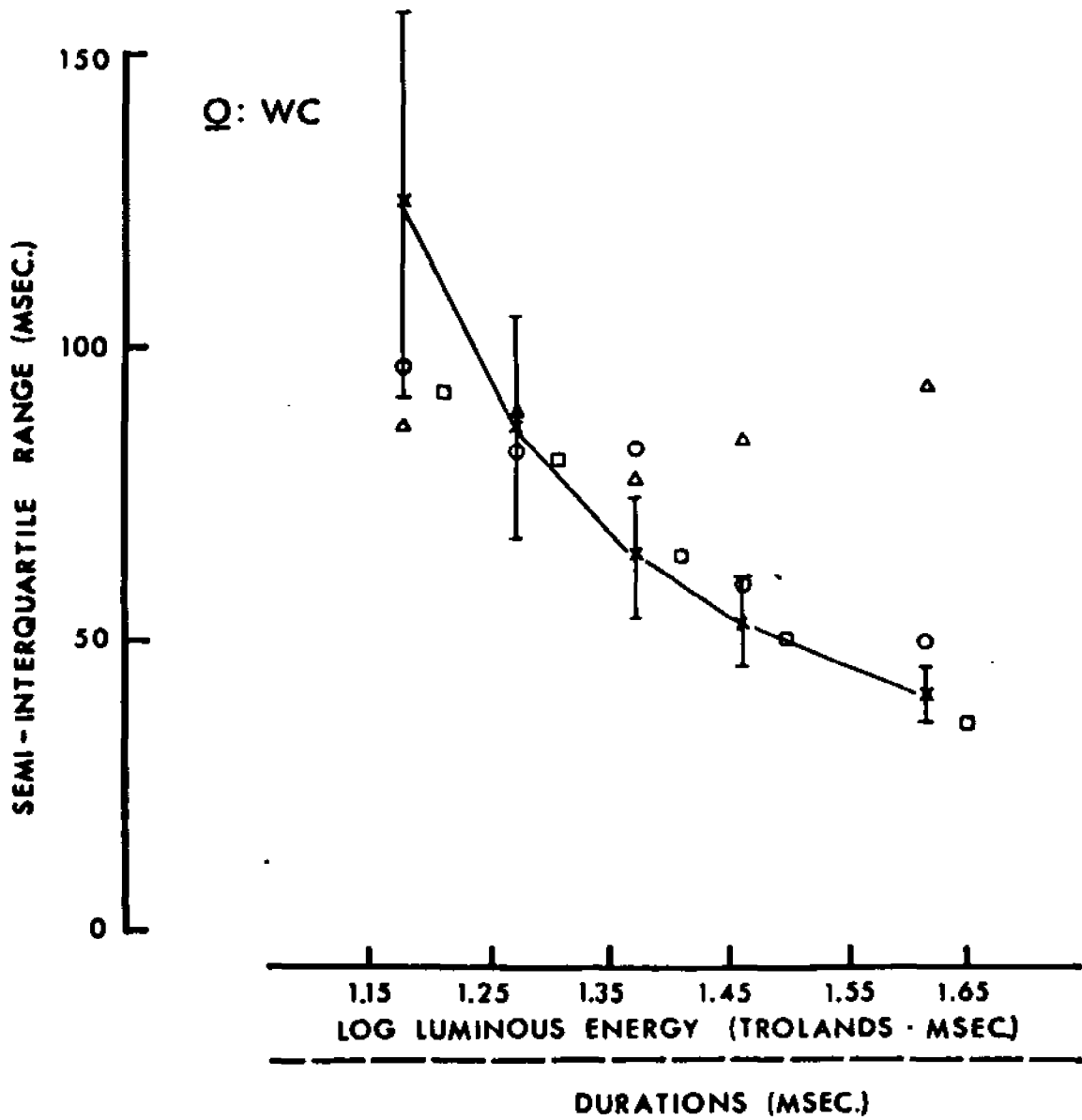
Thus, the results for both Os suggest that the critical duration for median RT was most likely in the region of 25-30 msec., which is shorter than the critical durations for the response frequency and P(A)' measures. The Os' duration-varied-II conditions ranging from about 30-50 msec. yielded considerably longer median RTs than their equal-energy luminance-varied pairs, although both the response frequency

and $P(A)'$ for these pairs were about the same. Increases in duration were, however, at least partially effective in reducing the median RT up to a utilization time of about 76 to 96 msec. for $\underline{O}:WC$ and 68.4 to 94.4 for $\underline{O}:GB$. The utilization times for median RT were therefore considerably shorter than for the response frequency and $P(A)'$ measures.

In Figures 20 and 21, the semi-interquartile ranges obtained for each of the \underline{O} 's' luminance-varied and duration-varied conditions are plotted as a function of the log luminous energy of these conditions. In general, increasing the luminous energy via luminance resulted in a decrease in the semi-interquartile range.⁶ The data points for the \underline{O} 's' duration-varied-I conditions fell along the luminance-varied functions demonstrating luminance-duration reciprocity at these short durations. Most importantly, the semi-interquartile ranges for the duration-varied-II conditions show reciprocity out to longer durations than seen for the median RT data. Note that the semi-interquartile range obtained by $\underline{O}:WC$ for the 30.1 msec. condition did not show the departure from reciprocity seen for the median RT for this condition. The largest difference in the critical durations for the median and semi-interquartile range is demonstrated in $\underline{O}:GB$'s data. Although his median RTs for the 30.0-50.8 msec. conditions showed obvious departures from reciprocity, his semi-interquartile ranges for these same conditions overlapped the luminance-varied function thereby demonstrating reciprocity at these durations. $\underline{O}:GB$'s data indicate that his critical duration for the semi-interquartile range was in the region of 50.8-68.4 msec. This is definitely

⁶The data points for $\underline{O}:WC$'s luminance-varied conditions were not fitted by a linear least-squares line because of the obviously poor fit of this function to the points.

Fig. 20. The RT semi-interquartile range vs. log luminous energy functions obtained by O:WC for the 1 msec. luminance-varied conditions (x), and the duration-varied-I (a), -II (o), and -III (Δ) conditions.

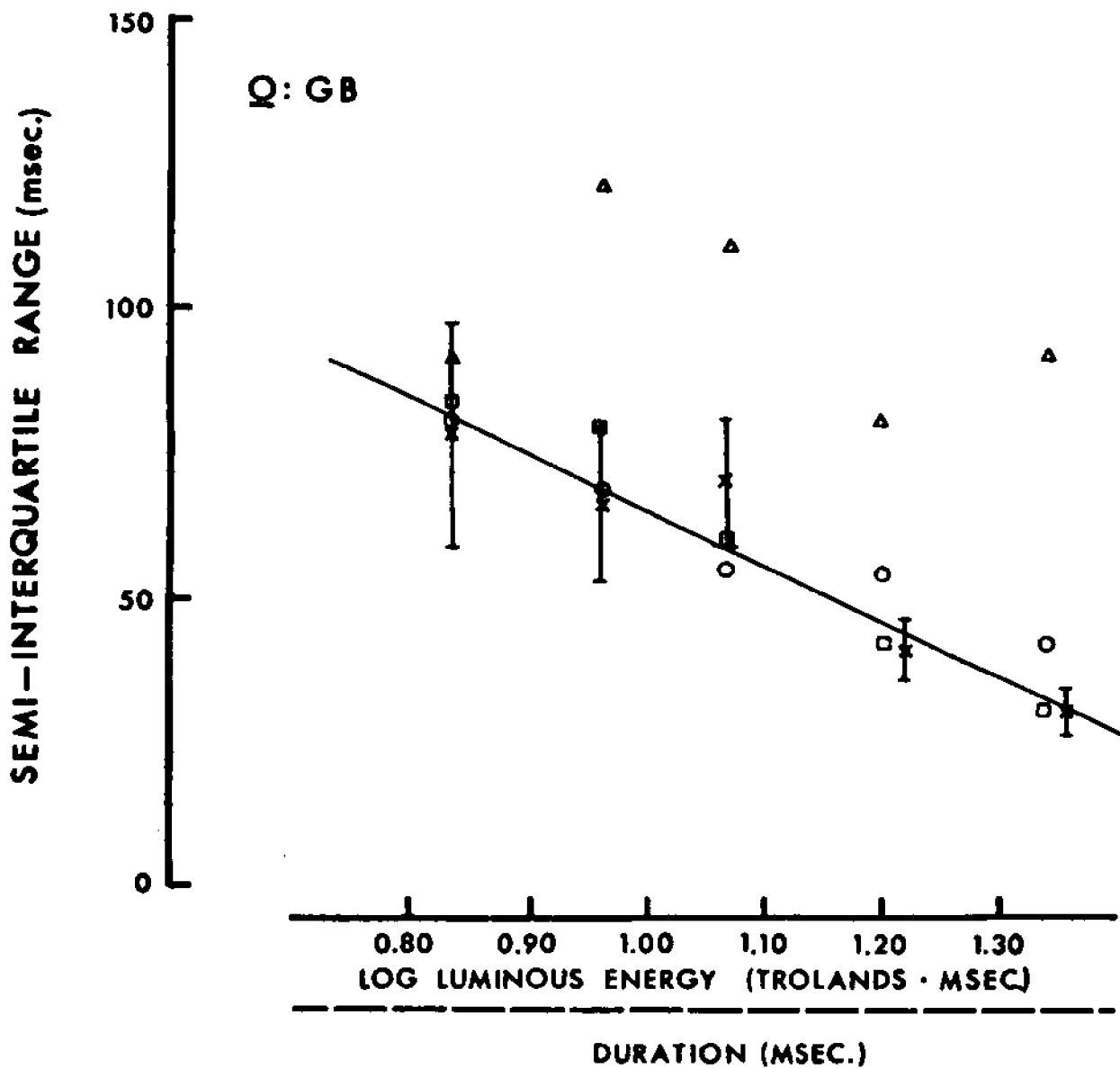


LOG LUMINOUS ENERGY (TROLANDS · MSEC)

DURATIONS (MSEC.)

□	□	□	□	□
3.39	4.21	5.31	6.50	9.21
○	○	○	○	○
24.2	30.1	38.0	46.5	65.8
△	△	△	△	△
61	76	96	118	166

Fig. 21. The RT semi-interquartile range vs. log luminous energy functions obtained by O:GB for the 1 msec. luminance-varied conditions (x), and the duration-varied-I (□), -II (○), and -III (△) conditions.



□	□	□	□	□
8.8	11.8	14.9	20.1	27.7
○	○	○	○	○
30.0	40.0	50.8	68.4	94.4
△	△	△	△	△
67	90	114	153	211

longer than his critical duration for median RT, but is in the same range as his critical durations for the response frequency and P(A)' measures. The Q's' semi-interquartile ranges did not, however, show longer utilization times than their medians. There was no evidence of any additional integration beyond the longest duration-varied-II conditions, i.e. 65.8 msec. for Q:WC and 94.4 for Q:GB.

CHAPTER VI

Discussion

Response frequency

The luminance-duration relations evident in the response frequency data obtained during the preliminary testing and the main experiment were highly similar. The relatively new paradigm used to estimate the characteristics of integration in the main experiment yielded results that would be predicted based on the more traditional IT vs. T functions obtained in the preliminary testing. There was a period of luminance-duration reciprocity during which increases in the luminous energy via duration resulted in a percent response psychometric function that was identical to that found for equivalent increases via luminance. The duration-varied and luminance-varied functions overlapped up to a critical duration in the region of 45-65 msec., beyond which, the percent response was lower for the duration-varied as compared to equal-energy luminance-varied conditions. The critical duration was followed by a period of partial integration during which increases in the luminous energy via duration were only partially as effective in increasing the percent response as equivalent increases via luminance. Although the duration-varied conditions were not long enough to allow an exact determination of the utilization time, the IT vs. T functions from the preliminary testing suggested that there was no additional integration beyond 200 msec.

These characteristics of temporal integration for the response frequency measure are in close agreement with those seen in most prior threshold studies and, in particular, with those evident in the IT vs. T function obtained by Sperling and Jolliffe (1965) for similar stimulus conditions as employed in the present study (see Figure 1). It is interesting, however, that Sperling and Jolliffe found different estimates of the critical duration and utilization time than determined in the present study. Their IT vs. T function suggests both a shorter critical duration (in region of 5-25 msec.) and a longer utilization time (in region of 200-500 msec.) than found in the response frequency data of the present study. This illustrates the difficulty of comparing the values of critical duration or utilization time across different studies. Even studies using similar stimulus conditions and the same response measure may yield different estimates of these values. What was responsible for these differences? When comparing across studies from different laboratories, using different \underline{O}_s , it should be clear that there is room for a large number of differences which could have contributed to the difference in the critical duration and utilization time. Just two of the possible differences are the \underline{O}_s ' criteria and the luminous energy at threshold. The present study did not, as commonly done in threshold studies, encourage the \underline{O}_s to avoid false alarms, and thereby, adopt a very strict criterion. The criteria of the \underline{O}_s in this study may, therefore, have been laxer than the criteria of the \underline{O}_s in many threshold studies, including Sperling and Jolliffe's study. Note also that a laxer criterion will result in a reduction of the luminous energy needed to reach threshold (e.g. Barlow, 1956). Barlow showed that a lowering of the criterion that resulted in just a 2% increase in the false alarm rate produced a 25% reduction in the threshold. Thus, the \underline{O}_s in Sperling and Jolliffe's study may not only have had a stricter criterion,

but also higher luminous energy thresholds than the \underline{O} s in the present study.

Unfortunately, Sperling and Jolliffe did not give any information on the criterion of their \underline{O} s or the absolute luminous energy of their stimuli.

The results of the present study illustrated how a criterion difference across stimulus conditions could influence the estimate of the critical duration for the response frequency measure. Thus, the laxer criterion adopted by the \underline{O} s for the duration-varied-III conditions resulted in a suggestion of a longer critical duration than observed for the duration-varied-II conditions. The possibility of such criterion differences across stimulus conditions influencing the value of the critical duration suggests the importance of at least monitoring the \underline{O} 's criterion in threshold studies of temporal integration. Reliable estimates of the false alarm rates should, therefore, be reported along with all threshold measures.

Signal detectability

In addition to monitoring the criterion, it may also be preferable to use signal detectability measures, e.g. $P(A)'$, that are not influenced by criterion shifts. Signal detectability measures are especially useful when there are criterion differences across stimulus conditions. In the present study, the $P(A)'$ measure allowed for the laxer criterion and resulting higher false alarm rates for the duration-varied-III conditions. As a result, the $P(A)'$ measure revealed differences between the shortest duration-varied-III conditions and their equal-energy luminance-varied pairs that were obscured in the response frequency data due to criterion differences. Thus, although the response frequency measure suggested that integration was complete for the shortest duration-varied-III conditions, the $P(A)'$ measure revealed departures from complete integration

that were consistent with the critical duration observed for the duration-varied-II conditions.

Despite the difference in integration suggested in the response frequency and signal detectability data for the duration-varied-III conditions, the overall results showed that the characteristics of integration for signal detectability were identical to those for the response frequency. Luminance-duration reciprocity was demonstrated for the signal detectability measure up to the same critical duration as for the response frequency measure. Likewise, partial integration was seen for the signal detectability measure over the same durations as for the response frequency measure.

The ROC curves obeyed Bloch's law, in that, equal-energy stimuli that were shorter than about 50 msec. yielded almost identical ROC curves. Stimuli that were longer than about 50 msec. yielded ROC curves of similar form, but with less area under the curves than equal-energy stimuli that were completely integrated. In general, the form of the ROC curves was asymmetrical. This supports Green and Swets' contention that, "Visual signals, perhaps without exception, yield asymmetrical [ROC] curves" (1966, p. 98). Moreover, when these asymmetrical ROC curves were plotted on double-probability paper they were well fitted by straight lines with slopes of less than unity. This agrees with the findings of prior studies of visual detection using the rating procedure (Nachmias, 1968; Nachmias & Steinman, 1963; Swets, Tanner, & Birdsall, 1961), which have obtained similar asymmetrical ROC curves. Green and Swets (1966, p. 94) suggested that such asymmetrical ROC curves are consistent with two different theoretical alternatives. First, they may imply that the signal-plus-noise and noise-alone distributions are not normal, but are exponential or Rayleigh distributions. The second alternative assumes that the distributions are

normal, but of unequal variance. In the latter case, the finding of asymmetrical ROC curves with slopes (on double probability axes) of less than one suggests that the variance of the signal-plus-noise distribution is greater than that of the noise-alone distribution. Furthermore, the decrease in the slope of the ROC curves with increasing luminous energy seen in the present study and by Nachmias and Steinman (1963) is consistent with the assumption that the variance of the signal-plus-noise distribution increases with its mean.

Response latency

Luminance-duration reciprocity was demonstrated in the RTs to very brief threshold level stimuli. This is contrary to Grossberg's (1968) suggestion that Bloch's law does not apply to RT at threshold, but agrees with similar demonstrations of luminance-duration reciprocity in the RTs to suprathreshold stimuli (Kaswan & Young, 1965; Kietzman and Gillam, in press; Lewis, 1964; Pease, 1971). Equal-energy stimuli of 30 msec. or less yielded similar RT distributions that were not significantly different from each other. Moreover, for stimuli less than about 30 msec., a single median RT vs. luminous energy function was obtained when varying either the luminance or duration of the stimuli over the same energy range. Thus, for these very short durations, increasing the luminous energy via duration was just as effective in reducing the median RT as equivalent increases in luminance. Overall, the RT data indicate the luminance-duration reciprocity held for the median RT up to a critical duration of about 25-30 msec.

Luminance-duration reciprocity was, therefore, demonstrated over a shorter period for the median RT measure than for the response frequency and signal detectability measures. The difference in the critical duration for these measures gives support to

Raab and Fehrer's (1962) contention that the critical duration for RT is shorter than the critical duration for threshold measures. Note particularly, that there was a range of durations ($\approx 30-50$ msec.) over which luminance-duration reciprocity failed for the median RT, but was evident for the response frequency and signal detectability measures. Thus, equal-energy stimuli that were equally detectable had quite different median RTs.

Partial integration was demonstrated for the median RT for durations well beyond the critical duration. However, the period over which partial integration was in evidence for the median RT--i.e. up to 65-95 msec. after stimulus onset--was considerably shorter than that for the response frequency and signal detectability measures. The median RTs, therefore, showed not only a shorter critical duration, but also a shorter utilization time than the response frequency and signal detectability measures.

Luminance-duration reciprocity was also demonstrated for the RT semi-interquartile ranges. This supports Grossberg's (1968) finding that the semi-interquartile range of RTs were consistent with Bloch's law. Moreover, the RT semi-interquartile ranges showed a critical duration that was longer than the critical duration for the median RT. Most interestingly, one O's critical duration for RT semi-interquartile range was the same as his critical duration for the response frequency and signal detectability measures. This would lend support for the notion that the variability of RT may serve as a sensitivity measure in psychophysics (e.g. see Steinman, 1944). However, the partial integration observed for the RT semi-interquartile range did not extend over as long a period as that for the response frequency and signal detectability measures. Rather, the utilization time for the RT semi-interquartile range agreed closely with the utilization time for the median RT.

The same characteristics of temporal integration were, therefore, demonstrated for RT as was found for the response frequency and signal detectability measures. The only difference between these response measures was the shorter values of the critical duration and utilization time for the median RT.

The interpretation of differences in the critical duration and utilization time for different response measures

Differences in the critical duration have been found not only for RT and psychophysical measures, but also for different psychophysical tasks (Kahneman & Norman, 1964). For example, Kahneman and Norman showed that the critical duration for an identification task was considerably longer than the critical duration for brightness matches obtained under the same stimulus conditions. Kahneman and Norman suggested that the different critical durations may correspond to the different perceptual processes involved in these tasks. Zacks (1970) has recently argued that the long critical duration for detectability is a property of the detection mechanism rather than the peripheral visual mechanism. Furthermore, Sperling (1970) has presented evidence for the existence of two parallel detection systems--a temporal system and a spatial system--each with its own critical duration. Thus, one possible interpretation of differences in the critical duration or utilization time for different response measures is that they stem from differences in the processes or mechanisms underlying these response measures.

Another possibility is that different response measures are related to different aspects or components of the neural responses, which have differing time constants of temporal integration. On the basis of his demonstration that equally detectable, equal-

energy flashes were discriminable from each other, Zacks (1970) concluded:

These results thus force the rejection of the hypothesis that equally detectable, equal-energy flashes are of the same detectability because they evoke identical neural responses (p. 198).

Equal detectability to equal-energy stimuli implies only that those aspects of the neural response that determined their detectability are equivalent. Other aspects of the neural response to these stimuli that determine their discriminability from each other may be different. The results of the present study showing that equally detectable, equal-energy stimuli had quite different RTs support Zacks' conclusions, and further, suggest that there may be differences in the latencies of the neural responses to equally detectable, equal-energy stimuli. Electrophysiological studies (Baker et. al., 1969; Hartline, 1934; Levick & Zacks, 1970; Wicke et. al., 1964; Zacks, 1967a) have actually demonstrated that equal-energy stimuli may yield neural responses of equivalent frequency, amplitude, or waveform, but of different latency. Moreover, the results of other behavioral studies (Boynton & Siegfried, 1962; Zacks, 1967b) have similarly provided evidence of differences in neural latencies to very short equal-energy stimuli. Thus, the finding of a shorter critical duration for the median RT as compared to that for the response frequency and signal detectability measures might be a direct reflection of a shorter critical duration for the latency of neural responses than for other neural components, such as frequency, amplitude, or waveform.

The differences in critical durations and utilization times between behavioral response measures demonstrate that the response measure is an important factor in the study of temporal integration. Models or theories attempting to explain the basis of

temporal integration should account not only for the influence of the stimulus conditions, but also the influence of the response measure.

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 the 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 on a diffusing glass located just behind the O's normal eye position and filled with the light from the glow modulator. The voltage reading from the Photometer, as displayed on the oscilloscope, was kept at a constant "common" level ($\approx 2\%$ error) by adding or eliminating filters to compensate for any change in the output of the glow modulator.

Absolute calibration of the retinal illuminance at this "common" level was carried out following the procedure outline by Westheimer (1966, p. 672). Briefly, the procedure involved measuring the luminance (\bar{B}) on a "perfectly" diffusing surface of a reflectivity (r)⁷ at a distance (X) beyond the point where the glow modulator's image was focused at the O's pupil. The obtained \bar{B} was corrected to take into account the increased output of the glow modulator (measured to be about 9%) that occurred when it was pulsed at 5 msec. "on"/5 msec. "off" during the above calibrations. The formula given by Westheimer (trolands = $10^7 \bar{B} X^2 r$) was used to calculate the retinal illuminance

⁷The diffusing plate (Photo Research Corp.) was found to reflect 99% of the light striking its surface from a horizontal candlepower standard lamp (Gamma Scientific 220-2).

of the "common" level--46,303 trolands.

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 2). With the glow modulator 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 to its own resistance box (Shallcross) which was pre-set at 100 killohms. Preceding each filter calibration, the voltage difference between the photomultipliers was "nulled" by reducing the resistance of photomultiplier 2 so that its voltage equaled 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 pre-amplifier gave the percent transmission of the filter:

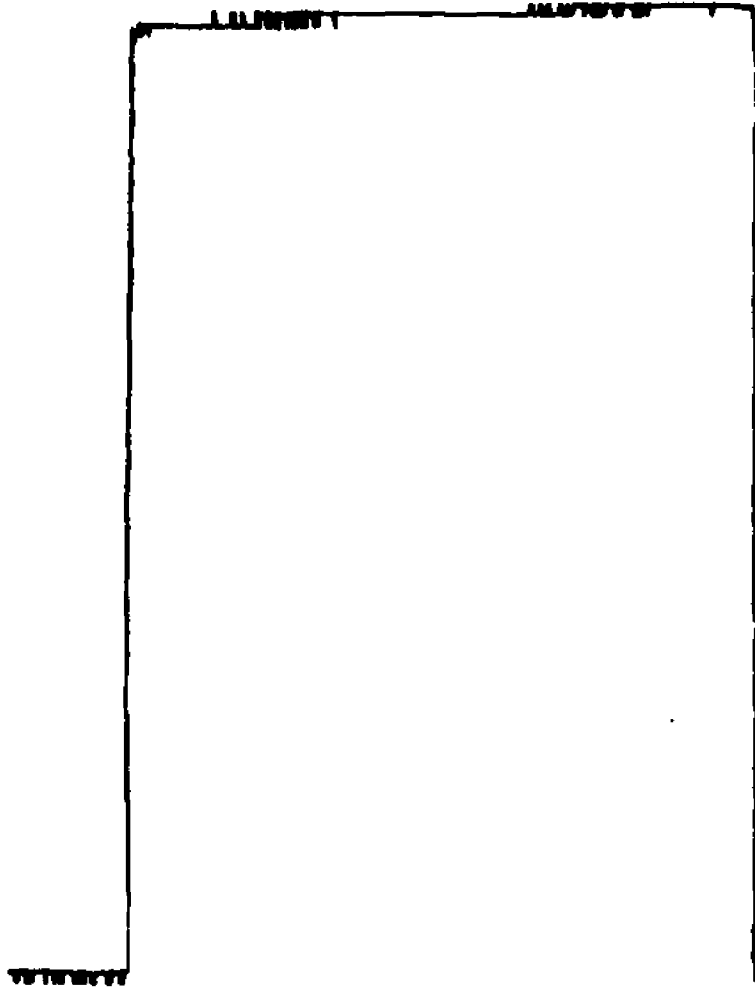
$$\frac{(10^{-5}) + (0.0125) (10^{-5})}{(1/R) (10^{-5}) + (0.0125) (10^{-5})} = \% \text{ Transmission}$$

APPENDIX III

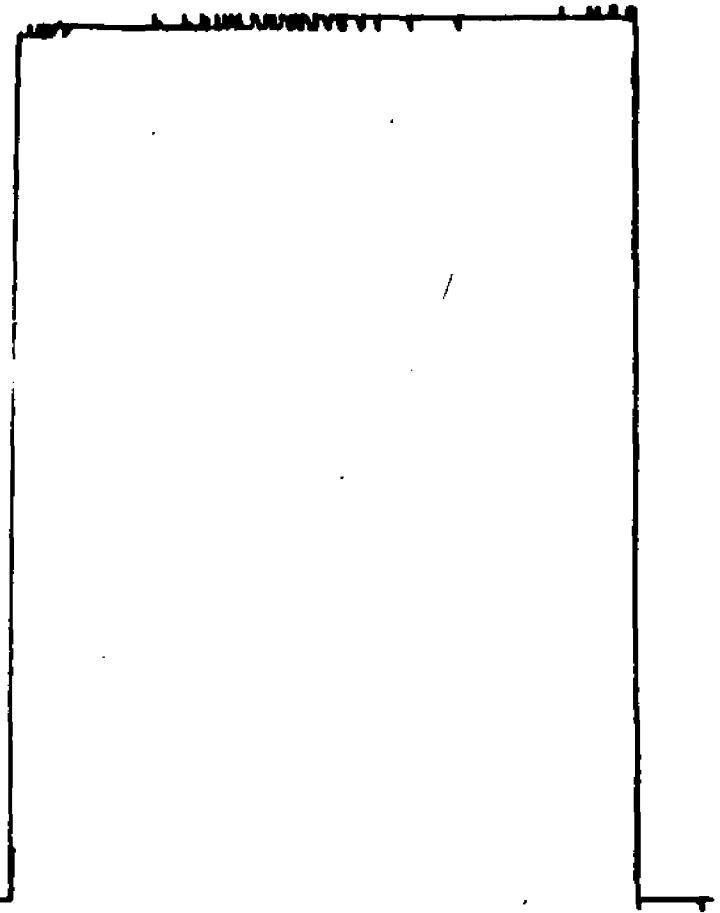
Heat-up of the glow modulator. A Fabri-Tec point signal averager (1052) was used to summate the voltage output of photomultiplier 2 resulting from 103 repetitions of a 211 msec. light pulse separated by an interstimulus interval of 8 sec. The summated voltage after being divided by 103 was readout using a Moseley AM Recorder (7030). The "X-Y plot" obtained using this procedure is shown in Figure 22 (a). There was a small increase in voltage with increasing duration which reached about 3% by the end of the pulse. To obtain a better idea of the relative magnitude of this increase, a watch glass (91% transmission) was used to reduce the luminance of the light pulses, and the voltage averaging procedure was repeated as outlined above. The obtained "X-Y plot" (Figure 22, b) did show an overall decrease in voltage of about 9%. Again, there was a small increase in voltage with increasing duration which reached about 3% by the end of the pulse.

Fig. 22. (a) "X-Y" readout of averaged voltage output of the photomultiplier to 103 repetitions of a 211 msec. light pulse. (b) "X-Y" readout after a watch glass (91% transmission) was used to reduce the luminance.

a



b



APPENDIX IV

Equal-energy checks. The retinal illuminance values given in Tables 1 and 2 were computed by reducing the "common" level value by the percent transmission of the filters used for each stimulus condition. Errors in the calibration of these filters would then be reflected in these retinal illuminance values and in the luminous energy levels based on these figures. Oscilloscope tracings such as those shown in Figures 3 and 4 were therefore used to check the luminous energy of the light pulses. For example, luminance-varied and duration-varied conditions of the same luminous energy should have oscilloscope tracings of equal area. Since the light pulses were rectangular, the product of the voltage and duration of their tracings (i.e., the area) can be used to compare the luminous energy in the luminance-varied and duration-varied conditions (see Tables 6 and 7). In the tracings of the pulses used for O:WC, the duration-varied-I conditions showed somewhat larger areas than the luminance-varied conditions. The voltage of the duration-varied-I conditions was .05 volts higher than would be expected if they were equal in luminous energy to the luminance-varied conditions. This discrepancy was found to be equivalent to an 8% difference in transmission. Comparisons of the tracings of the luminance-varied and duration-varied conditions for O:GB revealed fairly close agreement in the areas of equal-energy stimuli. The only substantial deviations from equal areas was evident in the larger

TABLE 6

Voltages, Durations, and Areas (Voltage Duration)
of the Oscilloscope Tracings of Q:WC's Luminance-varied
and Duration-varied Conditions

Conditions	Voltage	Duration (msec.)	Area (volts msec.)
Luminance varied			
E1	1.44	1.00	1.44
E2	1.74	"	1.74
E3	2.27	"	2.27
E4	2.70	"	2.70
E5	3.87	"	3.87
Duration varied I			
E1	.47	3.39	1.59
E2	"	4.21	1.98
E3	"	5.31	2.50
E4	"	6.50	3.06
E5	"	9.21	4.33
Duration varied II			
E1	.059	24.2	1.43
E2	"	30.1	1.78
E3	"	38.0	2.24
E4	"	46.5	2.74
E5	"	65.8	3.88
Duration varied III			
E1	.022	61	1.34
E2	"	76	1.67
E3	"	96	2.11
E4	"	118	2.60
E5	"	166	3.65

TABLE 7

Voltages, Durations, and Areas (Voltage Duration)
of the Oscilloscope Tracings of O: GB's Luminance-varied
and Duration-varied Conditions

Conditions	Voltage	Duration (msec.)	Area (volts msec.)
Luminance varied			
E1	4.5	1.00	4.5
E2	6.3	"	6.3
E3	7.8	"	7.8
E4	11.1	"	11.1
E5	15.1	"	15.1
Duration varied I			
E1	.52	8.8	4.6
E2	"	11.8	6.1
E3	"	14.9	7.8
E4	"	20.1	10.4
E5	"	27.7	14.4
Duration varied II			
E1	.15	30.0	4.5
E2	"	40.0	6.0
E3	"	50.8	7.6
E4	"	68.4	10.3
E5	"	94.4	14.2
Duration varied III			
E1			
E2			
E3			
E4			
E5			

Note.--The voltage for duration-varied-III conditions was not sufficiently large to allow a reliable reading. The voltage readings for the other conditions were obtained by eliminating a filter used for all of these conditions.

areas for luminance-varied conditions at E4 and E5. These conditions showed higher voltages (equivalent to about 5% higher transmission) than would be expected if they were equal in luminous energy to the duration-varied conditions. The deviations from equal energy suggested by the oscilloscope tracings of the light pulses were taken into account by adjusting the retinal illuminance values of the stimulus conditions that were believed to be in error.

APPENDIX V

Confidence limits. Tables 8 and 9 give the confidence limits for each of the response measures obtained for the luminance-varied and duration-varied-I, -II, and -III conditions.

TABLE 8

95% Confidence Limits for $\underline{O}:WC$

Conditions	Percent response	P(A)'	Median RT (msec.)	Semi-interquartile range (msec.)
Luminance varied				
E1	4.2	.037	52.5	33.1
E2	4.8	.045	29.9	18.8
E3	5.1	.052	16.7	10.5
E4	4.6	.048	12.0	7.5
E5	2.7	.030	8.3	5.2
Duration varied I				
E1	4.6	.043	34.2	21.5
E2	5.1	.050	23.5	14.8
E3	4.8	.050	15.1	9.5
E4	3.9	.042	10.7	6.8
E5	2.1	.024	7.1	4.4
Duration varied II				
E1	4.4	.039	38.7	24.4
E2	4.9	.046	28.2	17.8
E3	5.1	.058	21.5	13.5
E4	4.6	.049	13.4	8.5
E5	3.5	.038	10.4	6.5
Duration varied III				
E1	4.0	.031	39.3	24.8
E2	4.7	.041	32.4	20.4
E3	5.0	.048	23.9	15.0
E4	5.2	.051	23.0	14.5
E5	5.0	.052	23.3	14.6

TABLE 9

95% Confidence Limits for $\underline{O:GB}$

Conditions	Percent response	P(A)'	Median RT (msec.)	Semi-interquartile range (msec.)
Luminance varied				
E1	4.3	.045	32.8	20.7
E2	5.0	.051	20.7	13.0
E3	5.1	.048	17.8	11.2
E4	3.3	.029	8.4	5.3
E5	1.8	.010	5.9	3.7
Duration varied I				
E1	4.5	.046	33.1	20.8
E2	4.9	.051	26.0	16.4
E3	5.1	.049	15.0	9.5
E4	4.1	.041	9.1	5.7
E5	2.1	.019	6.1	3.8
Duration varied II				
E1	4.6	.046	30.5	19.0
E2	5.0	.051	22.3	14.1
E3	5.1	.051	14.8	9.3
E4	4.5	.042	12.1	7.6
E5	2.9	.025	8.5	5.3
Duration varied III				
E1	4.2	.038	39.2	24.7
E2	4.5	.042	46.3	29.1
E3	4.8	.046	38.9	24.5
E4	5.1	.051	24.1	15.2
E5	5.2	.052	24.7	15.6

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