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ONE-PULSE AND TWO-PULSE MEASURES OF VISUAL TEMPORAL  
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*City University of New York*

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ONE-PULSE AND TWO-PULSE MEASURES OF VISUAL TEMPORAL INTEGRATION

by

IRA J. BERENHAUS

A dissertation submitted to the  
Graduate Faculty in Psychology  
in partial fulfillment of the  
requirements for the degree of  
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1981

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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

### ONE-PULSE AND TWO-PULSE MEASURES OF VISUAL TEMPORAL INTEGRATION

by

Ira J. Berenhaus

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Visual temporal integration was investigated using one-pulse and two-pulse stimuli. The one-pulse stimuli were rectangular light flashes varying in duration from 20 to 316 msec; the two-pulse stimuli were two successive 2-msec rectangular light flashes separated by dark intervals varying from 0.1 to 88 msec. The visual field, in the form of a disk subtending 22' visual angle, was viewed binocularly by dark adapted observers.

The Random Method of Limits procedure enabled fast and reliable threshold determinations for all durations during a single testing session. In Experiment 1, both one-pulse and two-pulse thresholds were determined (during separate sessions) on each of 16 days. In Experiment 2, one-pulse thresholds were obtained on 8 days, and two-pulse thresholds were obtained on 8 subsequent days. Additionally in Experiment 2, thresholds of a constant duration control stimulus were obtained throughout each session to determine that neither practice nor fatigue effects were confounding the data. Two observers participated in each of the two experiments.

Two intersecting functions, each describing a relationship between threshold luminance and stimulus duration, were fitted to each

day's results. With  $\underline{L}$  as threshold luminance (in mL),  $\underline{E}$  as relative threshold energy (in mL-msec),  $\underline{T}$  as total stimulus duration (in msec), and C and K as constants, these two functions can be represented by  $L \times T = C$  and  $L = K$  for the one-pulse thresholds, and  $E = C$  and  $E / T = K$  for the two-pulse thresholds. The intersection of these functions for each of the two types of stimuli was used to provide an intercept measure of critical duration. This intercept measure of critical duration was about 100 msec for the one-pulse thresholds and about 50 msec for the two-pulse thresholds, estimates that are in general agreement with prior research.

In Experiment 1, one-pulse critical duration and two-pulse critical duration, though different in magnitude, were significantly correlated across days for one of the two observers ( $\underline{O:GB}$ ,  $r(14) = .75$ ,  $p < .001$ ;  $\underline{O:RP}$ ,  $r(14) = .41$ ,  $p > .05$ ). This result suggests that both measures were responsive to similar organismic (subject) variables which changed across days. Daily variations were obtained for both the intercept measure of critical duration and the range of durations displaying partial integration.

The relationship  $E / T = K$  (one of the functions fitted to the two-pulse thresholds) adequately described two-pulse partial integration when daily results were individually examined. This relationship was not as clearly observable when the daily thresholds were combined, i.e., when thresholds were averaged across sessions. The relationship  $E / T = K$  has been reported for two-pulse thresholds in the light-adapted fovea, but this apparently is the first study to identify this relationship in the dark-adapted fovea.

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## CHAPTER I

### General Background

It has repeatedly been demonstrated for brief visual stimuli that when stimulus duration ( $T$ , in msec) is increased, the luminance ( $L$ , in mL) required for the threshold is reciprocally decreased (Graham, 1965). In chemistry, the reciprocal relationship between intensity and duration in producing a constant photochemical effect is known as the Bunsen-Roscoe law; in visual psychophysics, this relationship was first demonstrated by Bloch (1885) and is referred to as Bloch's law of temporal integration.<sup>1</sup>

#### One-pulse temporal integration

Traditionally, temporal integration has been investigated by determining the threshold luminance for rectangular light flashes of various durations. For durations briefer than a critical duration (CD), it is found that the relative threshold luminous energy ( $E$ , in mL-msec), the product of luminance ( $L$ , in mL) and time ( $T$ , in msec), remains constant ( $C$ ) as stimulus duration (time  $T$ ) is increased, i.e., Bloch's law holds ( $E = C$  or  $L \times T = C$ ). The range of durations for which threshold energy is constant defines a region of complete integration. At longer durations, luminance alone determines threshold; increasing stimulus duration is not accompanied by a lowering of threshold luminance. The range of durations for which threshold luminance is constant defines a region of no integration. In other words, for durations briefer than CD, relative threshold energy is

constant ( $L \times T = C$ ), and for durations longer than CD, threshold luminance is constant ( $L = K$ ).

Although some investigators (Graham & Kemp, 1938; Keller, 1941; Long, 1951; Rouse, 1952) depicted an abrupt transition from complete integration ( $L \times T = C$ ) to no integration ( $L = K$ ), others found the transition to be more gradual (Barlow, 1958; Graham & Margaria, 1935; Karn, 1936; Sperling & Jolliffe, 1965). A gradual transition reflects a range of stimulus durations that show partial integration, where increasing stimulus duration allows for a less than equivalent decrease in threshold luminance. When partial integration is observed, the term critical duration has been used to identify the longest stimulus duration for which Bloch's law fully holds (Clark & Blackwell, 1959; Kietzman, 1979; Saunders, 1975). The longest duration demonstrating partial integration has been called utilization time (UT) after Piéron (1945/1952) (Bruder & Kietzman, 1973; Frumkes, 1979; Gottlieb, 1979; Kietzman & Gillam, 1972). For durations beyond UT, the threshold luminance is constant ( $L = K$ ) and there is no (further) integration.<sup>2</sup>

As shown in Figure 1, one-pulse threshold data can be plotted in two different ways. On top, where threshold  $\log E$  is presented as a function of  $\log T$ , a straight line of zero slope indicates complete integration and a straight line of unit slope (+1) reflects no integration. On bottom, where threshold  $\log L$  is plotted as a function of  $\log T$ , a unit negative slope (-1) depicts complete integration and a slope of zero shows no integration. When the ordinate and abscissa are identically scaled, as in Figure 1, the slopes of +1 and -1 are  $45^\circ$  diagonal lines. The dashed lines in

Figure 1. Two ways of presenting one-pulse threshold data. Relative threshold luminous energy  $\underline{E}$  (upper graph) and threshold luminance  $\underline{L}$  (lower graph) are plotted as a function of stimulus duration  $\underline{T}$ . Axes are logarithmic and identically scaled such that slopes of +1 and -1 appear as  $45^\circ$  diagonal lines. Dashed lines depict a region of partial integration.

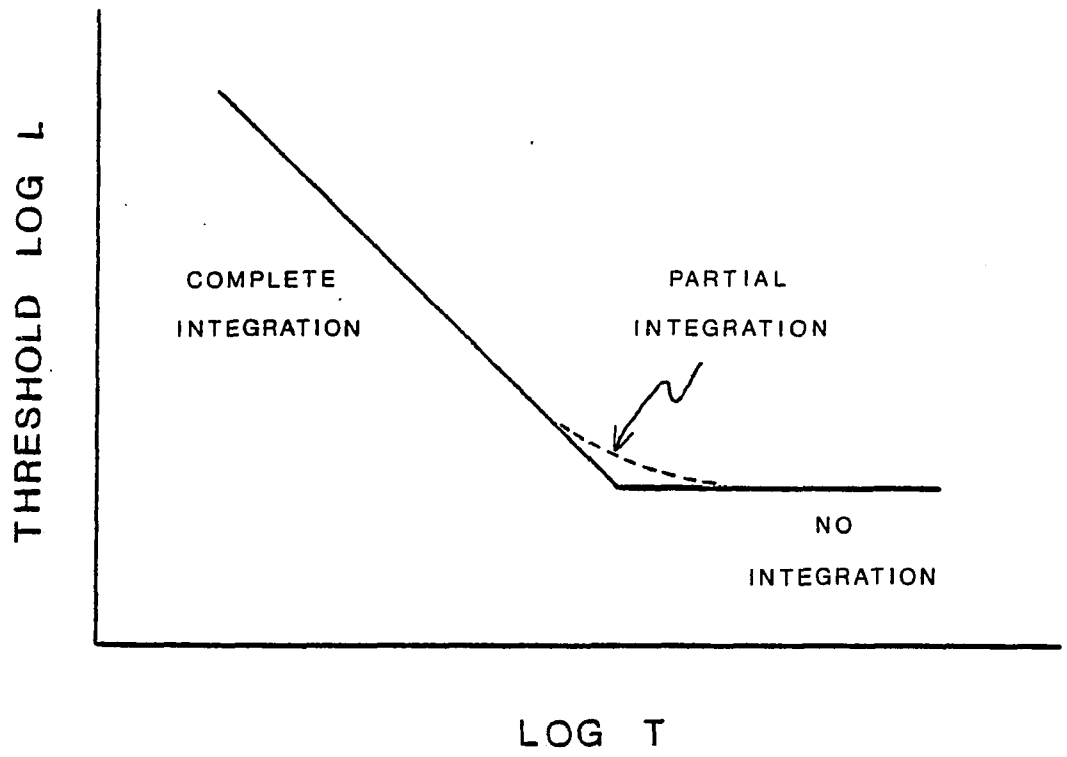
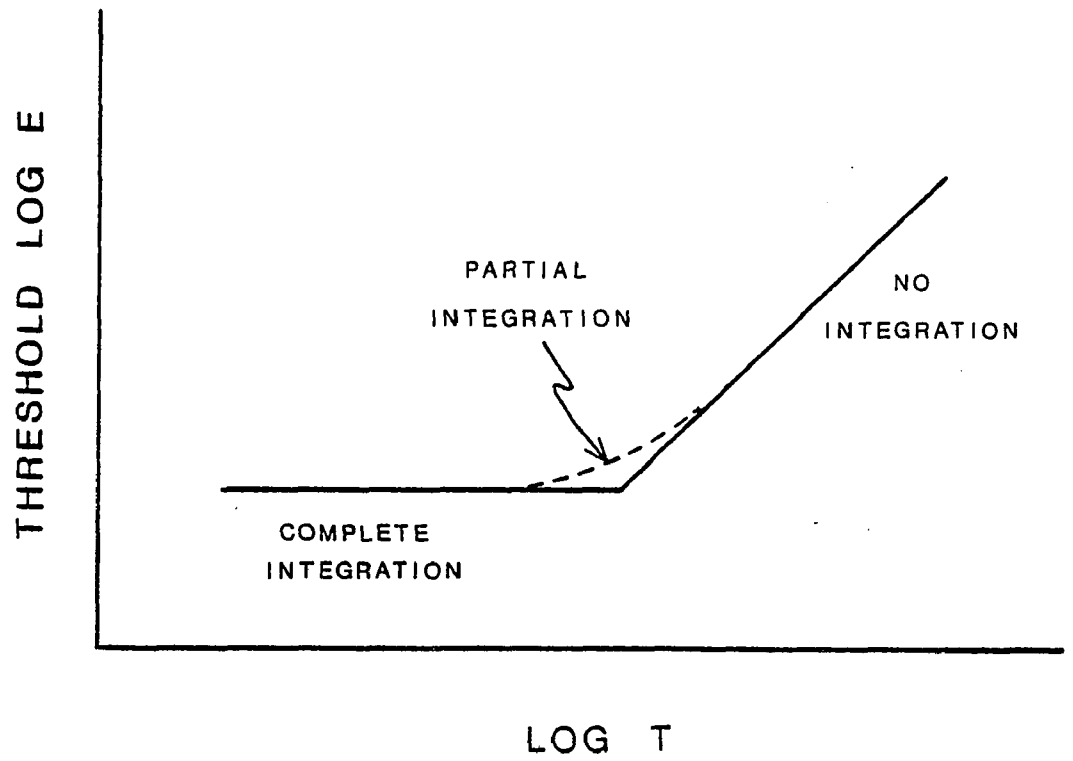


Figure 1 have been drawn to show partial integration, a gradual transition between complete integration and no integration. When partial integration is demonstrated, its temporal boundaries are CD and UT; when the transition between complete integration and no integration is abrupt, CD equals UT.

#### Two-pulse temporal integration

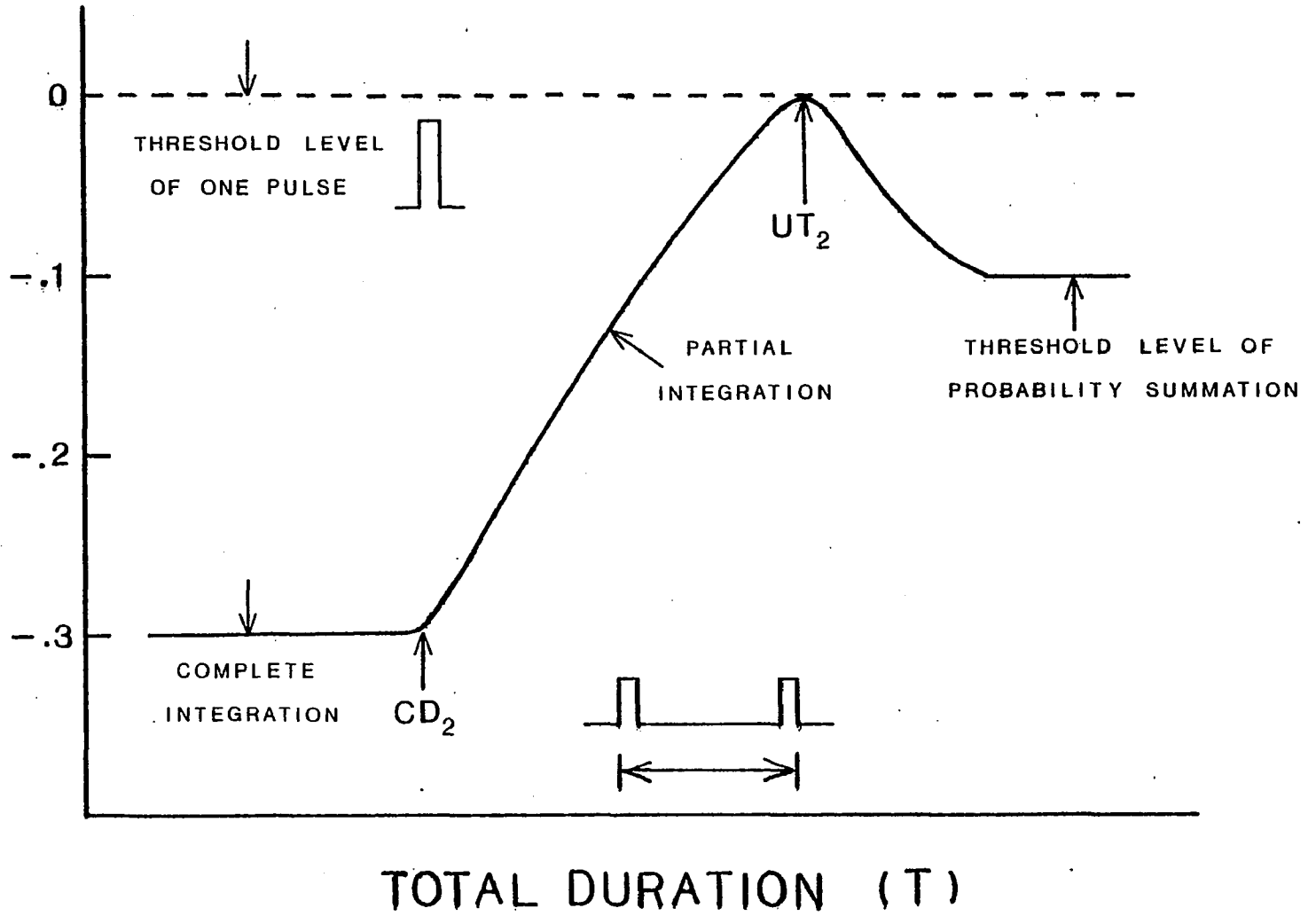
Temporal integration has also been studied using two identical light flashes of brief duration (e.g., 2 msec) which are separated by various dark intervals.<sup>3</sup> Total stimulus energy is presented in the two successive light flashes and threshold luminance (in an equal-performance paradigm) or per cent detection (in an equal-energy paradigm) is determined as a function of interpulse interval.<sup>4</sup> The results of the equal-performance paradigm and the equal-energy paradigm are intimately related (see Herrick, 1974). Two-pulse thresholds also provide estimates of critical duration (CD) and utilization time (UT). Subscripts are used to distinguish between the two-pulse measures ( $CD_2$  and  $UT_2$ ) and the one-pulse measures ( $CD_1$  and  $UT_1$ ) of temporal integration.

The equal-performance paradigm was used in the present study; the luminance of the stimulus necessary to obtain a fixed or equal performance level (threshold luminance) was obtained as a function of total stimulus duration (the onset of the first pulse to the offset of the second). The relationship between two-pulse threshold luminance and total stimulus duration is shown in Figure 2. Often, the threshold is also determined for a one-pulse comparison stimulus which is equal in duration to one of the two pulses. For example,

Figure 2. Two-pulse threshold luminance ( $\log L$ ) is plotted as a function of total stimulus duration ( $T$ ). Data typically show a region of complete integration and its endpoint critical duration ( $CD_2$ ), followed by a region of partial integration and its endpoint utilization time ( $UT_2$ ). At long stimulus durations, beyond  $UT_2$ , the two-pulse threshold is shown to be approximately 0.1 log mL below the threshold level of the one-pulse comparison stimulus due to probability summation.

RELATIVE 2-PULSE LOG L

(re 1-PULSE THRESHOLD)



if the two-pulse stimulus consists of two light pulses each of which are 2 msec in duration, the one-pulse comparison stimulus is a single 2-msec light pulse. In Figure 2, the two-pulse threshold luminance is expressed relative to the threshold luminance level for such a one-pulse comparison stimulus (indicated by a horizontal dashed line).

For brief durations, the threshold luminance of the two-pulse stimulus (e.g., two light pulses of 2 msec each) is 0.3 log mL less than (i.e., half) the threshold luminance of the one-pulse comparison stimulus (e.g., one 2-msec light pulse); this threshold difference is predicted by Bloch's law. Complete integration is demonstrated for the brief two-pulse stimulus when the threshold luminance remains constant as the total stimulus duration is increased. Since the total light time ( $\underline{t}$ ) is constant (4 msec in the present study) for all two-pulse durations, when threshold luminance ( $L$ ) is constant, threshold relative energy ( $L \times \underline{t}$ ) is also constant (i.e., Bloch's law holds). Threshold log  $E$  can be determined from threshold log  $L$  by adding the logarithm of the total light time (0.602 in the present study) to log  $L$ . Therefore, if threshold log  $E$  is plotted on the ordinate (e.g., Herrick, 1972, 1973a, 1974), the two-pulse data appear identical in form to the log  $L$  plot shown in Figure 2.

Critical duration ( $CD_2$ ) defines the endpoint of complete integration and the start of partial integration. As duration is further increased, the two-pulse threshold is elevated until it reaches the threshold level of the one-pulse comparison stimulus (the dashed line in Figure 2).<sup>5</sup> The two-pulse duration that marks the endpoint of partial integration is designated utilization time ( $UT_2$ ).<sup>6</sup>

As shown in Figure 2, beyond  $UT_2$  the two-pulse threshold decreases to approximately 0.1 log mL below the one-pulse comparison threshold due to probability summation (Clark & Blackwell, 1959; Herrick, 1972, 1973a; Ikeda, 1965; Meijer, van der Wildt, & van den Brink, 1978; Rashbass, 1970). If the total stimulus duration of the two-pulse stimulus is sufficiently long, the visual system responds to each pulse as an independent event. Probability summation implies that the threshold luminance for long two-pulse stimuli is lower than the threshold luminance for one pulse alone because there are two opportunities to see the stimulus compared with only one.

## CHAPTER II

### Related Literature and Purposes of this Investigation

The time course of temporal integration is influenced by several stimulus factors such as background luminance, target size, retinal location, and stimulus wavelength. For example, it has been shown for one-pulse stimuli (Biersdorf, 1955; Graham & Kemp, 1938; Keller, 1941) and two-pulse stimuli (Herrick, 1972; Roufs, 1973; van den Brink & Bouman, 1954) that critical duration is decreased as background luminance is increased. Few studies have actually compared, as the present study does, one-pulse and two-pulse measures of critical duration. The one-pulse and two-pulse measures of critical duration that were determined in the present study are identical to the CD measures obtained by Herrick (1972); they are described below.

#### One-pulse critical duration

The term critical duration has been used by some investigators to designate the longest one-pulse duration for which Bloch's law fully holds (Clark & Blackwell, 1959; Kietzman, 1979; Saunders, 1975). However, many investigators have used the intersection of the two functions representing complete integration ( $L \times T = C$ ) and no integration ( $L = K$ ) as an estimate of one-pulse critical duration (Sperling, 1979). As shown in Figure 1, when there is a range of durations displaying partial integration, this intersection measure of critical duration (called intercept-CD<sub>1</sub> for this report) comes at a

longer duration than the initial departure from strict reciprocity. The intercept- $CD_1$  measure is the ratio of  $C / K$ , where  $C$  is the brief-duration energy (in mL-msec) and  $K$  is the long-duration luminance (in mL).

The intercept- $CD_1$  measure has proven to be valuable in temporal integration research in evaluating the influences of several factors: background luminance level (Biersdorf, 1955; Herrick, 1956; Keller, 1941); target size (Biersdorf, 1955; Roufs & Meulenbrugge, 1967; Ueno, 1978); stimulus wavelength (Krauskopf & Mollon, 1971; Ronchi, 1974; Uetsuki & Ikeda, 1971); retinal location (Ueno, 1978); and dark adaptation (Montellese, Sharpe, & Brown, 1979; Stewart, 1972). Intercept- $CD_1$  was determined for one-pulse thresholds in the present study.

#### Two-pulse critical duration and the TEpee effect

The two-pulse measure of critical duration used in the present study is based on Herrick's TEpee effect (Herrick, 1972, 1973a, 1974). The TEpee effect refers to four straight line functions having slopes of 0, +1, -1, and 0 when threshold energy ( $E$ )--or threshold luminance ( $L$ )--and stimulus duration ( $T$ ) are plotted on log-log coordinates. The intercept- $CD_2$  measure used in the present study (designated  $T_{C2}$  by Herrick), is the intersection of the complete integration function (slope of 0) and the partial integration function (slope of +1). In the present study, there was less interest in the  $UT_2$  measure (designated  $T_M$  by Herrick) and the two functions with slopes of -1 and 0 associated with longer duration stimuli.

Herrick postulated a slope of +1 for two-pulse partial integration

which implies that the ratio  $E / T$  is constant ( $K$ ); relative energy ( $E$ , in mL-msec) divided by total stimulus duration ( $T$ , in msec) is average-luminance ( $E / T$ , in mL). Average-luminance has special significance in flicker research. Above the critical flicker frequency threshold, the flickering stimulus (which appears fused) matches in brightness a steady light having the same average-luminance; this is known as the Talbot-Plateau law (see Brown, 1965, p. 288), and average-luminance is also called Talbot luminance level. Average-luminance ( $E / T$ ) for one-pulse stimuli is simply threshold luminance.

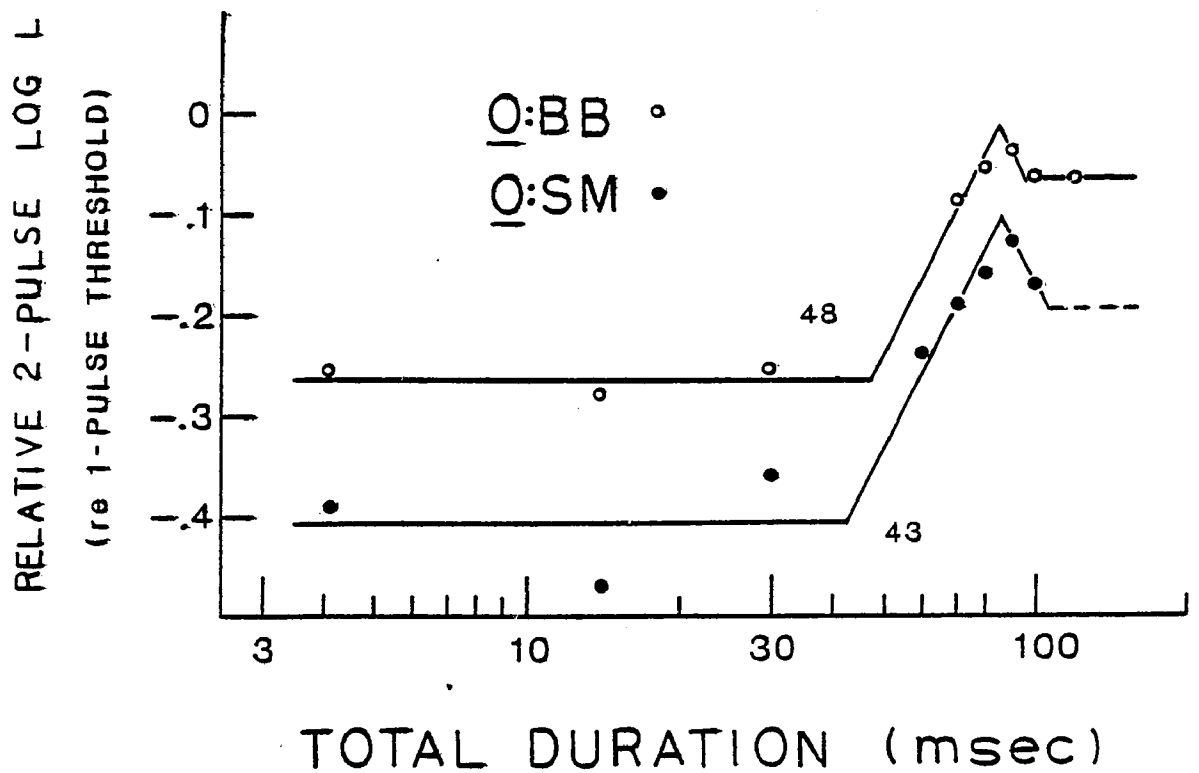
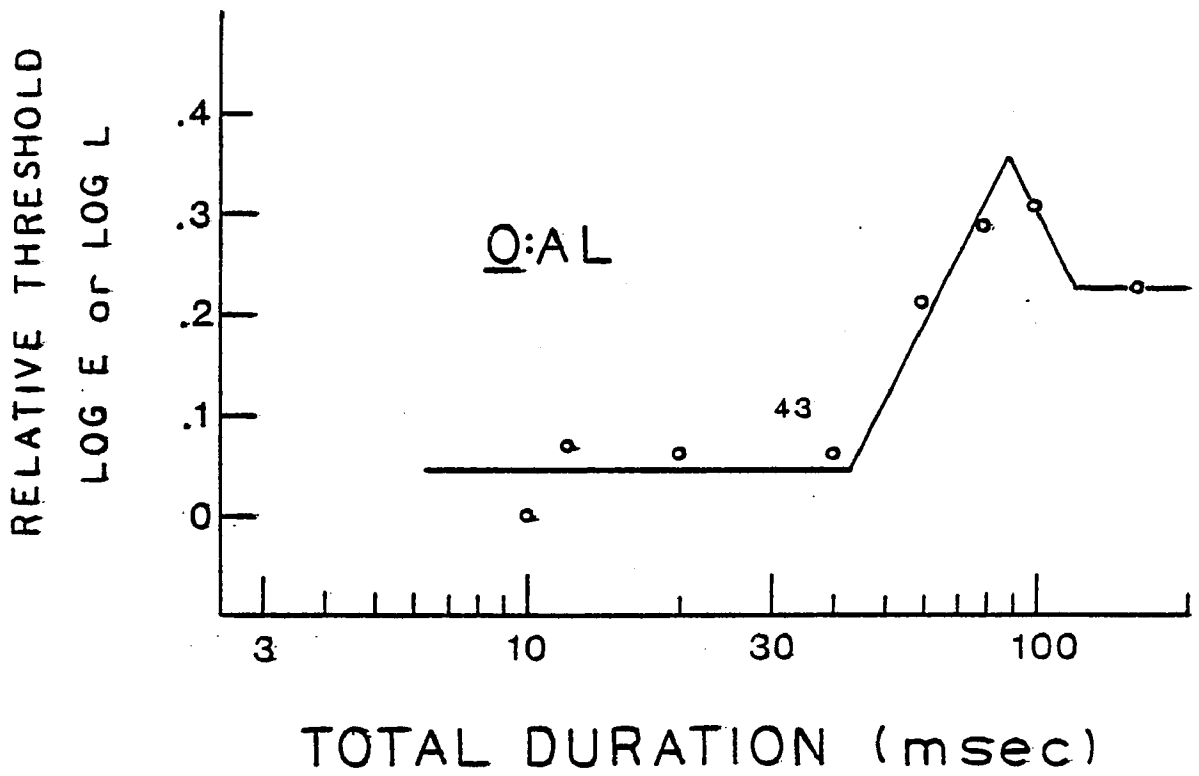
Figure 3 gives examples of TEpee fits to data obtained by Herrick (1972, Figure 4, O:AL) and pilot data obtained from observers (O:BB and O:SM) in the present study. Each of the three TEpee fits was based on data obtained in a single experimental session. Intercept- $CD_2$  for the present study's pilot data, which were obtained after dark adaptation (bottom), was found to be similar in magnitude to intercept- $CD_2$  for Herrick's data (top), which were obtained using a 0.1 mL background.

#### Purposes of the present study

The present study was designed to suggest answers to the following three questions, specifically with reference to a binocularly viewed stimulus 22' in diameter presented to the dark-adapted fovea:

- (1) What is the relationship between intercept- $CD_1$  and intercept- $CD_2$ ?
- (2) To what extent does critical duration vary from day to day?
- (3) Is Talbot luminance level (average-luminance) constant for two-pulse partial integration?

Figure 3. On top, data from Herrick (1972, Figure 4, Q:AL) were obtained using two-pulse stimuli that were luminance increments of a  $1^{\circ} 7'$ , 0.1 mL, foveal background. Each of the luminance increments was 5 msec in duration. On bottom, pilot data from the present study (Q:BB and Q:SM) were obtained using two successively presented 2-msec light flashes,  $22'$  in diameter, presented to the dark-adapted fovea. TEpee functions were fit with the method of least squares (slopes were constants), and intercept- $CD_2$  (in msec) is indicated next to each TEpee function.



A discussion of the literature relevant to these three questions is present below.

1. What is the relationship between intercept- $CD_1$  and intercept- $CD_2$ ?

One-pulse and two-pulse luminance thresholds were both determined as a function of stimulus duration in the following studies: Clark and Blackwell (1959)<sup>7</sup>, Herrick (1972, 1973a, 1973b), Rashbass (1970), Roufs (1973), and Tittarelli and Marriott (1970). Of the above mentioned studies, four found  $CD_2$  to be briefer than  $CD_1$  (Herrick, 1972, 1973a; Rashbass, 1970; Roufs, 1973), one found  $CD_1$  and  $CD_2$  to be comparable in magnitude (Clark & Blackwell, 1959), and two did not compare CDs (Herrick, 1973b; Tittarelli & Marriott, 1970). The stimulus conditions of the present study (e.g., target size, binocular viewing, dark adaptation, foveal fixation) were most similar to the stimulus conditions of Clark and Blackwell (1959).

Clark and Blackwell (1959) (see Footnote 7) were first to determine both one-pulse and two-pulse thresholds under identical stimulus conditions. Foveal stimuli were either 13.8' or 18.2' in diameter, and thresholds were obtained under both dark adaptation and light adaptation (10 ft-L, 25° background). They reported that  $CD_1$  and  $CD_2$  are the same.

Recent studies by Herrick (1972, 1973a), Rashbass (1970), and Roufs (1973) reported that  $CD_2$  was briefer than  $CD_1$  for the light-adapted fovea. The results of Herrick and Roufs are most relevant to the present study since these studies used stimuli that were within the boundaries of the fovea. Rashbass's stimuli were luminance

increments of a  $17^\circ$ , 700 troland background, that extended well beyond the limits of the fovea.

Herrick (1972), using a  $1^\circ 7'$  foveal stimulus superimposed on a similar sized background, determined both  $CD_1$  and  $CD_2$  at seven background luminance levels (0.055, 0.1, 0.93, 1.02, 8.9, 45, and 66 mL); complete data for one of the two subjects was presented. Herrick's  $CD_1$  estimate was the intersection of  $L X T = C$  and  $L = K$ , while his  $CD_2$  estimate was the intersection of  $E = C$  and  $E / T = K$ . Intercept-CD estimates in the present study were determined in the same fashion. As in the present study, each CD determination was based on thresholds from a single experimental session; the values of  $CD_1$  (Herrick, 1972, Figure 10) and  $CD_2$  (Herrick, 1972, Figure 6) that were plotted as a function of background luminance level, were averages of two to four determinations each. The  $CD_1$  was definitely longer than the  $CD_2$  at low background luminance levels; at higher luminance levels the estimates of  $CD_1$  and  $CD_2$  were more similar in magnitude.

Herrick (1973a) extended his earlier work to multiple-pulse stimuli (3 to 100 pulses). He found that when  $CD_n$  was plotted as a function of  $\frac{n-1}{n}$  (where  $n$  is the number of pulses), the slope was equal to  $CD_1$  for that luminance level, and for all luminance levels the y-intercept was 5 msec (Herrick, 1973a, Figure 9). This relationship between  $CD_n$  and  $\frac{n-1}{n}$  is described by the equation:  $CD_n = (\frac{n-1}{n}) (CD_1) + t$ , where  $n$  is the number of pulses and  $t$  is the duration of each pulse. For Herrick's two-pulse stimuli (each pulse was 5 msec)  $CD_2 = \frac{1}{2} CD_1 + 5$  indicating that  $CD_2$  is approximately half of  $CD_1$ . The relationship

between  $CD_1$ ,  $CD_2$ , and  $CD_n$  as background luminance level is increased is shown by Herrick (1973a) in Figure 17 (p. 877). The difference between  $CD_1$  and  $CD_2$  (in msec) is decreased as background luminance level is increased.

Since intercept- $CD_1$  and intercept- $CD_2$  in the present study were determined in the same way that Herrick (1973a) determined  $CD_1$  and  $CD_2$ , the present study can evaluate the validity of the relationship  $CD_2 = \frac{1}{2} CD_1 + t$  for the dark-adapted fovea.

Roufs (1973), similar to Herrick, used foveal stimuli that were luminance increments of a  $1^\circ$  circular background. Roufs, however, compared one-pulse and two-pulse measures of temporal integration differently than Herrick. Temporal modulation transfer functions were determined for luminance levels between 1 and 1200 trolands. One-pulse and two-pulse increment thresholds were then predicted from these transfer functions (based on a model presented by Roufs, 1972), and thresholds were determined for several stimulus durations to generally confirm these predictions. Roufs then compared the predicted relationship between one-pulse and two-pulse thresholds as a function of stimulus duration (see Figure 6 of Roufs, 1973, p. 316). Roufs reported that  $CD_1$  was comparable in magnitude to  $UT_2$ , and that  $CD_2$  was approximately one third of  $CD_1$ .

Thus, both Herrick and Roufs found  $CD_1$  to be briefer than  $CD_2$  for the light-adapted fovea, contrary to the reported findings of Clark and Blackwell. The present study provides data to further evaluate the relationship between  $CD_1$  and  $CD_2$  for the dark-adapted fovea.

2. To what extent does intercept-CD vary from day to day?

Roufs (1972, 1973), at each background level, obtained one-pulse thresholds for all durations within a single experimental session; the results from different sessions were not combined. Other investigations of temporal integration that presented single session threshold data were Barlow (1958), Biersdorf (1955), Herrick (1972, 1973a), and Ronchi and Nováková (1971). Roufs (1972) stated that he obtained thresholds at a particular background level during a single experimental session to avoid "the effect of day-to-day variations" (p. 263). It is not clear, however, to what extent a temporal integration measure such as CD varies from day to day.

When threshold for a constant duration stimulus is repeatedly determined over many days, threshold varies as much as 0.3 log units (Jackson, 1965; Roufs, 1974; Sturr, 1957). In the present study, the range and standard deviation of the individual testing day estimates of intercept- $CD_1$  and intercept- $CD_2$  (16 in Experiment 1 and 8 in Experiment 2 for each observer) provide measures of between day variability. To the author's knowledge the present study is the first to examine changes in critical duration across days.

Assume for a moment that the transition between complete integration ( $L \times T = C$ ) and no integration ( $L = K$ ) for one-pulse thresholds is abrupt, and that the intersection of these two functions (intercept- $CD_1$ ) changes across days. When the data from different days are combined, the variation of intercept- $CD_1$  across days can produce a rounding between the two functions. A gradual transition between complete integration and no integration is usually assumed

to indicate partial integration, viz., an incomplete reciprocity between increased stimulus duration and decreased threshold luminance. In the dark-adapted fovea, some investigators have found a range of durations showing partial integration (Karn, 1936; Sperling & Jolliffe, 1965; Young & Cole, 1973), while other investigators have not (Clark & Blackwell, 1959). In the present study, the contribution of the between day changes of intercept- $CD_1$  to this gradual transition can be evaluated.

3. Is Talbot luminance level (average-luminance) constant for two-pulse partial integration?

Herrick (1972) was first to suggest for partially integrated two-pulse stimuli (i.e., between  $CD_2$  and  $UT_2$ ) that threshold average-luminance ( $E / T$ ) is constant. Herrick (1974) replotted data from six foveal two-pulse studies (all conducted under light-adapted conditions) and found that the TEpee effect, with its unit slope for partial integration, described the data. The TEpee effect also describes multiple-pulse (3 to 100 pulses) thresholds in the light-adapted fovea (Herrick, 1973a).

Herrick (1972, 1973a, 1974) has presented a convincing argument for the TEpee effect in the light-adapted fovea. However, it is not known whether the TEpee effect describes two-pulse thresholds in the dark-adapted fovea. For those studies that have compared the slopes of two-pulse partial integration under light-adapted and dark-adapted conditions, the results differ in a nonsystematic way (Clark & Blackwell, 1959; Uetsuki & Ikeda, 1970; van den Brink & Bouman, 1954). The present study evaluates for the dark-adapted fovea whether the

first two line segments of the TEpee effect (having slopes of 0 and +1) describe the data.

A complication in evaluating the slope of two-pulse partial integration is Herrick's notion that "averaging data from different sessions distorts the shape of the TEpee function" (Herrick, 1974, p. 363).<sup>8</sup> Herrick (1972, 1974) attributes deviations from the TEpee function in the data of other investigators to the combining of data from different sessions (Clark & Blackwell, 1959; Uetsuki & Ikeda, 1970) or from different subjects (Blackwell, 1963).

In the present study, the slope of two-pulse partial integration is evaluated both for the data of individual sessions, and the data combined across sessions.

## CHAPTER III

### Method

#### A Preview of the Paradigms for Experiments 1 and 2

The present study consisted of two experiments. In Experiment 1, one-pulse and two-pulse thresholds were determined during separate experimental sessions on each of 16 testing days. In Experiment 2, one-pulse thresholds were determined on 8 testing days, and two-pulse thresholds were determined on 8 additional testing days. Two observers participated in each phase of the two experiments.

One-pulse durations ranged from 20 to 200 msec in Experiment 1, and from 20 to 316 msec in Experiment 2. Two-pulse durations ranged from 4.1 to 92 msec in both experiments; two-pulse stimuli of these durations are usually seen as one flash of light at threshold. In Experiment 2, thresholds of constant duration control stimuli, 20 msec (one-pulse) or 4.1 msec (two-pulse), were also determined. In both experiments, one-pulse and two-pulse stimuli were 22' circular targets presented binocularly under conditions of dark adaptation.

For each observer in Experiment 1, the "average" threshold for each duration was based on 64 threshold determinations, 4 from each of the 16 sessions. In Experiment 2, the average threshold for each duration was based on 32 threshold determinations, 4 from each of 8 testing days (two sessions per day). Thresholds were determined using the Random Method of Limits procedure (Herrick, 1973c) and sessions were organized similar to Herrick (1972). The averages of

four threshold determinations per duration were stable enough to allow curve fitting to individual session data in Experiment 1 and individual testing day data in Experiment 2. In the present study, combined data (thresholds averaged across sessions) and individual session or testing day data (with two-function curve fits) are both presented. The two-function curve fits provided the estimates of intercept- $CD_1$  and intercept- $CD_2$ .

### Observers

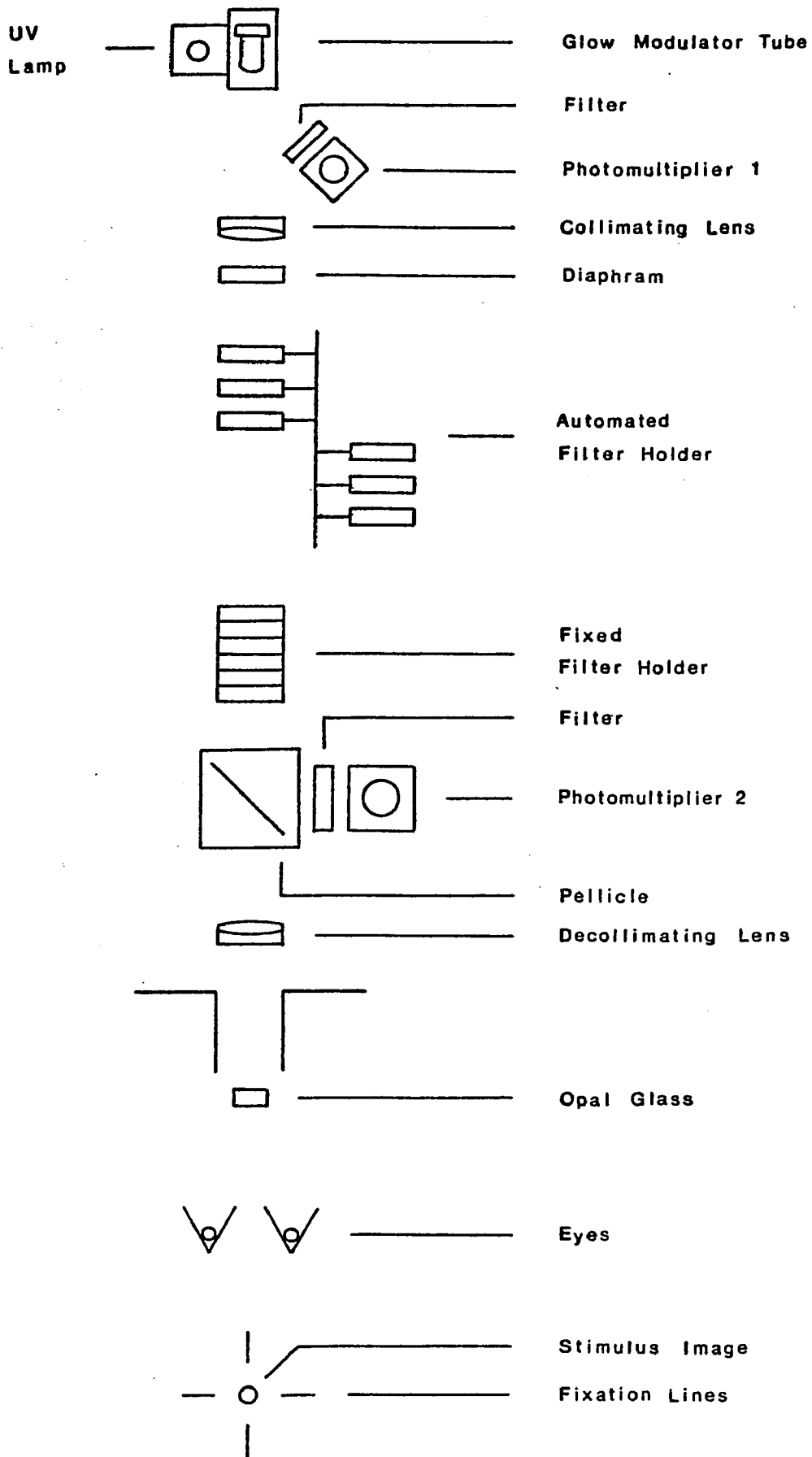
There were three male observers: O:RP, O:GB, and O:AL. O:RP and O:GB participated in Experiment 1, while all three participated in Experiment 2. Observers were in their mid- to late-twenties and had acuity within normal limits; two of the observers wore corrective lenses. Participants were unaware of the specific stimulus conditions or purposes of the study. Two of the subjects, O:RP and O:AL, had previous experience in psychophysical experiments. Subjects received practice in the current paradigm prior to data collection. Observers were paid for their participation.

### Apparatus

Optical system. A single-channel optical system (a light source, collimating lens, filters, and a decollimating lens) was used to transilluminate the white-appearing circular target viewed by the observer (see Figure 4).

The light source was a glow modulator gas-discharge tube (Sylvania R1131C) which was operated at a constant current of 23 milliamperes and activated with timing and gating circuits. It was irradiated by an argon ultraviolet lamp (General Electric AR-4) to

Figure 4. A diagram of the one-channel optical system.



provide short and stable ionization times of less than 10  $\mu$ sec.  
(Ionization time refers to the lag between timer activation and light source onset.)

Light from the glow modulator tube, after collimation, was passed through a six filter (neutral density Tiffen metallic) intensity programmer and additional gelatin filters (neutral density Kodak Wratten No. 96) mounted in an adjacent fixed filter holder, before being decollimated to transilluminate the stimulus target. Prior to each stimulus presentation, the switch controlled, solenoid driven intensity programmer lifted any of the sixty-four possible filter combinations into the collimated light path. The intensity programmer provided luminance control over a 1.4 log unit range; filter combinations were selected to vary luminance in either 0.10 or 0.13 log unit steps. Additional luminance control was accomplished by manually changing filters in the fixed filter holder. Low density watch glasses were also placed in the fixed filter holder for daily calibration.

Two photomultiplier tubes (RCA 1P21), whose inputs were filtered (Kodak Wratten No. 106) to approximate the C.I.E. photopic-luminous-efficiency curve, monitored relative luminance before and after filtering. Photomultiplier 1 received its input directly from the glow modulator tube while photomultiplier 2 received reflected light from a pellicle beamsplitter (National Photocolor Corp.) situated on the other side of the filters from the light source. Filter combinations were calibrated within the system using the two photomultipliers and a procedure outlined in Appendix I. An oscilloscope (Tektronix 532) display of the photomultiplier outputs enabled the experimenter to

monitor intensity and duration characteristics of the stimuli during the testing session.

After passing the filters and pellicle, the light was decollimated and transilluminated the opal glass target which was viewed from the other side by the observer. The stimulus was a white appearing, circular target, subtending a visual angle of 22 minutes. By displacing the opal diffusing glass just beyond the focal length of the decollimating lens, the stimulus appeared homogeneous with luminance differences around the circumference, as assessed with a Pritchard photometer (Photo Research Corp.), of less than 10 per cent.

The subject was seated in a light tight booth and binocularly viewed the stimulus at an accommodation distance of 52 cm. Stable head position was maintained with the aid of an adjustable chin and forehead rest. Four dim red fixation lines which surrounded the target in an incomplete cross pattern assisted the observer in maintaining foveal fixation.

Daily calibration. A Pritchard photometer (Photo Research Corp.) was modified to convert luminous flux, in the plane of the stimulus target, into a voltage output on an oscilloscope display. Before each testing day, low density watch glasses were placed in the fixed filter holder until the Pritchard photometer output was lowered to 0.8 volts. Corrections were made for slight deviations from this arbitrary voltage level during data analysis. Maximum target luminance without filtering was 1.414 millilamberts.

Glow modulator rise and decay times. Rise and decay times of the glow modulator (from 10 to 90 per cent of final value) were

27  $\mu$ sec and 14  $\mu$ sec. By careful measurement of an oscilloscope photograph of the output of photomultiplier 2, the effective duration (i.e., corrected for ionization, rise, and decay times) was found to be approximately 5  $\mu$ sec less than the duration set on the timer. For the stimulus conditions used in the present study, the duration loss was too small to warrant introducing a correction factor.

Heat-up of the glow modulator. The light output of the glow modulator increased as much as seven per cent, 316 msec after stimulus onset--the longest duration used in the present study. Appendix II outlines the procedure used to determine output growth and luminance corrections for thresholds of the different duration stimuli. These correction factors ranged from 2.1 per cent (.009 log mL) for the 20 msec stimulus to 5.4 per cent (.023 log mL) for the 316 msec stimulus. Since these luminance corrections were small, they did little to influence the evaluation and interpretation of the data. Two-pulse stimuli remained uncorrected.

Timers. Trial events, including the presentation of a warning click, the timing of the preparatory interval, and the presentation of the stimuli, were controlled by a nine-channel multivibrator timer (Logical Instruments Co.) with an indeterminacy of 1 part in 10,000. The timer's stimulus channels delivered logic pulses to a gating device that activated the glow modulator tube for the preset durations.

#### Stimuli

One pulse. One-pulse stimuli were square wave light pulses ranging in duration from 20 to 316 msec. Stimulus durations were: 20, 30, 40, 54, 78, 100, 126, 158, and 200 msec for Experiment 1

with an additional 316 msec stimulus added in Experiment 2. Logarithmic durations were approximately equally spaced, i.e., adjacent stimulus durations were 0.1 to 0.2 log msec apart.

Two pulse. Two-pulse stimuli consisted of two, 2-msec square wave light pulses separated by dark intervals of 0.1 to 88 msec. Total stimulus durations (the onset of the first pulse to the offset of the second) were 4.1, 14, 30, 40, 46, 54, 62, 70, 78, and 92 msec. Logarithmic durations for the seven longest stimuli were approximately equally spaced, 0.05 to 0.07 log msec apart. Two-pulse duration in the present study refers to total stimulus duration.

Two-pulse stimuli at these durations are usually seen as one flash of light at threshold.

#### Procedures common to Experiments 1 and 2

The observer dark adapted for five minutes in the test booth. He then assumed his position in the chin and forehead rest awaiting the start of the session. The observer was required to binocularly fixate between the four red fixation lines during each trial. By lowering his gaze between trials, the subject avoided excessive fatigue. The observer viewed the stimulus with his natural pupils; a comparison of thresholds obtained using natural pupils and artificial pupils is presented in Appendix III.

After setting the timers and adjusting the filters, the Experimenter signaled his readiness with a tone (Sonalert). The observer initiated each trial by pressing a telegraph key. The warning click, indicating successful initiation, was followed by a 1.5 second preparatory interval after which the light stimulus was either presented

(stimulus trials) or withheld (blank or catch trials). The observer verbally reported seeing the stimulus by responding "yes", and not seeing the stimulus by responding "no". The time between stimulus presentations was 8 to 10 seconds.

Blanks were presented on approximately 10 per cent of the trials. Observers were encouraged to maintain a strict criterion. They were informed when a blank trial was correctly identified and cautioned when a false alarm was made. A threshold (explained below) was re-determined when a false alarm occurred. All three observers successfully maintained a strict criterion: false alarms were infrequent (see Appendix IV for specific false alarm rates).

Thresholds were determined using the Random Method of Limits procedure (Herrick, 1973c). The Random Method of Limits entails randomly presenting six luminances that bracket threshold and then determining an ascending threshold and a descending threshold as if the data were provided by the method of limits. The highest luminance presented should be definitely detectable, and the dimmest luminance should be undetectable. It was often necessary to extend the range of luminances beyond six levels (to seven, eight, or nine) particularly for the smaller step size (0.10 log units). A larger step size (0.13 log units) was also used in Experiment 1; however, the smaller step size appeared preferable and was used exclusively in Experiment 2.

A single threshold determination required six to nine trials. The average of an ascending threshold, responses changed from "no" to "yes", and a descending threshold, responses changed from "yes" to "no", was considered one threshold.

A typical testing day proceeded as follows: (1) the subject dark adapted for 5 minutes, (2) six blocks, of 36 to 54 trials each, were presented with 2 minute rest periods between blocks, (3) the subject left the booth for 30 minutes to one hour, (4) the subject participated in a second session which proceeded as described above.

#### Procedures specific to Experiment 1

A session provided four thresholds for each of nine one-pulse durations or each of ten two-pulse durations. Each observer participated in two sessions, a one-pulse session and a two-pulse session, on each of 16 days. Session order, one pulse first or two pulse first, was alternated across days. Each data point in the individual session plots represents the average of four threshold determinations.

Two thresholds were obtained for each duration before proceeding to the next. Duration was increased during the first three blocks and decreased during the second three blocks for half the testing days, decreased and then increased for the other half; order was counterbalanced (ABBAABBA) across testing days. By consecutively changing durations, the pair of thresholds obtained for one duration provided guidance in selecting the six luminance levels for the pair of thresholds at the next duration.

One-pulse durations ranged from 20 to 200 msec while two-pulse durations ranged from 4.1 to 92 msec. Thresholds were obtained using a step size of 0.10 log units between luminance levels on half the testing days, the first four and the last four days, and a step size of 0.13 log units on the other half, the middle eight days.

O:RP received a total of 8,401 trials while O:GB received a total

of 8,343 trials.

### Procedures specific to Experiment 2

A session provided two thresholds for each of ten stimulus durations (test stimuli). An additional 20 thresholds were determined for control stimuli; two control stimulus thresholds were obtained either before or after each pair of test stimulus thresholds. One-pulse control stimuli were 20 msec in duration and two-pulse control stimuli were 4.1 msec in duration. Each day, two sessions provided four test-stimulus thresholds and four control-stimulus thresholds for each duration. Each data point in the individual testing day plots represents the average of four thresholds, similar to the individual session plots from Experiment 1.

Two thresholds were obtained for each test stimulus or temporally paired control stimulus before proceeding to the next stimulus condition. When test and control threshold pairs were arranged as TCCTTCCT in the first session, they were then ordered as CTCCTTC in the second session and vice versa. The two possible test-control threshold orders for the first session were counterbalanced across days. When stimulus duration was increased during the first session, it was decreased during the second session and vice versa; the two possible duration orders for the first session were alternated across days.

One-pulse durations ranged from 20 to 316 msec while two-pulse durations ranged from 4.1 to 92 msec. All thresholds were obtained using a step size between luminance levels of 0.10 log units.

O:RP and O:GB provided eight sets of one-pulse data from eight testing days and O:AL and O:GB provided eight sets of two-pulse data

from eight subsequent testing days. O:AL replaced O:RP in the two-pulse portion of Experiment 2 since O:RP was no longer available for testing.

O:RP received 4,600 one-pulse trials, O:AL received 4,705 two-pulse trials, and O:GB received a total of 9,157 one-pulse and two-pulse trials. Together the three observers generated 32 sets of test stimulus thresholds, 16 one-pulse and 16 two-pulse. Also provided were 32 sets of control stimulus thresholds; each control stimulus threshold, within a set of ten, represents the average of four thresholds determined in close temporal proximity to the test duration with which it was paired.

Data analysis: Two-function curve fits to individual session thresholds

Two functions were fitted to each session's thresholds in Experiment 1 and each testing day's thresholds (from two sessions) in Experiment 2. The intersection of these functions provided the estimates of intercept- $CD_1$  and intercept- $CD_2$ . The one-pulse functions represent complete integration ( $L \times T = C$ ) and no integration ( $L = K$ ), while the two-pulse functions represent complete integration ( $E = C$ ) and constant average-luminance ( $E / T = K$ ). The logarithmic reduction equations for the brief-duration and the long-duration functions are presented in Table 1.

The method used to fit two intersecting functions to each set of threshold data was similar to a procedure suggested by Bogartz (1968). The method entailed using thresholds of all durations, even those close to the intersection of the two functions, and determining  $N$  minus 2 ( $N$  is the number of durations) least squares solutions.

Table 1  
Equations Used For Curve Fitting

Brief-Duration Function	Long-Duration Function
One-pulse	
$\log L = (-1) \log T + \log C$	$\log L = K$
Two-pulse	
$\log L = \log C - \log 4$	$\log L = (+1) \log T + (\log K - \log 4)$

E (and C) = relative luminous energy (in mL-msec)

L (and K) = luminance (in mL)

T = total duration (in msec); light time plus dark interval for two-pulse stimuli

4 = total two-pulse light time (in msec)

Intercept- $CD_1 = C / K$

Intercept- $CD_2 = C / K$

A modification of the standard method of least squares was used to fit each of the two functions.<sup>9</sup> The first solution used thresholds of the two briefest durations in fitting the brief-duration function, with the remaining thresholds used in fitting the long-duration function. Each successive solution added a duration to the brief-duration function and removed it from the long-duration function; the final solution used only the two longest duration thresholds in fitting the long-duration function. Of the solutions which provided functions that intersected between the two fits, the solution with the smallest sum of squared deviations (points to fitted lines) was chosen.

Two-function curve fits to the one-pulse thresholds used all presented durations. In contrast, two-function curve fits to the two-pulse thresholds did not routinely include all durations. Although two-pulse threshold luminance increases for intermediate stimulus durations, at longer durations (beyond  $UT_2$ ) the threshold either asymptotes or decreases. Since it was desirable to exclude from the two-pulse curve fits those stimulus durations beyond  $UT_2$  (the endpoint of partial integration), an objective method was adopted (when simple inspection was inconclusive) for excluding long duration thresholds. This involved determining the best solutions for the briefest five durations, six durations, seven durations, eight durations, etc., and selecting from among those, the solution which provided the smallest variance of residuals<sup>10</sup> for the long-duration function.

## CHAPTER IV

### Results

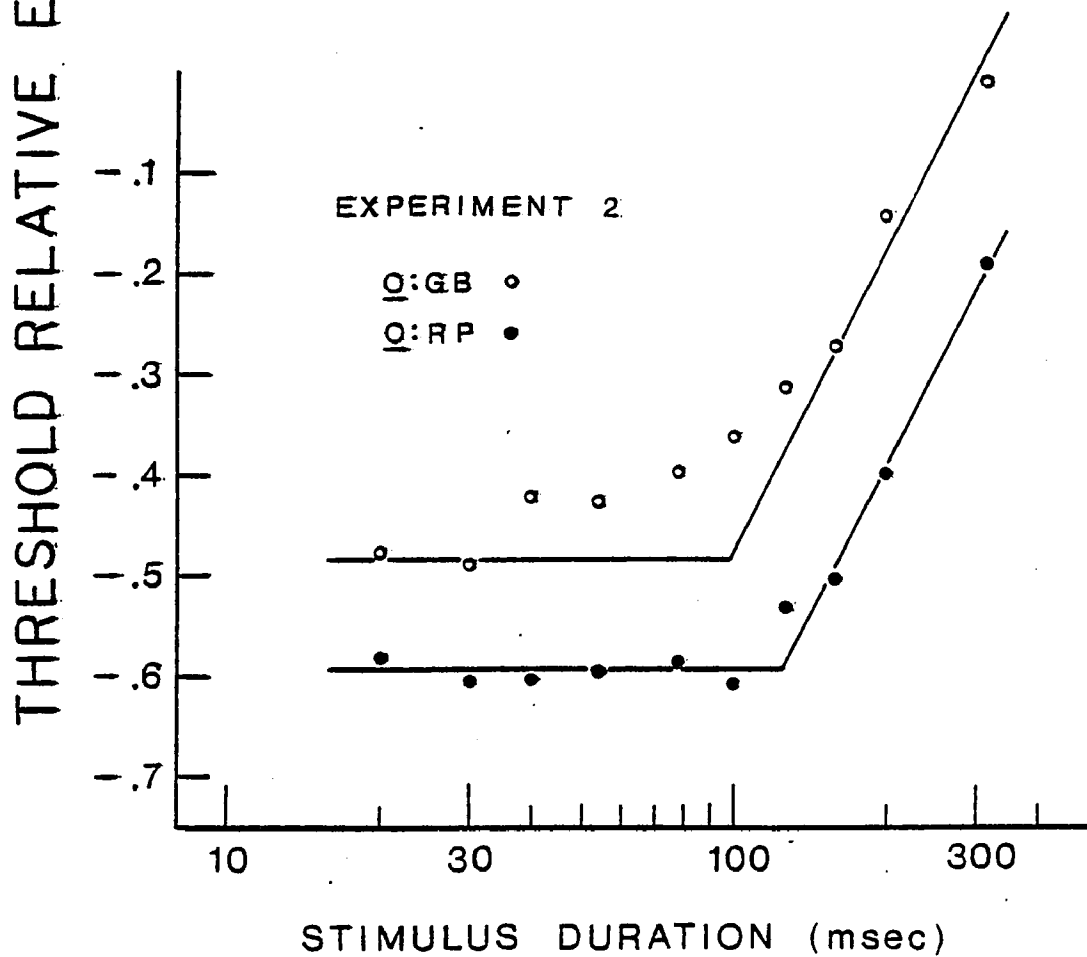
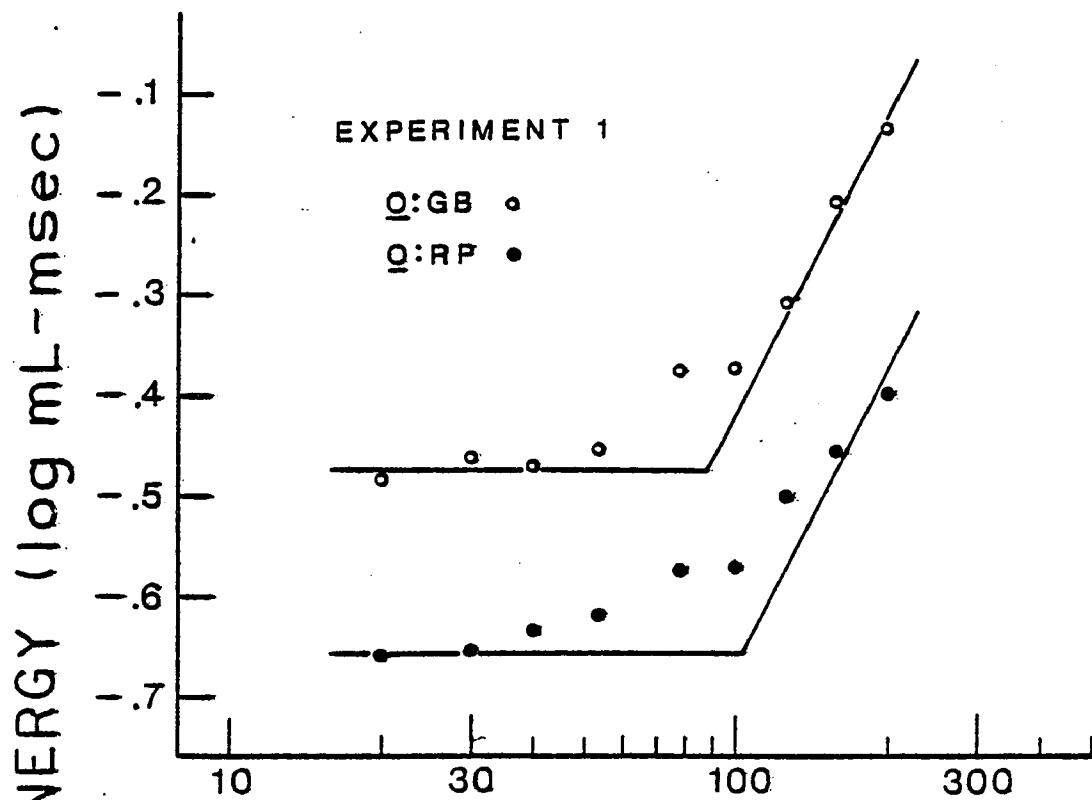
The results are presented in three main sections. One-pulse thresholds and two-pulse thresholds are presented separately in the first two sections; combined data (thresholds averaged across sessions) and individual session or testing day data (with two-function curve fits) are both shown. In the third section, the one-pulse and two-pulse results are compared.

Answers to the questions raised earlier are presented as follows. In the first two sections, the ranges and standard deviations of the intercept-CDs, listed by subject and experiment, indicate the extent of day to day variability (Question 2). In the second section, the relationship  $E / T = K$  (average-luminance is constant) for two-pulse partial integration is evaluated (Question 3). In the third section, the one-pulse and two-pulse thresholds of Experiment 1 are compared, and the relationship between intercept- $CD_1$  and intercept- $CD_2$  is examined (Question 1).

#### One-pulse thresholds

Combined data. One-pulse thresholds for each duration were averaged across sessions. The data from both experiments are presented in Figure 5. Threshold relative energy (in log mL-msec) is plotted as a function of stimulus duration (spaced logarithmically in msec). The straight line functions drawn through each set of data show complete integration ( $L \times T = C$ ) and no integration ( $L = K$ ). A gradual transition

Figure 5. Experiments 1 and 2, O:RP and O:GB. One-pulse threshold energy (in log mL-msec) plotted as a function of stimulus duration (spaced logarithmically in msec). Each point represents the average of thresholds from 16 days (Experiment 1, top) or 8 days (Experiment 2, bottom). The straight lines show the relationships  $L \times T = C$  (slope of 0) and  $L = K$  (slope of 1).



between these two functions indicates partial integration.

The combined data show a range of durations displaying partial integration for both observers in Experiment 1 and one observer (O:GB) in Experiment 2. In Experiment 2, compared with Experiment 1, the range of durations showing partial integration is broader for O:GB and narrower for O:RP. In fact, the combined data of O:RP from Experiment 2 show a rather abrupt transition between complete integration and no integration; only the 126 msec threshold falls above the two straight line functions.

Individual session and testing day data. The individual session thresholds from Experiment 1 are shown in Figures 6 (O:RP) and 7 (O:GB), and the individual testing day thresholds from Experiment 2 are shown in Figures 8 (O:RP) and 9 (O:GB). Each data point presented in these figures represents the average of four threshold determinations; four thresholds were determined in one session (in Experiment 1) or two successive sessions (in Experiment 2).

The two straight line functions (representing complete integration and no integration) that were fitted to each day's thresholds are shown in Figures 6 through 9.<sup>11</sup> (The procedure used to fit these functions is described in the Data analysis section in Chapter III.) The intercept- $CD_1$  measure, provided by the intersection of these functions, is indicated in these figures next to each day's thresholds.

Estimates of intercept- $CD_1$  ranged from 58 msec (O:GB, Experiment 1, session 10) to 150 msec (O:RP, Experiment 1, session 15). The mean, range, and standard deviation of intercept- $CD_1$  is listed by observer and experiment in Table 2.<sup>12</sup> The average of the four intercept- $CD_1$

Figure 6. Experiment 1, O:RP. One-pulse threshold luminance (in log mL) plotted as a function of stimulus duration (spaced logarithmically in msec) for each of 16 consecutive sessions. Each data point represents the mean of four thresholds. For clarity, each session's data is displaced downward 0.3 log units from those of the preceding session. Horizontal dashed lines on the ordinate represent  $-2.0$  log mL for each session; the session number and the data symbol used for that session appear above this line. Intercept- $CD_1$  (in msec), viz., the intersection of  $L X T = C$  (slope of  $-1$ ) and  $L = K$  (slope of  $0$ ), is indicated below this line. The ordinate scale refers to the data of sessions 1 (left graph) and 9 (right graph), and should be displaced downward 0.3 log units for each successive session.

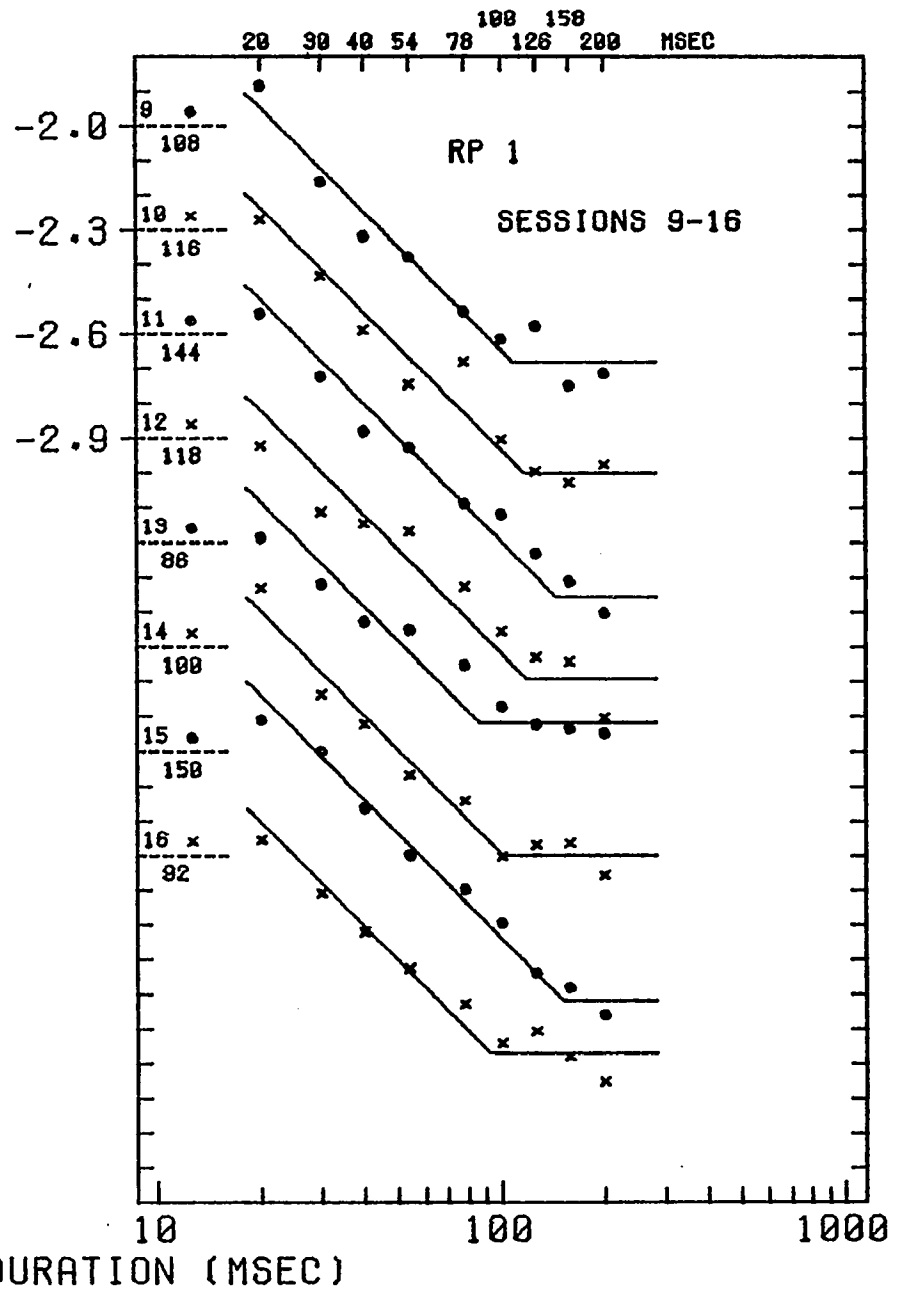
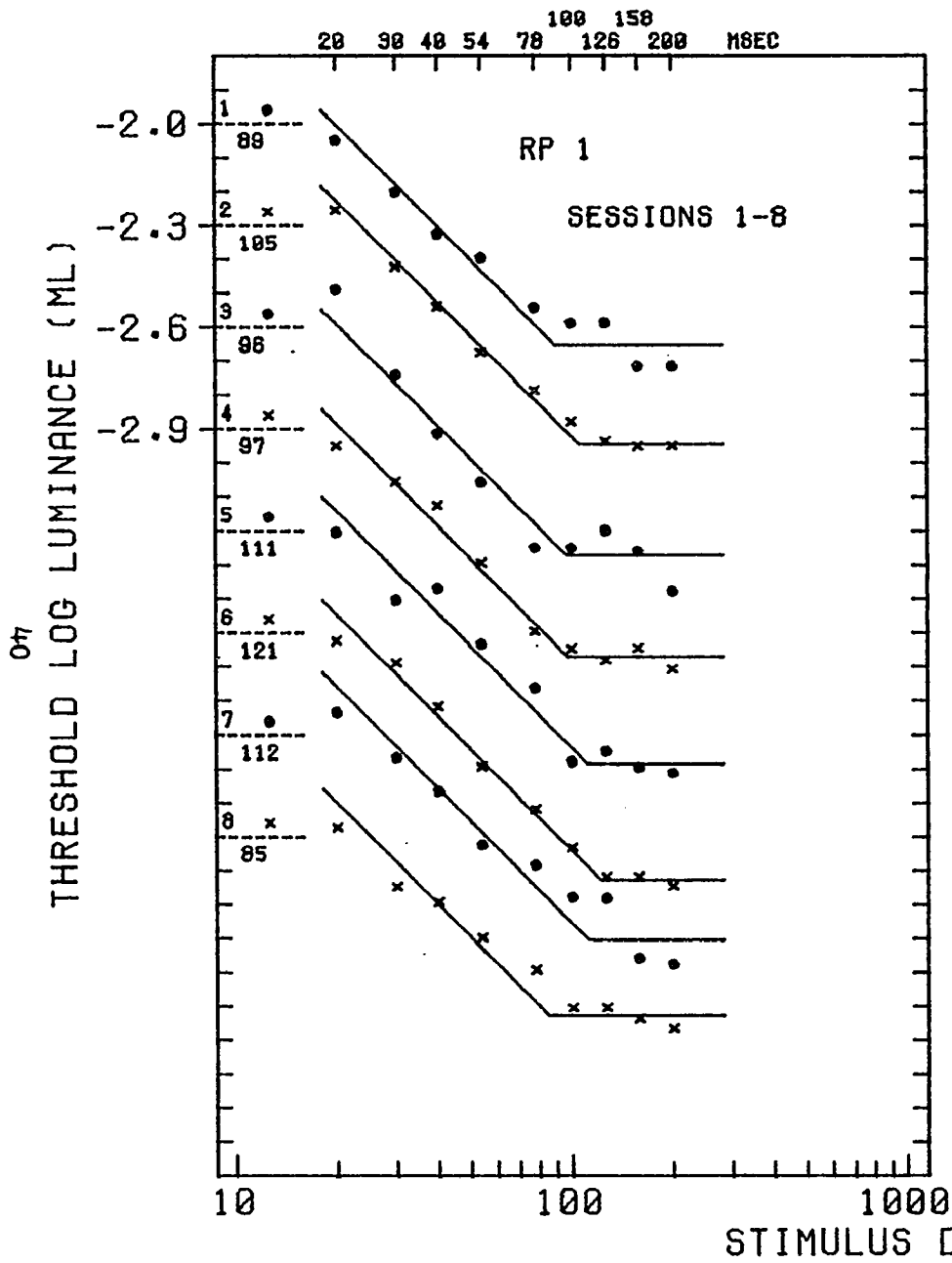


Figure 7. Experiment 1, O:GB. One-pulse threshold luminance (in log mL) plotted as a function of stimulus duration (spaced logarithmically in msec) for each of 16 consecutive sessions. Each dashed line on the ordinate represents  $-1.7 \log \text{mL}$  for the session indicated. Presentation as in Figure 6.

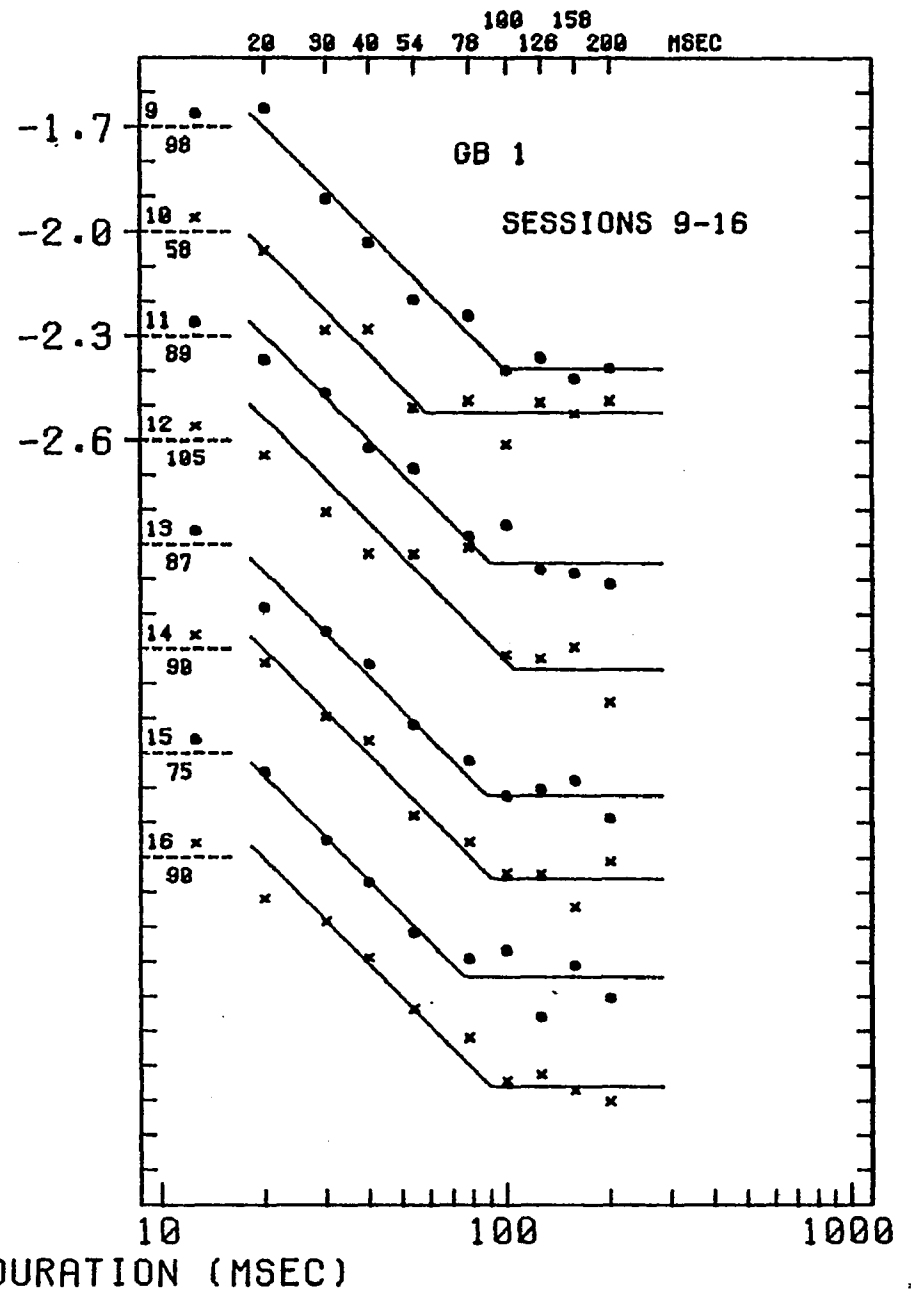
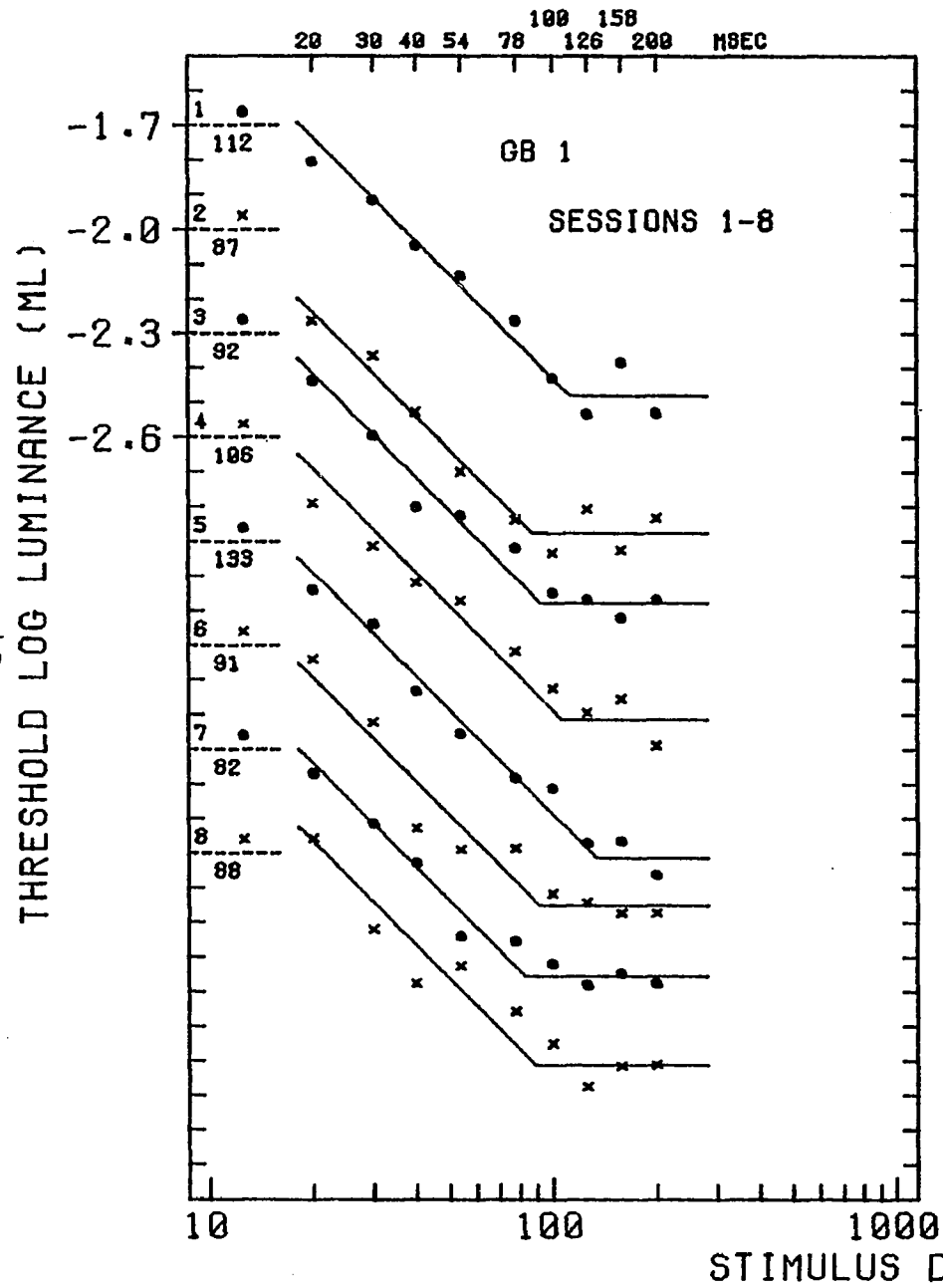


Figure 8. Experiment 2, Q:RP. On the left, one-pulse threshold luminance (in log mL) is plotted as a function of stimulus duration (spaced logarithmically in msec) for each of 8 testing days. On the right, control-stimulus (20 msec) threshold is plotted as a function of the test stimulus (varied duration) with which it was paired; horizontal solid lines show the mean control-stimulus threshold for each day. Each data point is the mean of four thresholds. Each dashed line on the ordinate represents  $-1.9 \log \text{mL}$  for the testing day indicated.

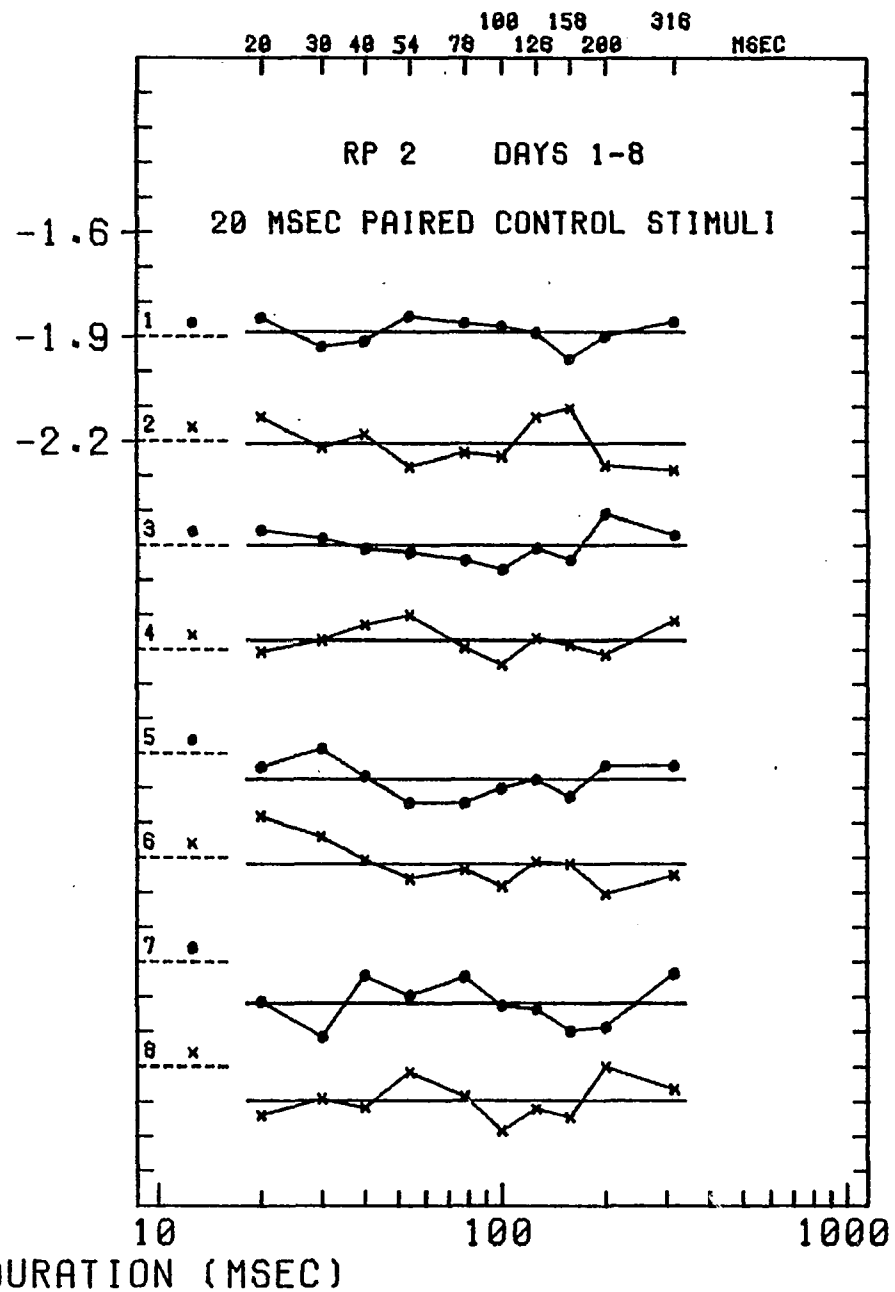
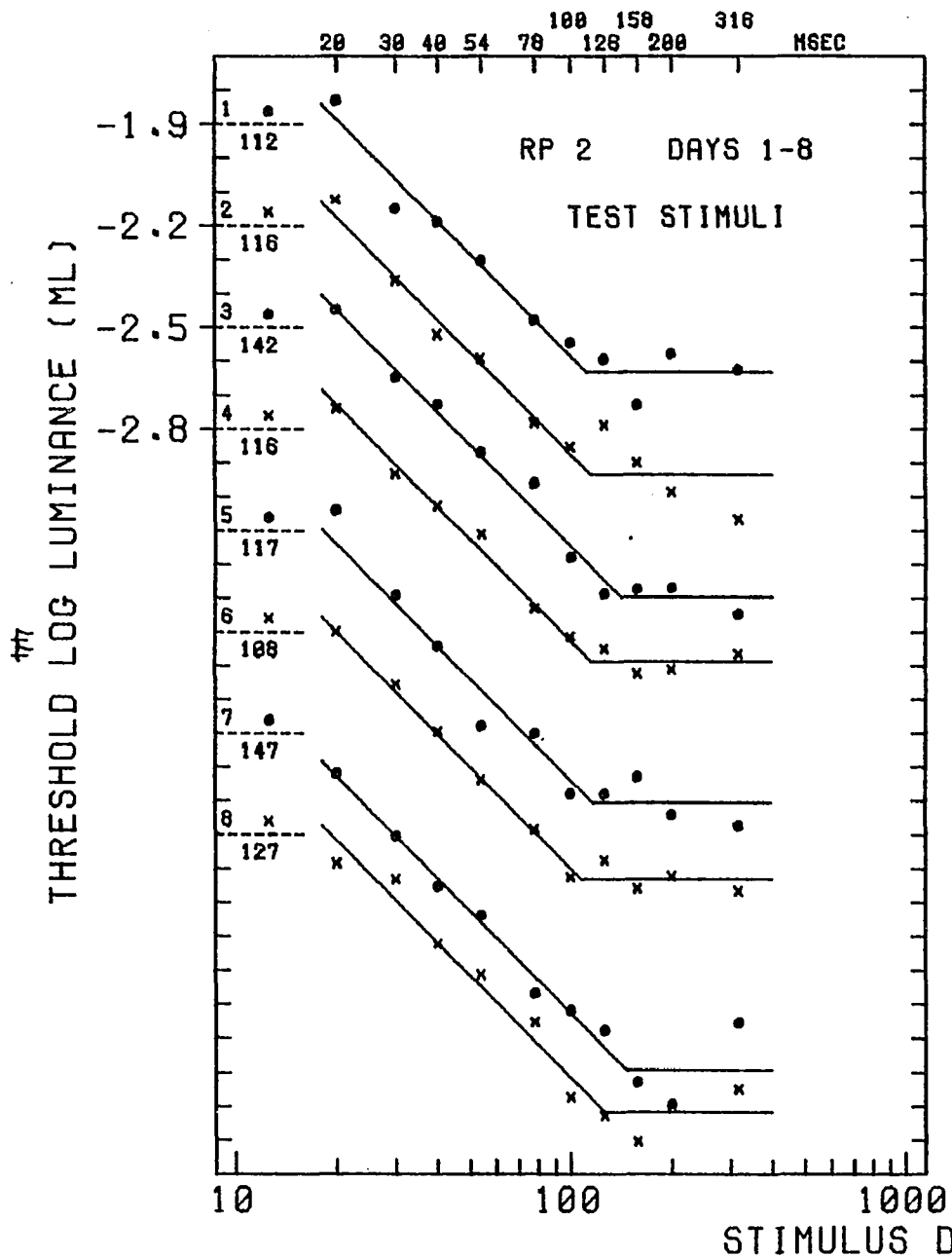


Figure 9. Experiment 2, O:GB. On the left, one-pulse threshold luminance (in log mL) is plotted as a function of stimulus duration (spaced logarithmically in msec). On the right, control-stimulus (20 msec) threshold is plotted as a function of the test-stimulus duration with which it was paired. Each dashed line on the ordinate represents  $-1.8 \log \text{ mL}$  for the testing day indicated.

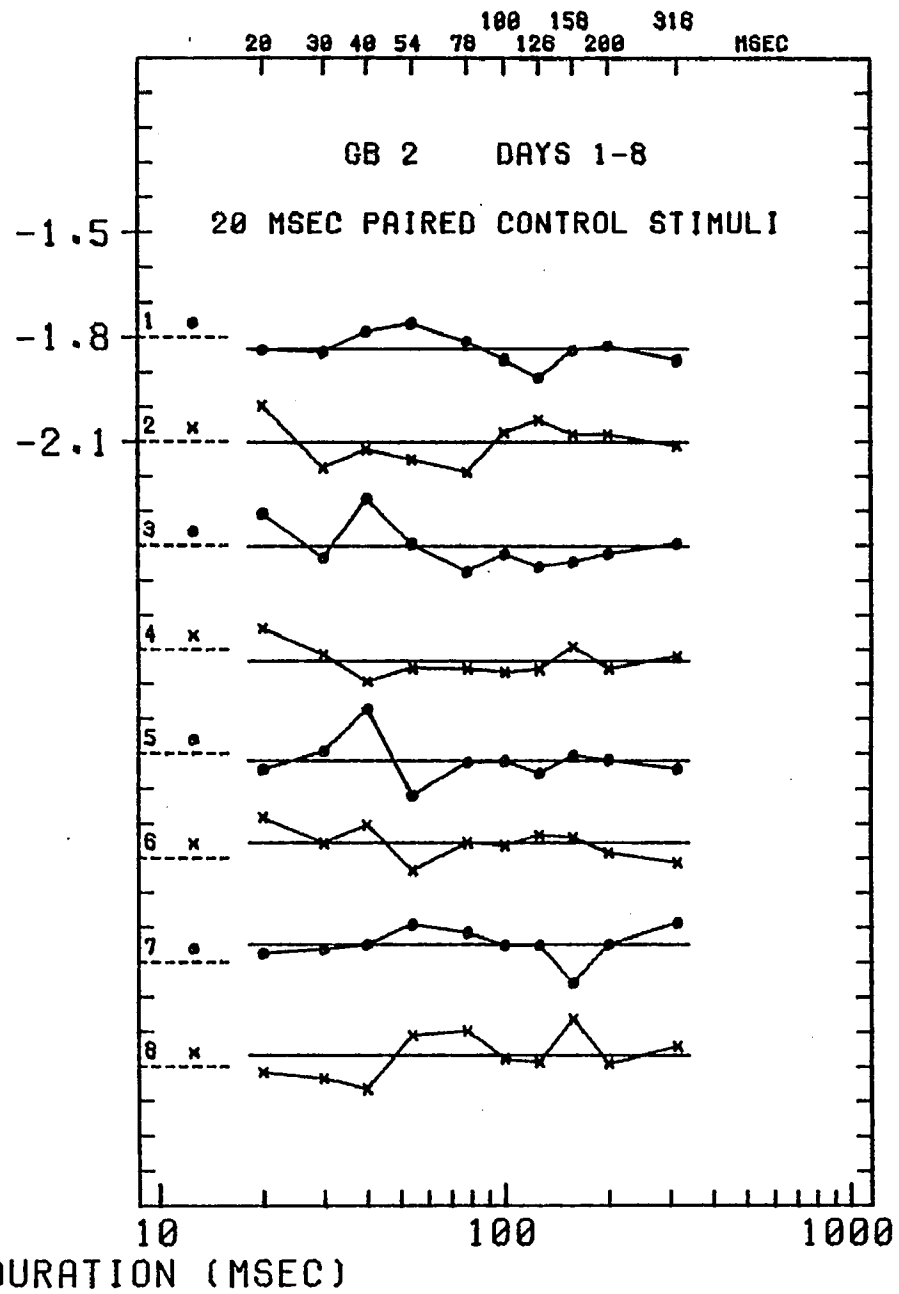
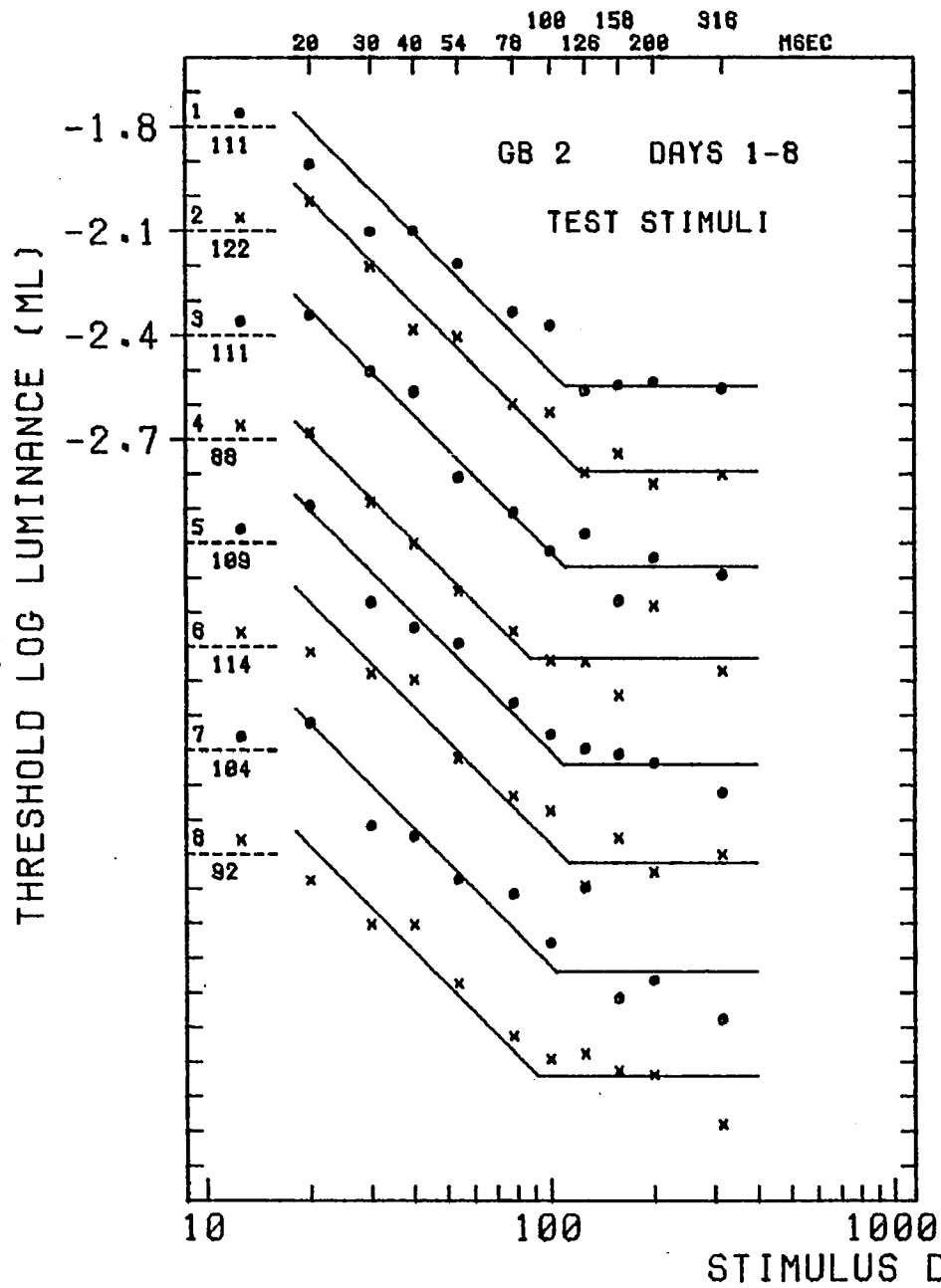


Table 2

Mean, Range, and Standard Deviation (in msec)  
of Intercept- $CD_1$  for the Two Observers in Experiments 1 and 2

Subject	Experiment	Mean (msec)	Range (msec)	Standard Deviation (msec)
RP	1	108	85 - 150	19
GB	1	93	75 - 133	16
RP	2	123	108 - 147	14
GB	2	106	88 - 122	11
		$\bar{X} = 105$		15

means is 105 msec, and the average of the four standard deviations is 15 msec. The ranges and standard deviations presented in Table 2 provide a rough indication of the extent of day to day variability.<sup>13</sup>

Control-stimulus thresholds determined in Experiment 2 are presented on the right sides of Figures 8 (O:RP) and 9 (O:GB). The thresholds of the 20-msec control stimuli were determined either immediately before or immediately after the thresholds of the different-duration test stimuli. Each data point is the average of four thresholds (like the test-stimulus data points) which were obtained close in time to the test-duration thresholds. These control-stimulus thresholds are plotted as a function of the durations with which they were paired.

Variations of the control-stimulus thresholds reflect the influences of non-duration factors (e.g., quantum fluctuations of the light source output, changes in observer sensitivity, measurement error due to small sample size). In Figures 8 and 9, the control-stimulus thresholds are connected by solid lines to aid in visualizing the variability around the session mean. Most control-stimulus thresholds are within 0.1 log mL of the session mean (which is shown by the horizontal solid line).

Averages of the curve-fit threshold estimates. The combined data presented in Figure 5 showed a range of durations displaying partial integration for both observers in Experiments 1, and O:GB in Experiment 2. Partial integration was identified by the gradual transition between complete integration and no integration. As was mentioned earlier, the daily changes of intercept- $CD_1$  alone can produce a rounding between these two functions when the thresholds of different sessions are combined.

The contribution of daily changes of intercept- $CD_1$  to the rounding between the two functions can be evaluated by graphically comparing the combined thresholds (averaged across sessions) with the averages (across sessions) of the threshold estimates given by the two-function curve fits. The curve fits depict an abrupt transition between complete integration and no integration for each day's data. In Figure 10, solid lines connect the average curve fit estimates at each duration, and dashed lines are drawn to show an abrupt transition between the two functions. The solid lines show that the daily changes of intercept- $CD_1$  produce only a slight rounding between the two functions, and that such daily changes contribute little to the gradual transition identified as partial integration.

Averages of control-stimulus thresholds. There was some concern that the consecutive ordering of stimulus durations might have contributed to the appearance of partial integration in Experiment 1. In Experiment 2, the control-stimulus thresholds were determined close in time to the test-stimulus thresholds, and would therefore be similarly affected by any practice or fatigue effects.

In Figure 11, the across session averages of the control-stimulus thresholds are plotted as a function of the test durations with which they were paired. These average control-stimulus thresholds are never more than 0.05 log mL from the grand mean (which is indicated by the horizontal solid line). Since the threshold averages of the control stimuli that were paired with the intermediate duration test stimuli (54 to 126 msec) are not above the grand mean, the possibility that order effects contributed to the partial integration evidenced by

Figure 10. Experiments 1 and 2, Q:RP and Q:GB. The data points show thresholds averaged across 16 days (Experiment 1, top) or 8 days (Experiment 2, bottom). The 95 per cent confidence limits (vertical bars) are based on one threshold per day. The averages of the threshold estimates (provided by the two-function curve fits) at each duration are joined by solid lines. Dashed lines are drawn to show an abrupt break between complete integration ( $L \times T = C$ ) and no integration ( $L = K$ ). For clarity, the data of Q:RP have been displaced 0.2 log mL downward. Individual testing day thresholds and curve-fit threshold estimates contributing to these averages were presented in Figures 6, 7, 8, and 9.

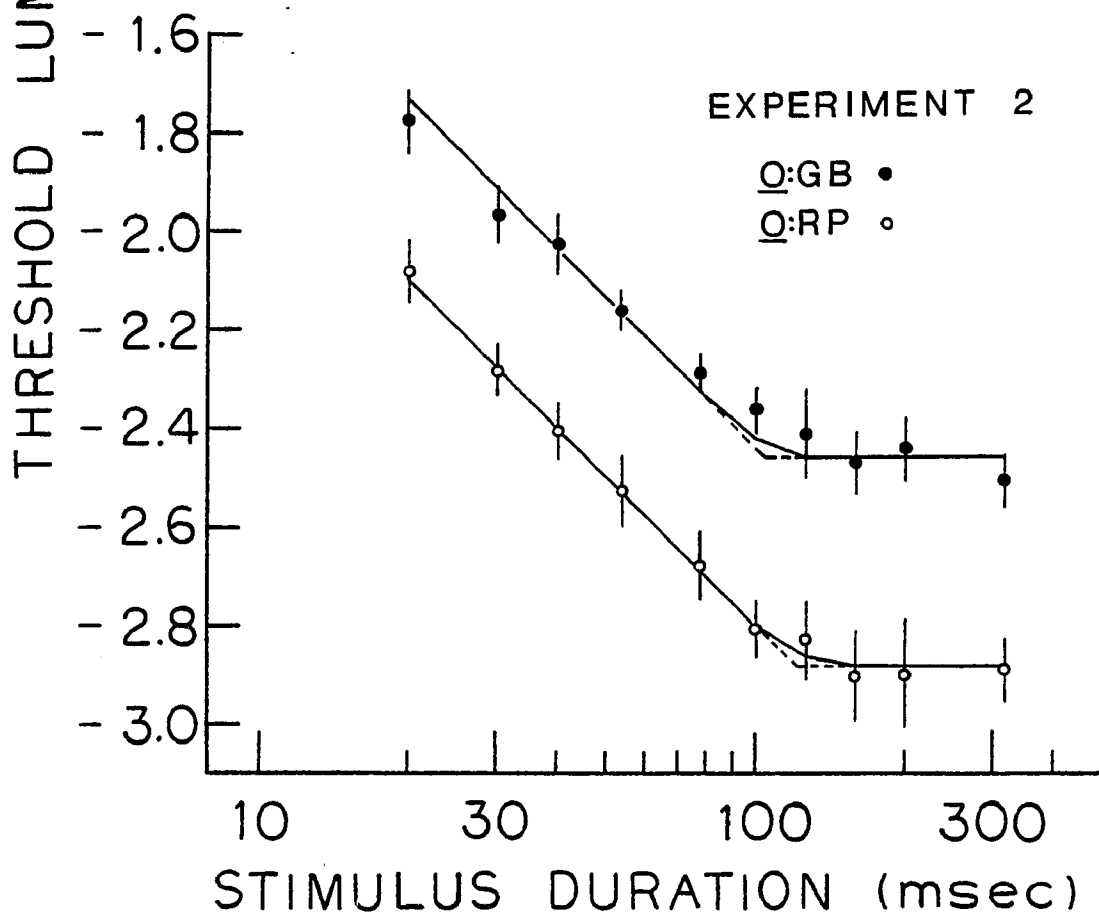
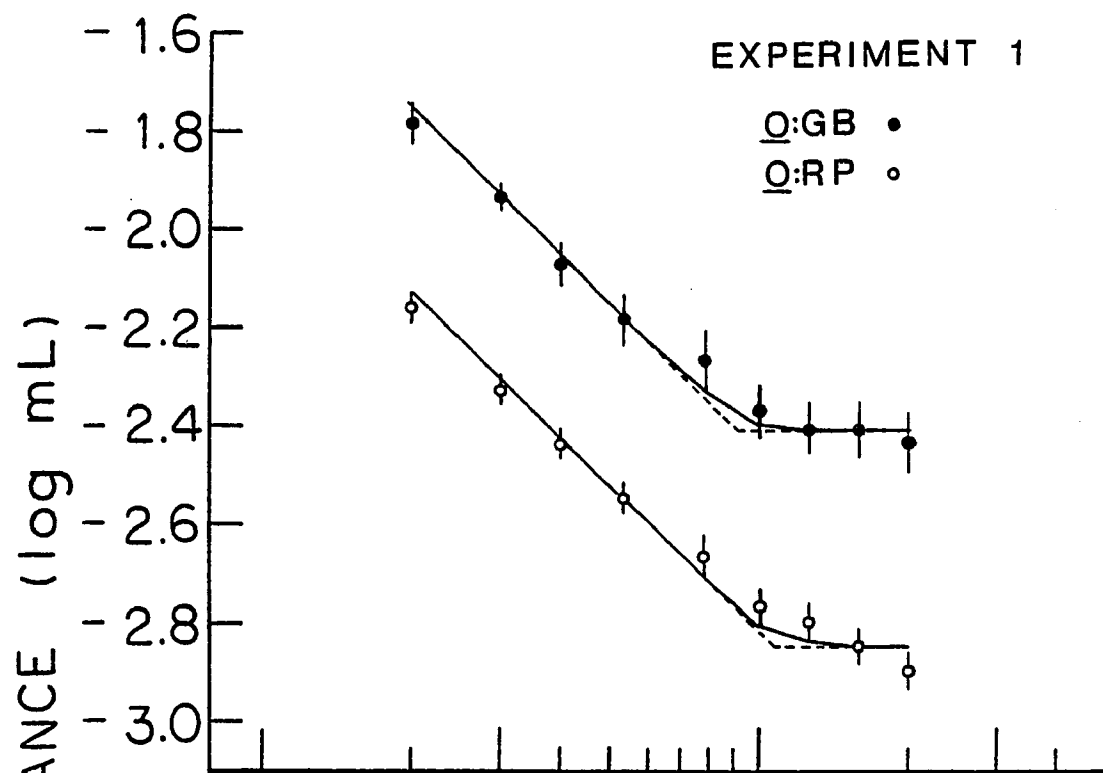
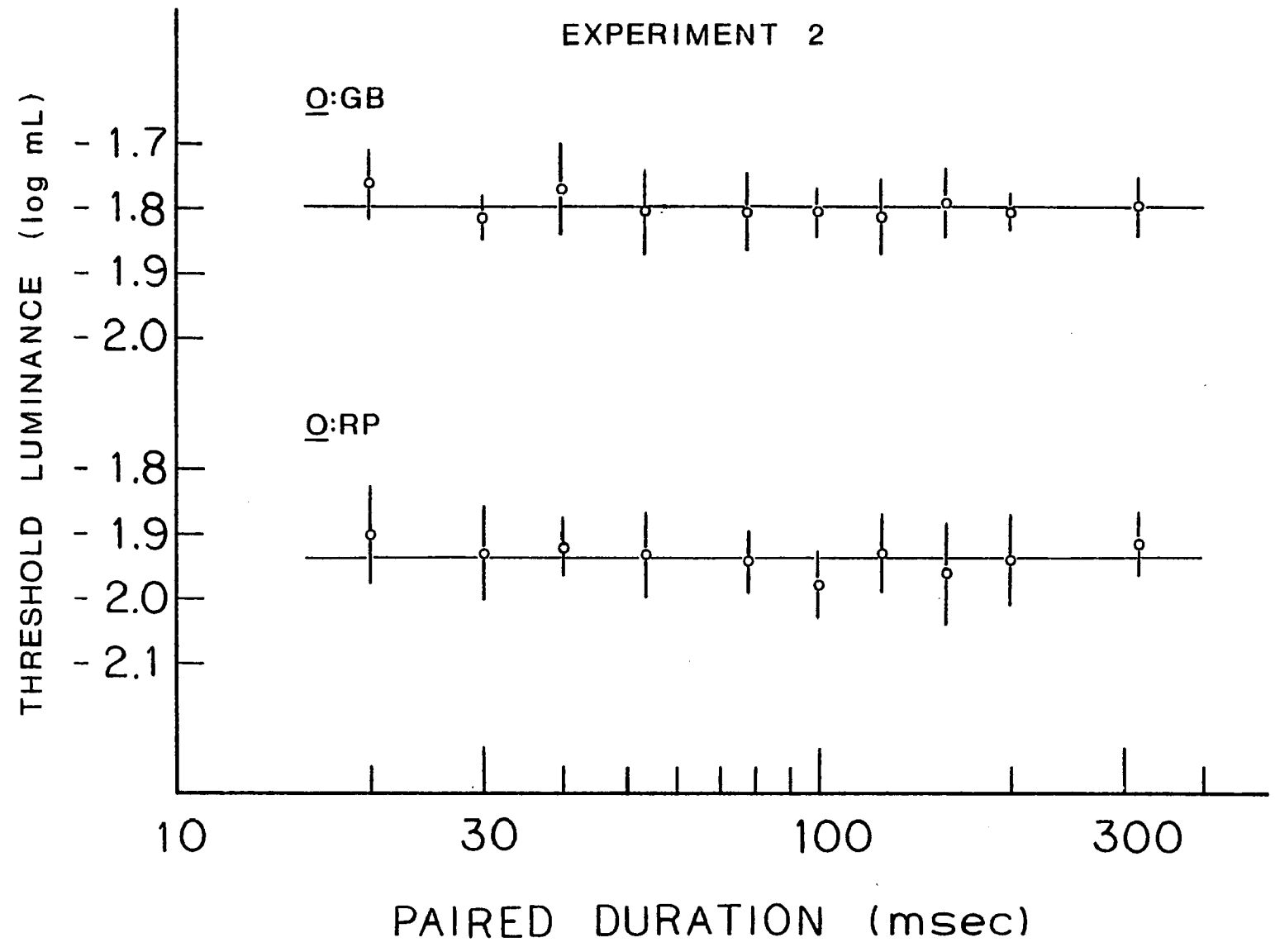


Figure 11. Experiment 2, Q:RP and Q:GB. Control-stimulus (20 msec) thresholds averaged across eight testing days. Vertical bars indicate 95 per cent confidence limits. Control-stimulus threshold is plotted as a function of the test duration with which it was paired. The horizontal solid line is the grand mean across paired durations and days.

EXPERIMENT 2



O:GB in Experiment 2 is ruled out.

### Two-pulse thresholds

Combined data. Two-pulse thresholds for each duration were averaged across sessions. The data from both experiments are presented in Figure 12. Threshold relative energy (in log mL-msec) is plotted as a function of total stimulus duration (spaced logarithmically in msec). The straight line functions drawn through each set of data show complete integration ( $E = C$ ) and constant average-luminance ( $E / T = K$ ). These are the two functions of the TEpee effect (Herrick, 1972, 1973a, 1974) that were fitted to each day's thresholds.

The combined data show complete integration up to 14 or 30 msec. The elevation of threshold above  $E = C$  indicates partial integration. Herrick (1972, 1974) suggested that when thresholds from different sessions are combined, deviations from the TEpee effect can occur (see Footnote 8). Figure 12 shows that except for the data of O:GB from Experiment 2, the slope of partial integration is more gradual than  $E / T = K$  of the TEpee effect.

In the next section, the thresholds of individual testing days (and two-function curve fits) are presented, and in the following section, the applicability of the relationship  $E / T = K$  to the data of individual testing days is demonstrated.

Individual session and individual testing day data. The individual session thresholds from Experiment 1 are presented in Figures 13 (O:RP) and 14 (O:GB), and the individual testing day thresholds from Experiment 2 are shown in Figures 15 (O:AL) and 16 (O:GB). Control-stimulus thresholds determined in Experiment 2

Figure 12. Experiments 1 (O:RP and O:GB) and 2 (O:AL and O:GB). Two-pulse threshold energy (in log mL-msec) plotted as a function of total stimulus duration (spaced logarithmically in msec). Each point represents the average from 16 sessions (Experiment 1, top) or 8 sessions (Experiment 2, bottom). The straight lines show the relationships  $E = C$  (slope of 0) and  $E / T = K$  (slope of 1).

THRESHOLD RELATIVE ENERGY (log mL-msec)

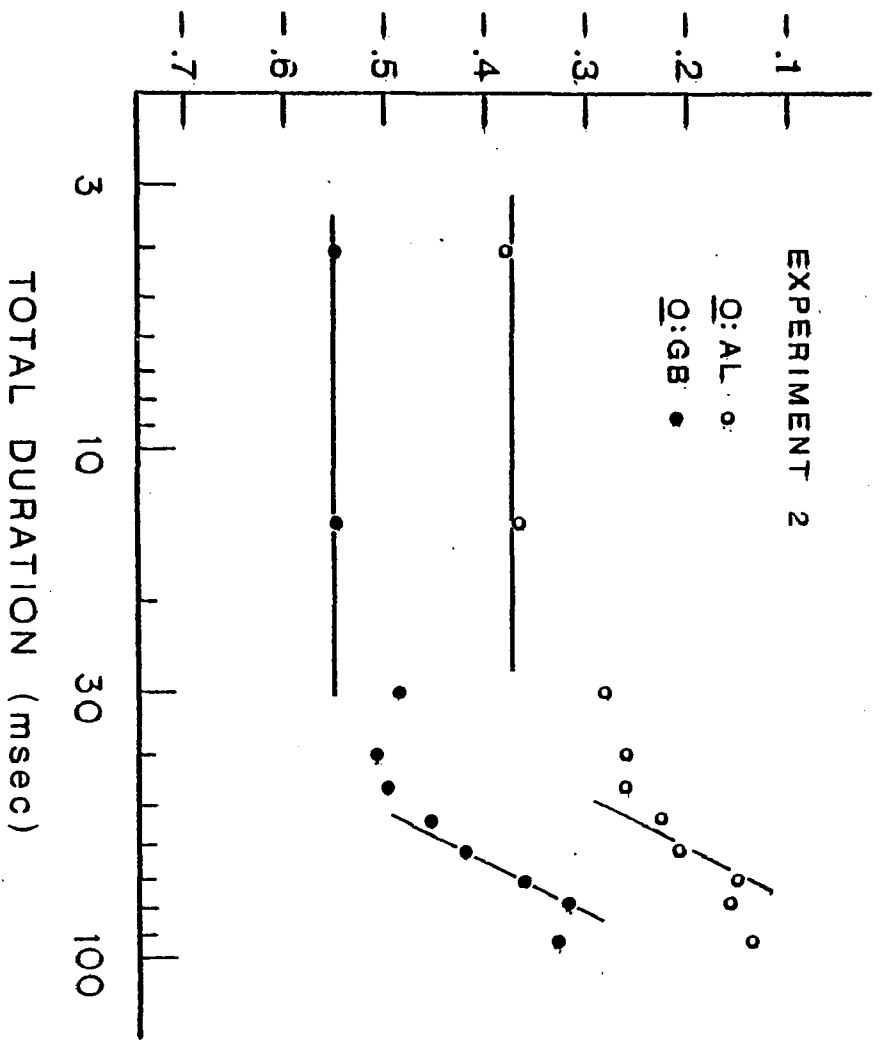
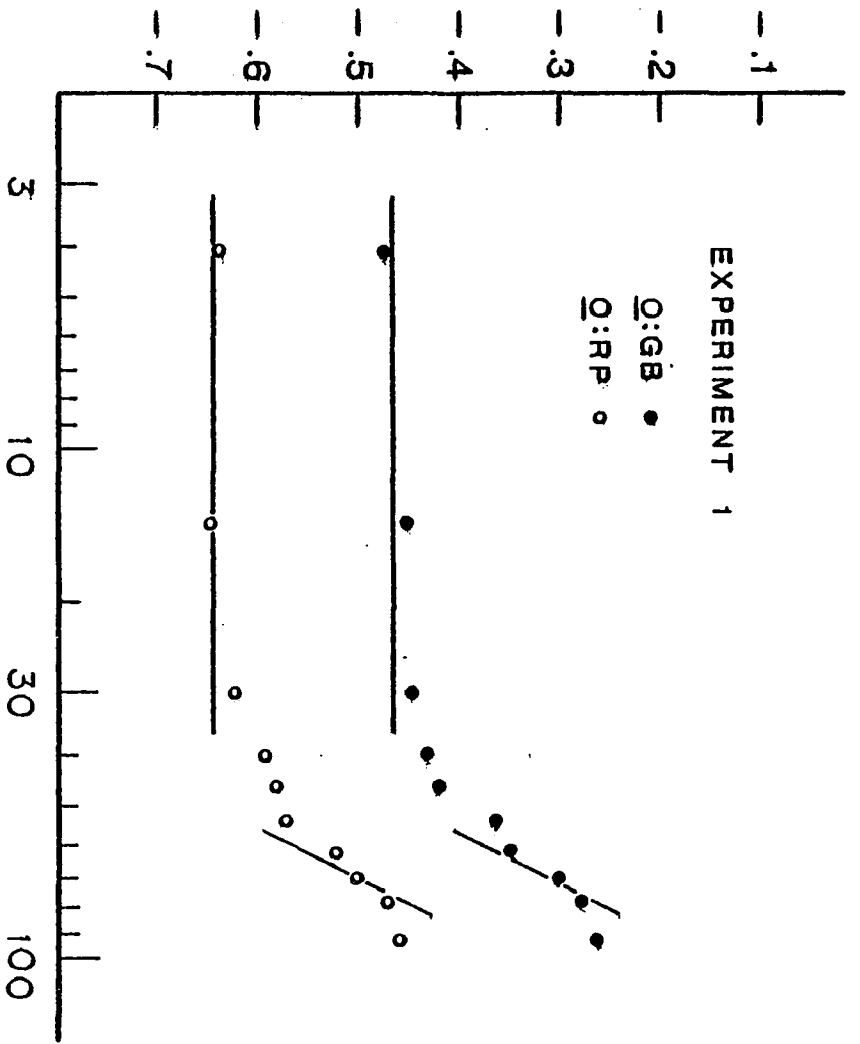


Figure 13. Experiment 1, O:RP. Two-pulse threshold luminance (in log mL) plotted as a function of total stimulus duration (spaced logarithmically in msec) for each of 16 consecutive sessions. Each data point is the mean of four thresholds. Horizontal dashed lines on the ordinate represent  $-1.2 \log \text{mL}$  for each session; the session number and the data symbol used for that session appear above this line. Intercept- $\text{CD}_2$  (in msec), viz., the intersection of  $E = C$  (slope of 0) and  $E / T = K$  (slope of 1), for each session is indicated below this line. Only durations shorter than  $\text{UT}_2$  were used for these curve fits; a dashed line (slope of 1) extends beyond the threshold of the longest duration included. One-pulse thresholds obtained on the same 16 days were presented in Figure 6.

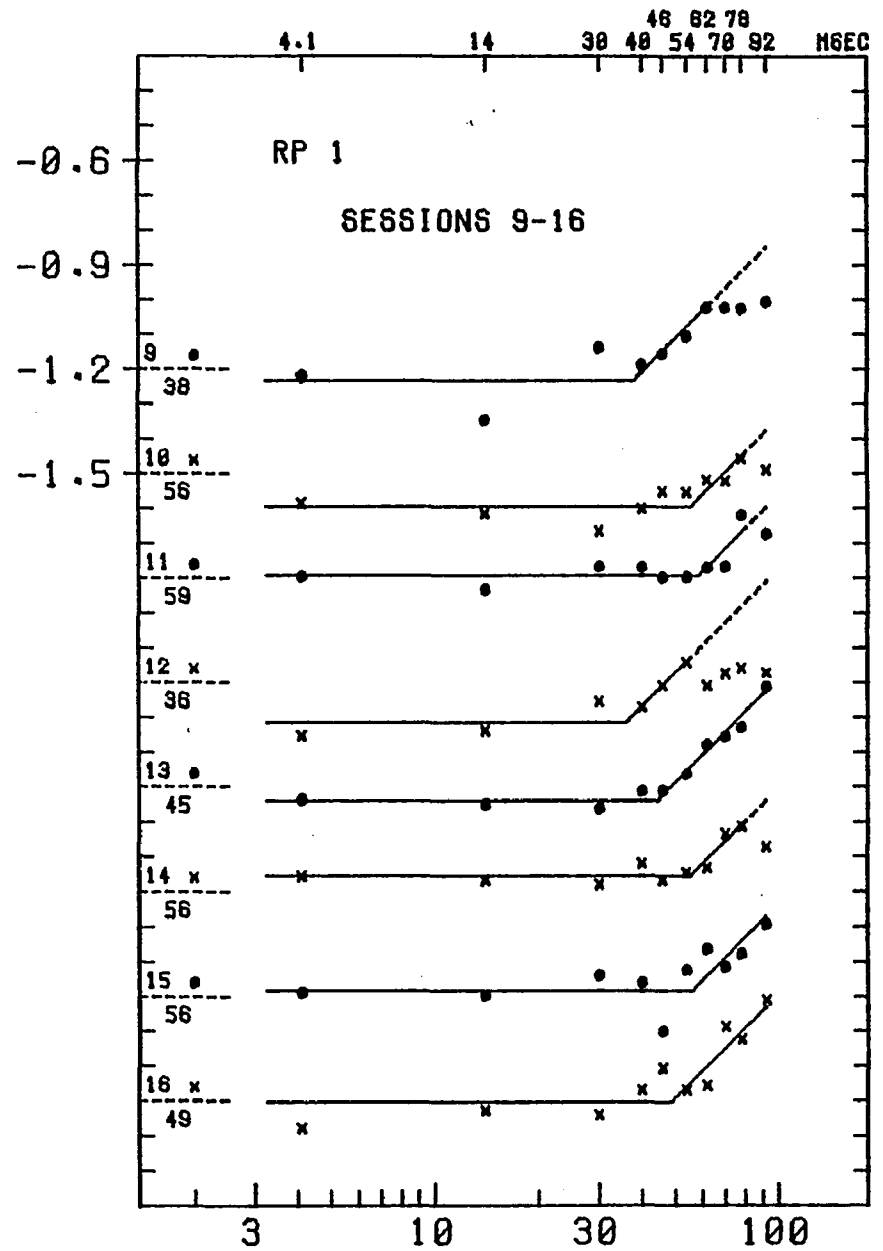
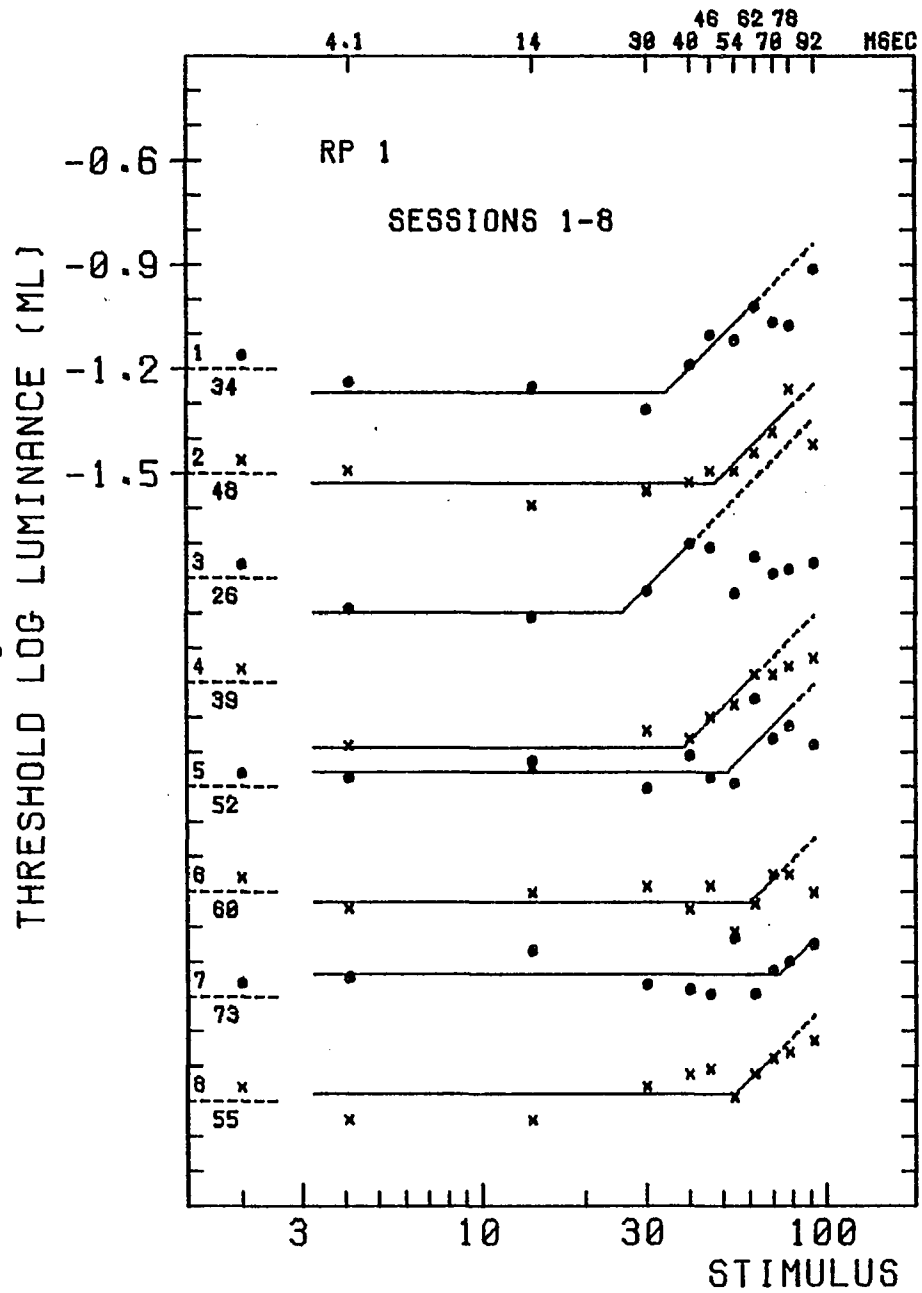


Figure 14. Experiment 1, O:GB. Two-pulse threshold luminance (in log mL) is plotted as a function of total stimulus duration (spaced logarithmically in msec) for each of 16 consecutive sessions. Presentation as in Figure 13. One-pulse thresholds obtained on the same 16 days were presented in Figure 7.

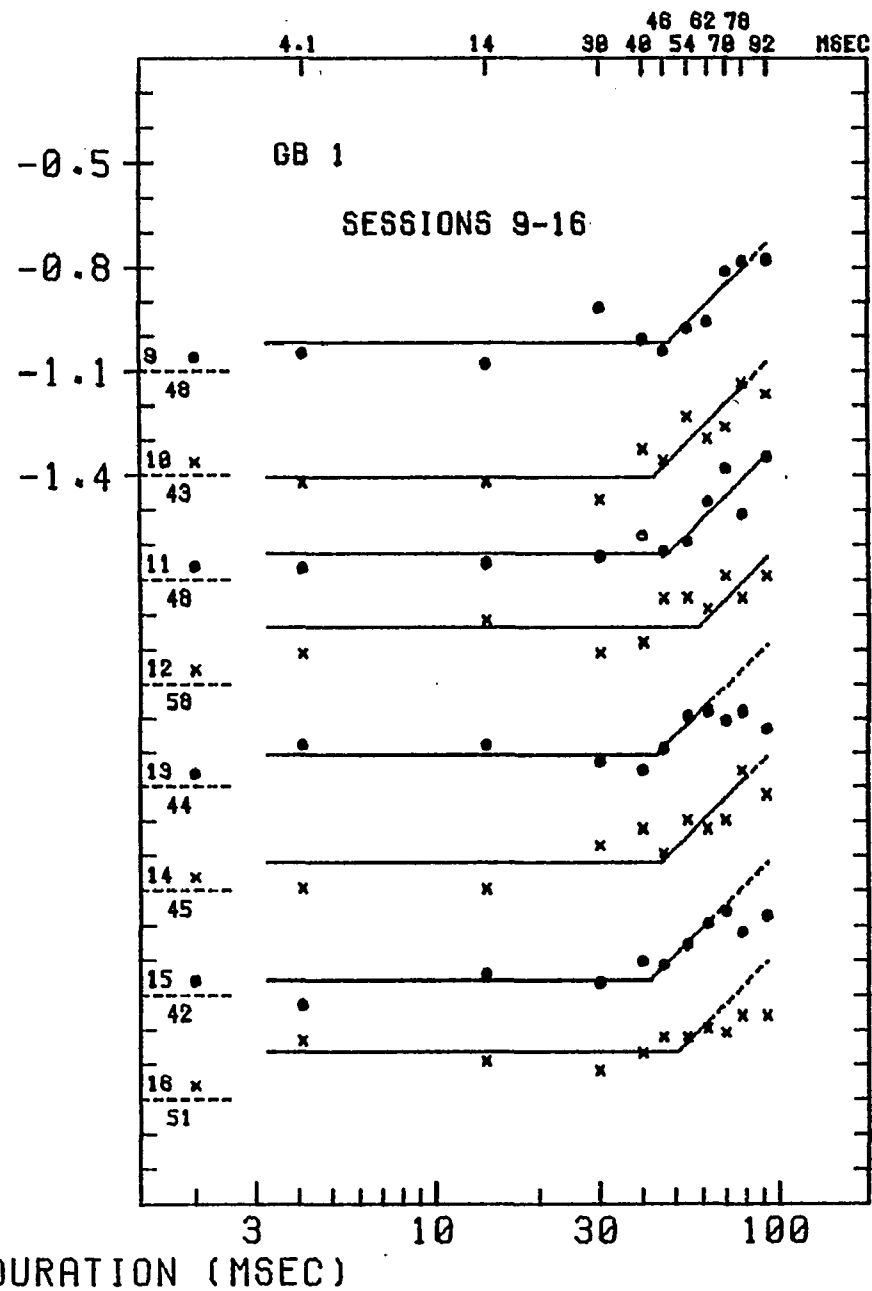
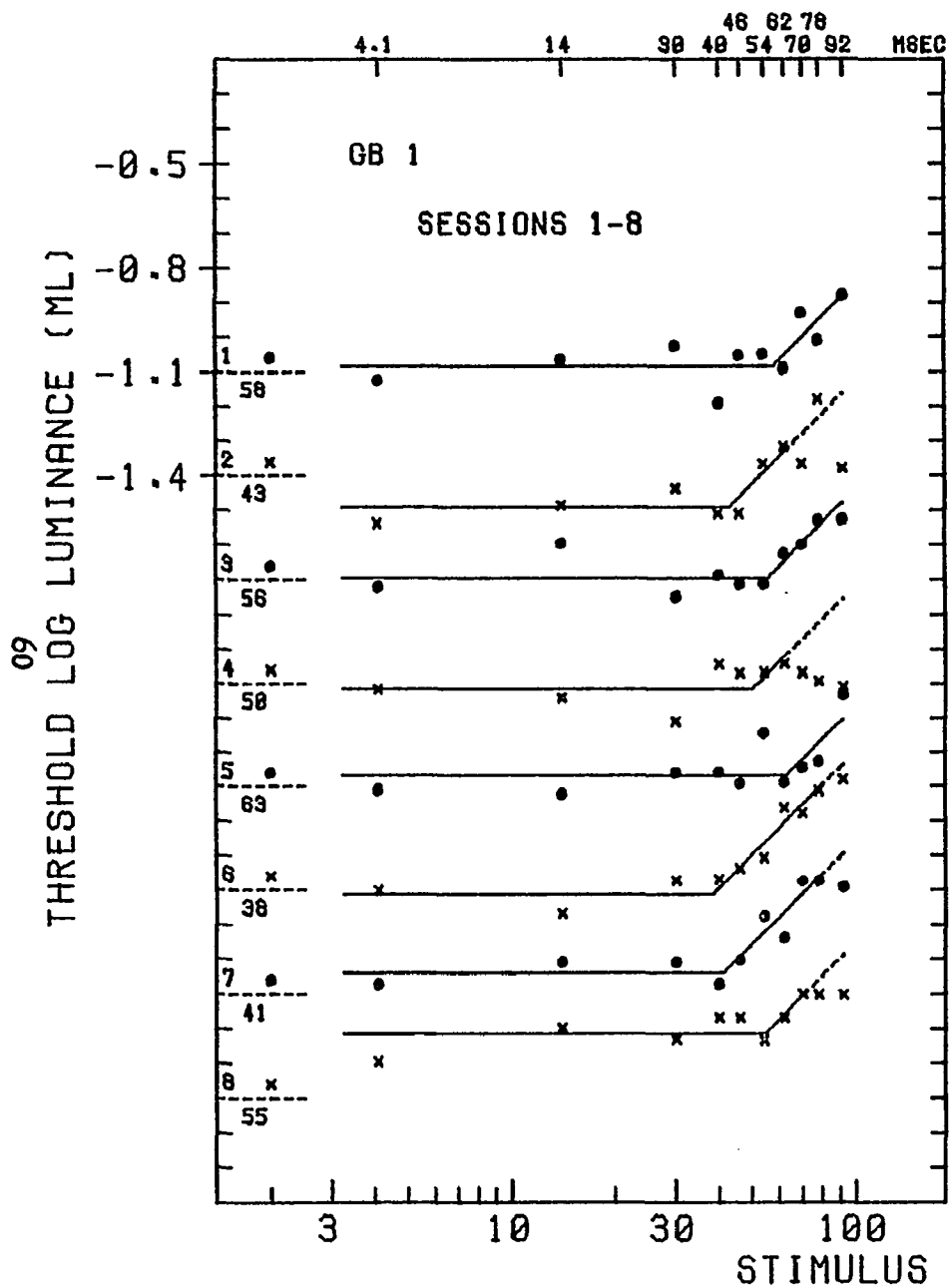


Figure 15. Experiment 2, Q:AL. On the left, two-pulse threshold luminance (in log mL) is plotted as a function of total stimulus duration (spaced logarithmically in msec) for each of eight testing days. On the right, control-stimulus (4.1 msec) threshold is plotted as a function of the test-stimulus duration with which it was paired. Control-stimulus thresholds paired with test-stimulus durations used in the corresponding curve fits (i.e., less than  $UT_2$ ) are connected by solid lines; horizontal solid lines show the means of the connected control-stimulus thresholds.

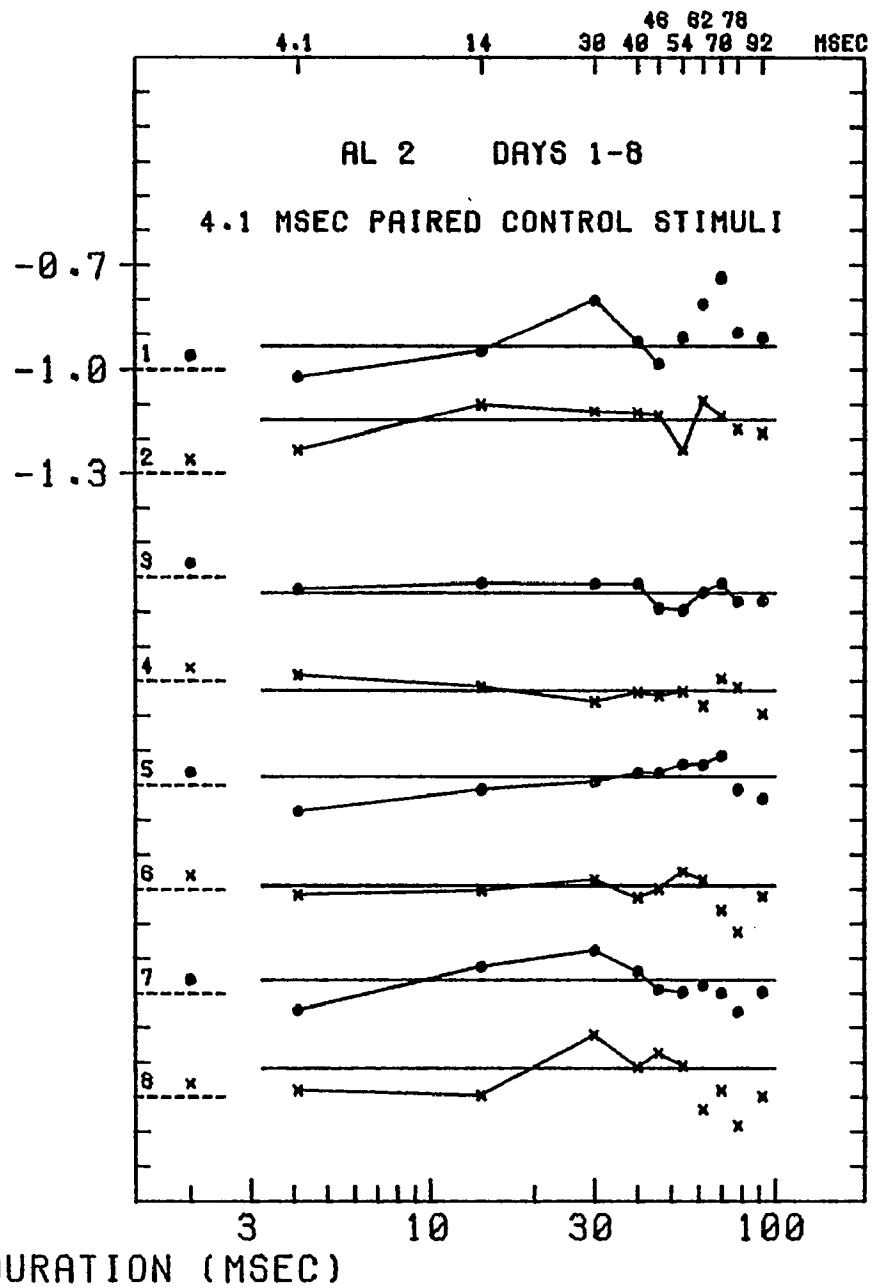
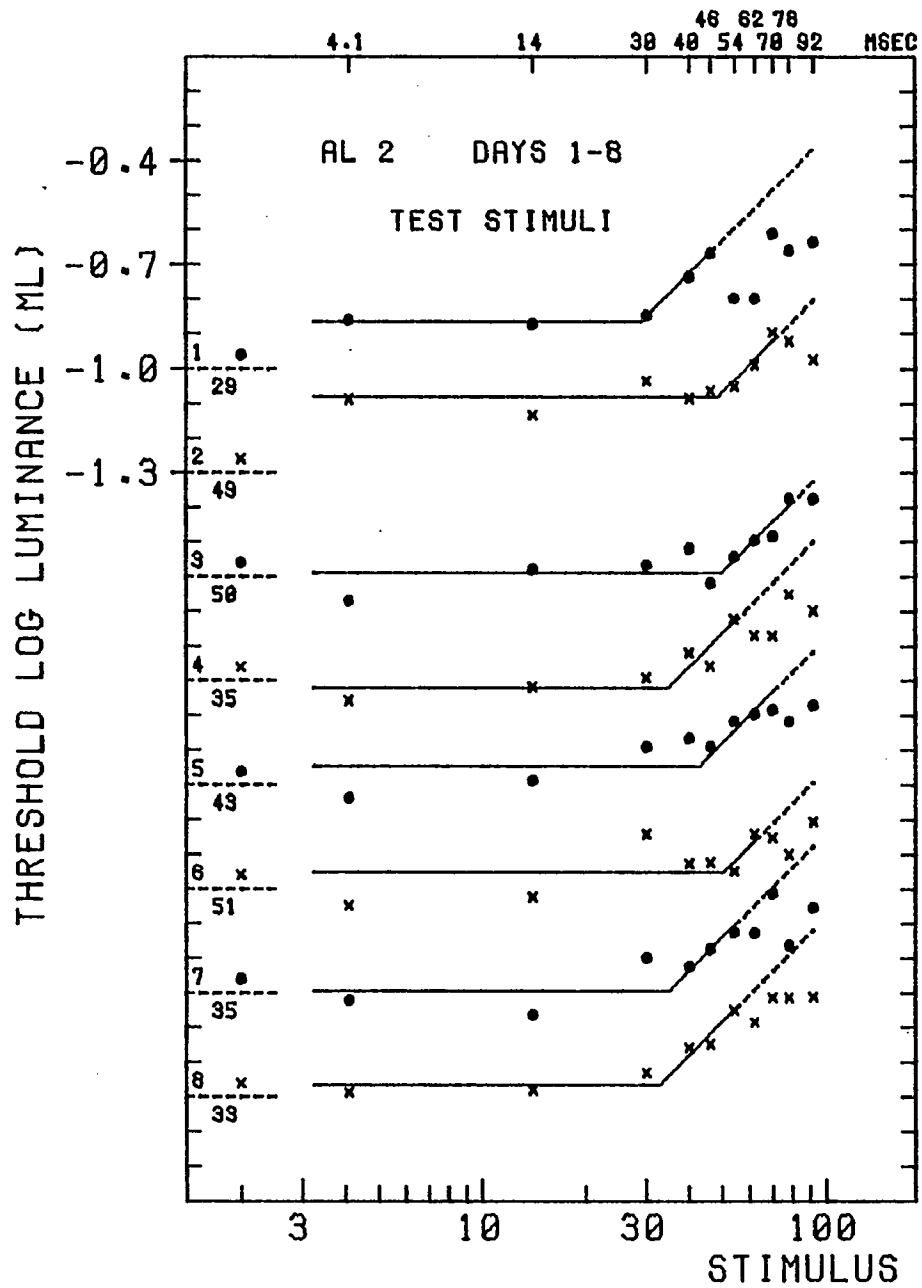
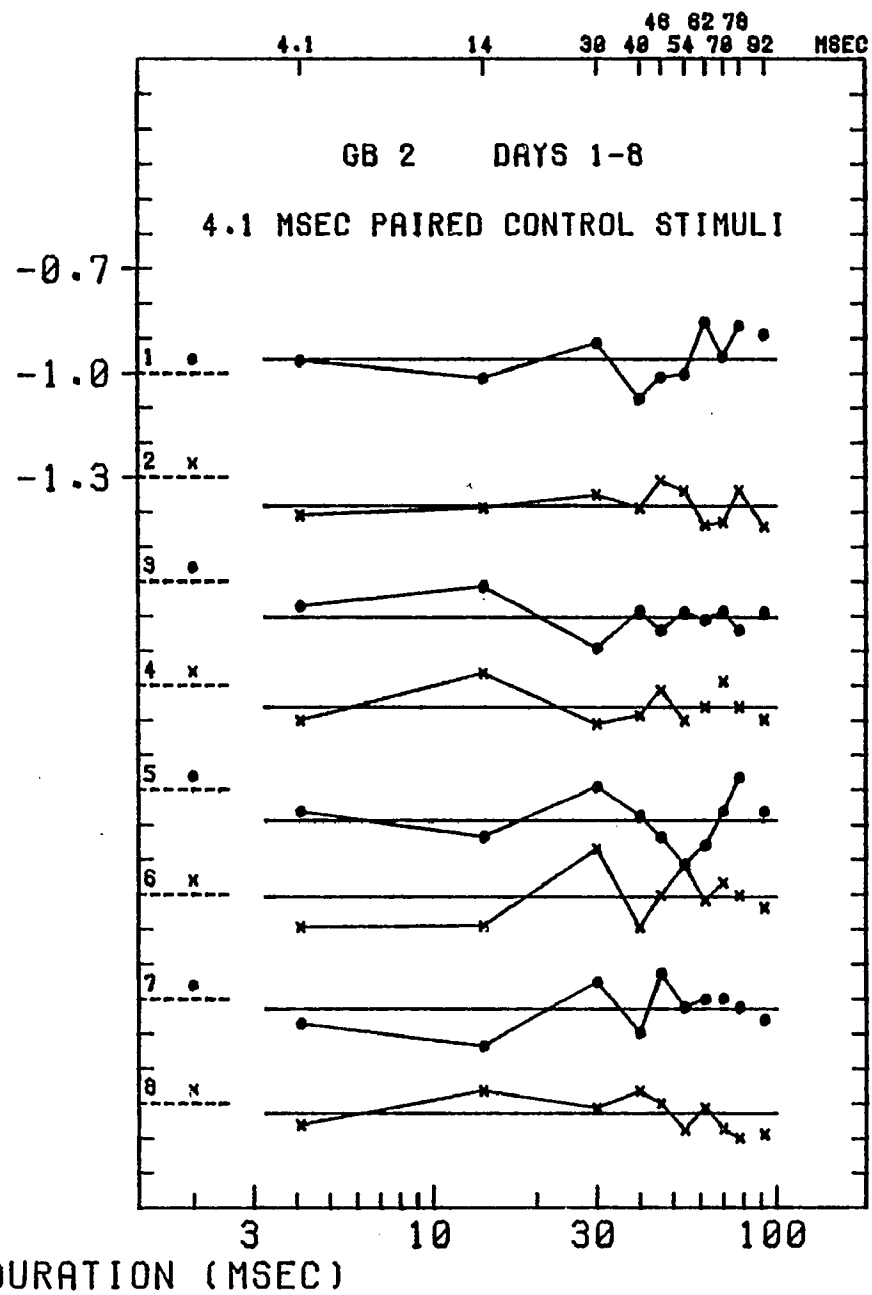
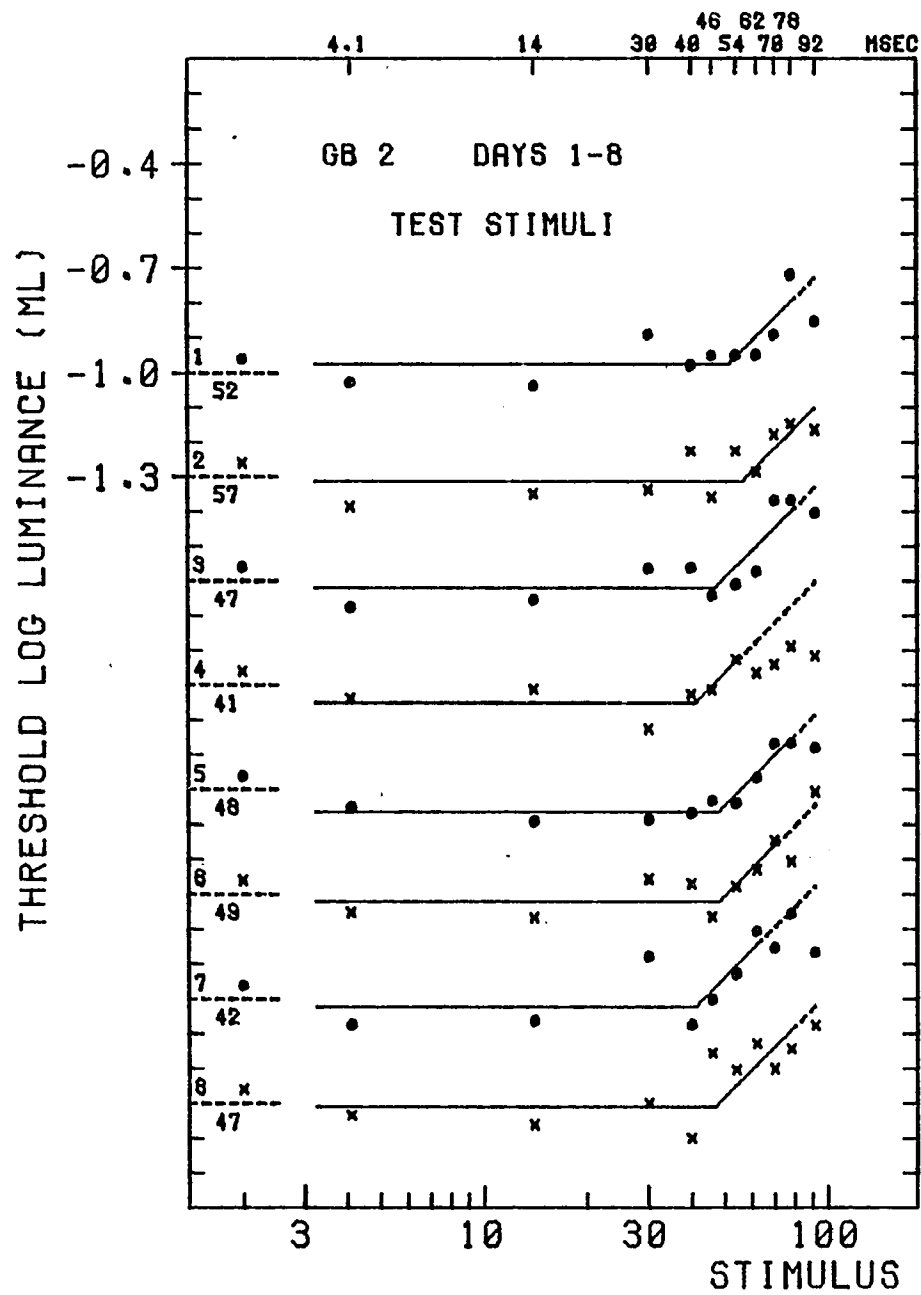


Figure 16. Experiment 2, O:GB. On the left, two-pulse threshold luminance (in log mL) is plotted as a function of total stimulus duration (spaced logarithmically in msec). On the right, control-stimulus (4.1 msec) threshold is plotted as a function of the test-stimulus duration with which it was paired.



are presented on the right sides of Figures 15 and 16. Each data point presented in these figures (for both test-stimulus and control-stimulus thresholds) is the average of four threshold determinations; four thresholds were determined in one session (Experiment 1) or two successive sessions (Experiment 2).

The two straight-line functions (representing complete integration and constant average-luminance) that were fitted to each day's thresholds are shown in Figures 13 through 16. The brief-duration function ( $E = C$ ) is the solid line with a slope of 0, and the long-duration function ( $E / T = K$ ) is the solid line with a slope of 1. The solid line with a slope of 1 extends only through those thresholds that were used in fitting the long-duration function; a dashed line (also slope of 1) extends beyond the longest duration used. Long-duration thresholds beyond  $UT_2$  were excluded from the two-function curve fit on the basis of visual inspection or when necessary statistical criteria (for details see the Data analysis section in Chapter III). The intercept- $CD_2$  measure provided by the intersection of these two functions is indicated next to each day's thresholds in Figures 13 through 16.

Estimates of intercept- $CD_2$  ranged from 26 msec ( $\underline{O}$ :RP, Experiment 1, session 3) to 73 msec ( $\underline{O}$ :RP, Experiment 1, session 7). The mean, range, and standard deviation of intercept- $CD_2$  is listed by observer and experiment in Table 3 (see Footnote 12). The average of the four intercept- $CD_2$  means is 47 msec, and the average of the four standard deviations is 8 msec. The ranges and standard deviations presented in Table 3 provide a rough indication of the extent of day to day variability.

Table 3

Mean, Range, and Standard Deviation (in msec)  
of Intercept-CD<sub>2</sub> for the Two Observers in Experiments 1 and 2

Subject	Experiment	Mean (msec)	Range (msec)	Standard Deviation (msec)
RP	1	49	26 - 73	12
GB	1	49	38 - 63	7
AL	2	41	29 - 51	9
GB	2	48	41 - 57	5
	$\bar{X} =$	47		8

The threshold change due to the manipulation of two-pulse duration (0.15 mL to 0.35 mL) is relatively small when compared to the threshold change that can result from non-duration factors (see the control-stimulus thresholds presented in Figures 15 and 16). Nevertheless, it appears that the two functions,  $E = C$  and  $E / T = K$ , provide a reasonable description of the individual testing day thresholds presented in Figures 13, 14, 15, and 16.

The thresholds of durations beyond  $UT_2$  are not described by the function  $E / T = K$ ; after  $UT_2$ , these thresholds either asymptote or decrease. However, the thresholds of all durations (even those beyond  $UT_2$ ) were included in the averages of Figure 12. It seems likely that the daily changes of  $UT_2$  are partly responsible for the gradual slope (more gradual than  $E / T = K$ ) of partial integration observed for the combined data in Figure 12.

To further evaluate the adequacy with which  $E / T = K$  describes two-pulse partial integration, the following analysis was performed. Thresholds were again averaged across sessions; however, the thresholds beyond  $UT_2$  were excluded from these averages. The threshold estimates (for durations less than  $UT_2$ ) provided by the two-function curve fits were also averaged. In the next section, these two averages are graphically compared.

$E / T = K$  describes two-pulse partial integration for the thresholds of individual testing days. The threshold averages presented in Figures 17 (Experiment 1) and 18 (Experiment 2) are based only on the thresholds of those durations that were determined to be less than  $UT_2$  for purposes of the daily two-function curve

Figure 17. Experiment 1, Q:RP (top) and Q:GB (bottom). Two-pulse thresholds (only those used for the two-function curve fits) averaged across sessions. Vertical bars indicate 95 per cent confidence limits. Average curve-fit threshold estimates for each duration are joined by solid lines. The number of thresholds (and curve fit estimates) contributing to each duration's average is listed in Table 4. The individual session thresholds and curve fit estimates contributing to these averages were presented in Figures 13 (Q:RP) and 14 (Q:GB).

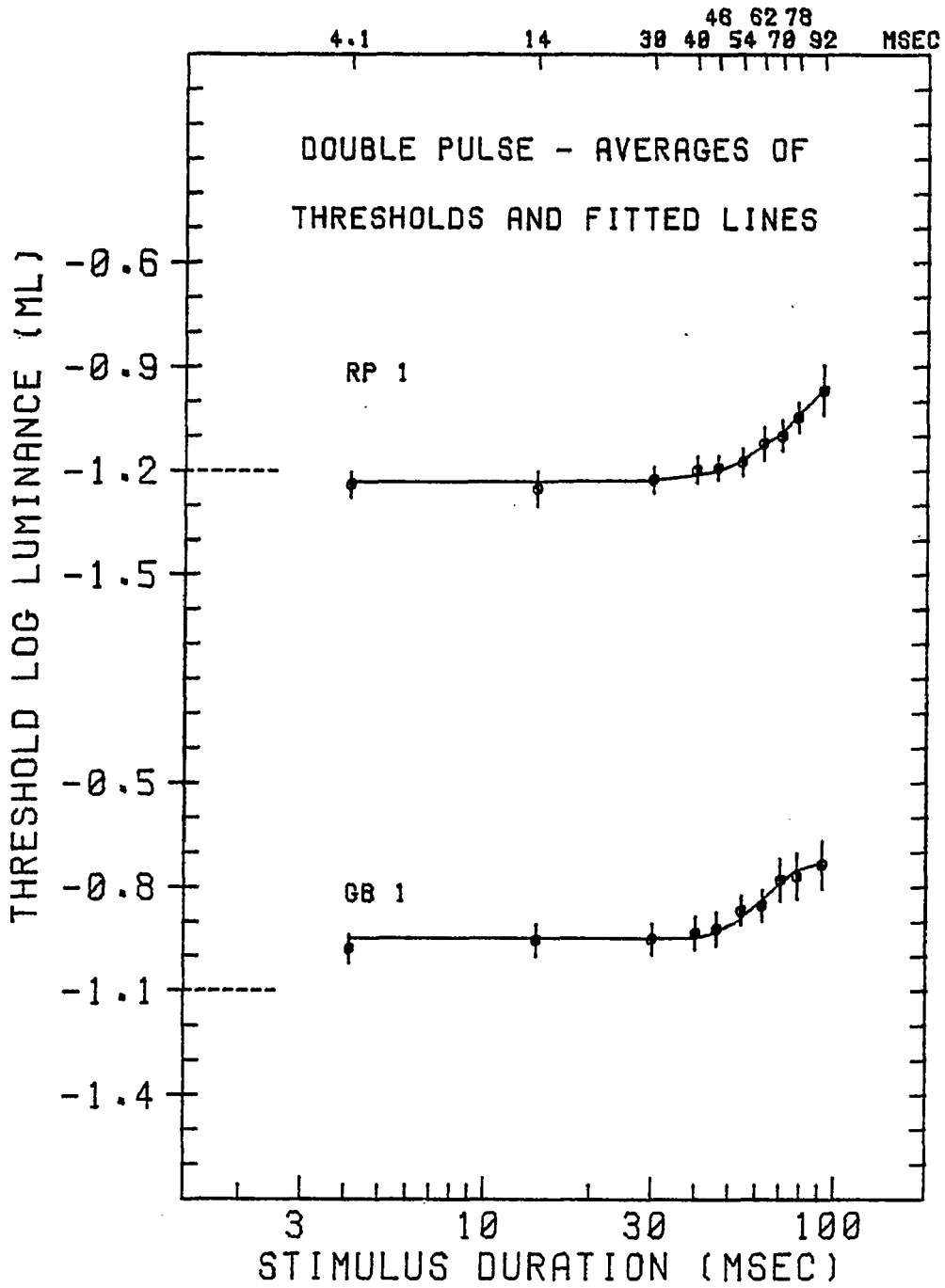
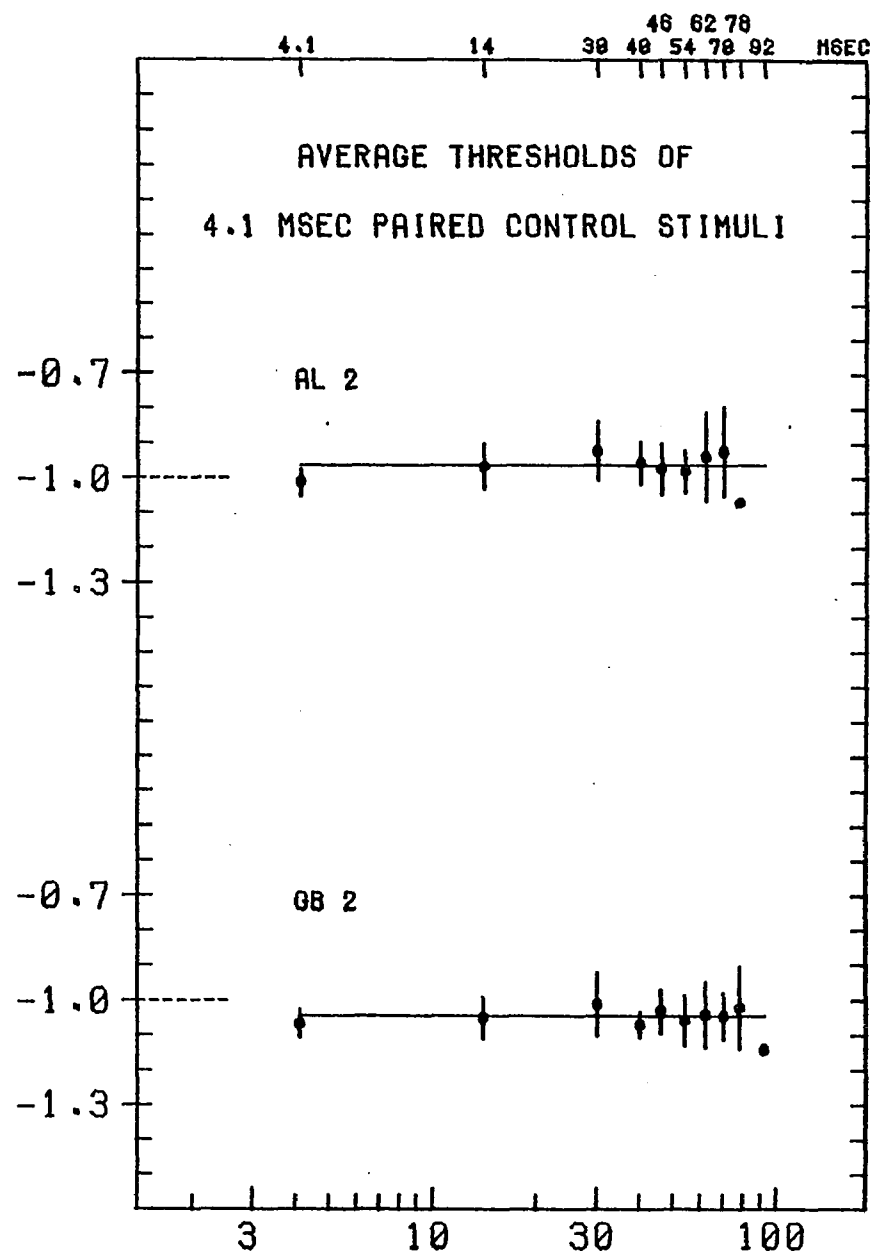
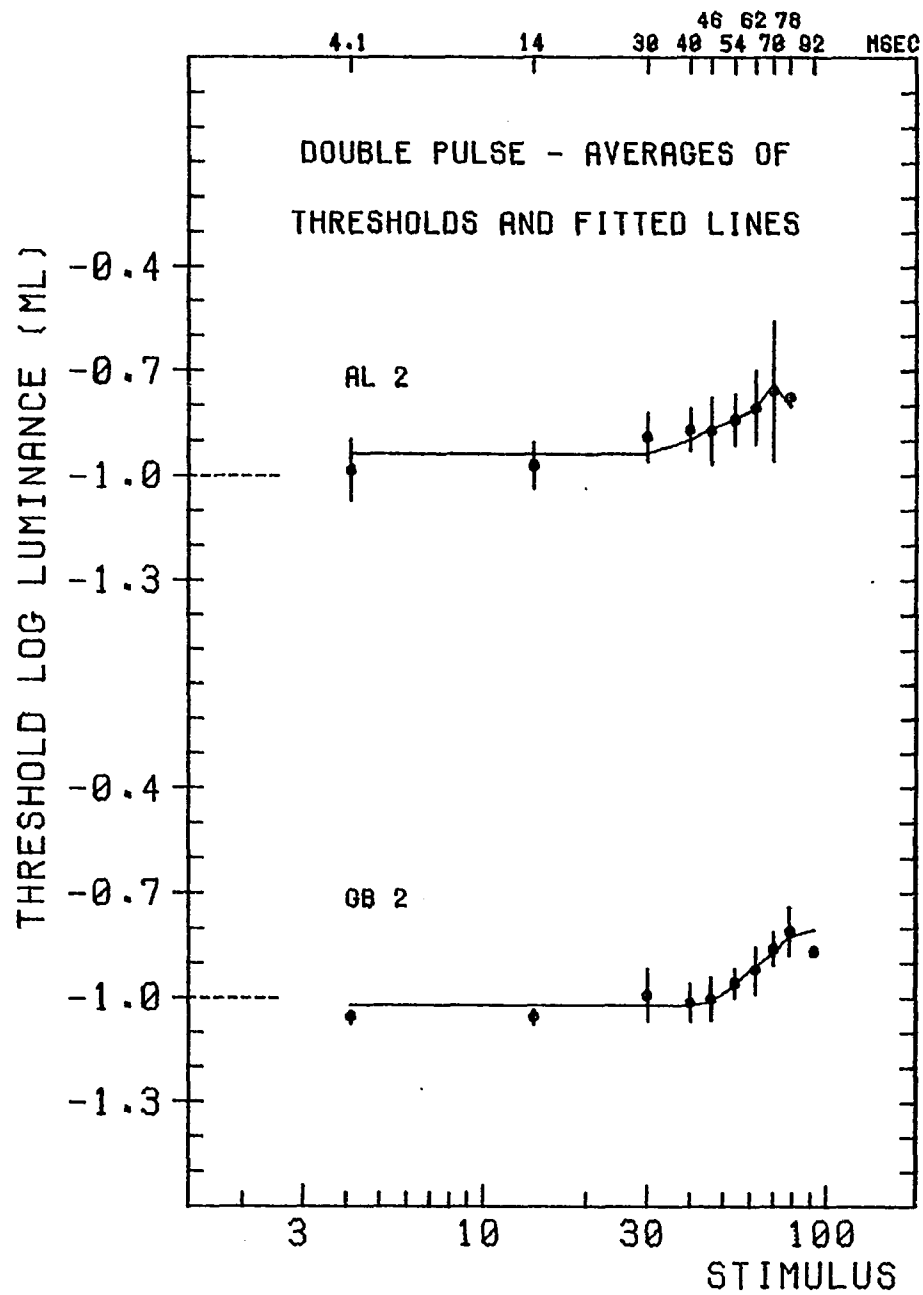


Figure 18. Experiment 2, Q:AL (top) and Q:GB (bottom). Two-pulse thresholds (only those used for the two-function curve fits) averaged across sessions. Vertical bars indicate 95 per cent confidence limits. Curve-fit threshold estimates averaged across days for each duration are connected by solid lines. On the right, averages across sessions of the control-stimulus (4.1 msec) thresholds (using only those paired with test durations included in the two-function curve fits); the horizontal solid line indicates the overall mean of the individual testing day averages. The number of measures at each duration which contributed to the test-stimulus and control-stimulus threshold averages, and the curve-fit estimate averages, are the same, and are listed in Table 4. Individual testing day thresholds and curve fit estimates contributing to these averages were presented in Figures 15 (Q:AL) and 16 (Q:GB).



fits. The numbers of thresholds contributing to the averages at longer durations are less than the 16 (Experiment 1) or 8 (Experiment 2) thresholds that contribute to the averages at shorter durations (see Table 4). Since the averages at longer durations are based on thresholds from only some of the sessions, the apparent slopes in these figures should be ignored. Of more importance is the degree of correspondence between the threshold averages (data points) and the averages of the curve-fit threshold estimates at each duration (shown connected by solid lines in Figures 17 and 18).

When the individual testing day thresholds are examined (see Figures 13 through 16), the thresholds are on some days above and on other days below the long-duration function ( $E / T = K$ ) at each duration. However, when random measurement error is minimized by averaging, the thresholds and their curve fit estimates closely correspond (see Figures 17 and 18). This close correspondence, particularly at longer durations (40 to 92 msec), indicates that based on individual testing day thresholds,  $E / T = K$  adequately describes two-pulse partial integration.<sup>14</sup>

#### The one-pulse and two-pulse results compared

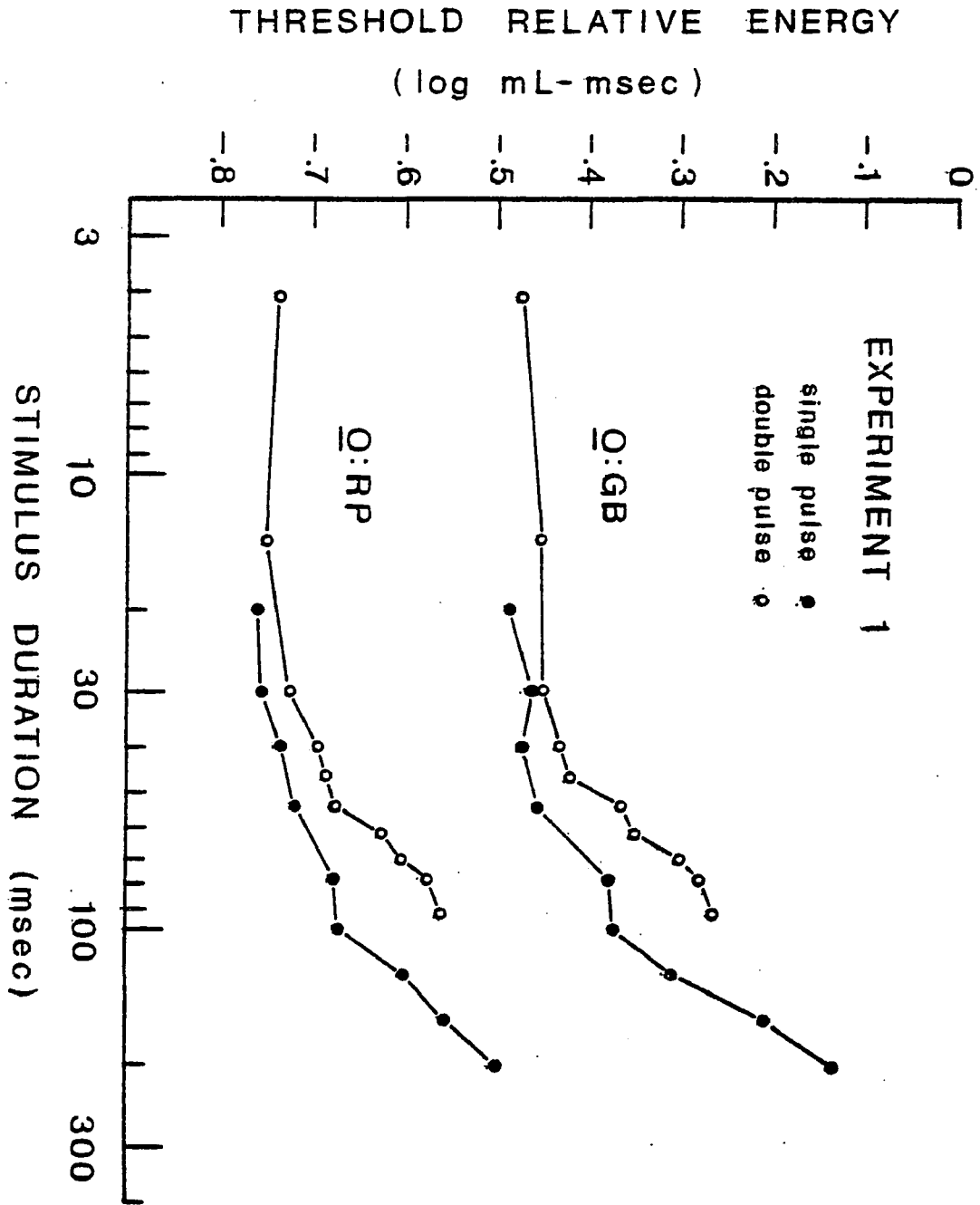
Thresholds. Since one-pulse and two-pulse thresholds were both determined (during separate sessions) on each day of Experiment 1, these are the data that are most meaningfully compared. In Figure 19, the one-pulse and two-pulse thresholds from Experiment 1 are both presented on the same graph, with threshold energy (in log mL-msec) plotted as a function of stimulus duration (spaced logarithmically in msec); these combined thresholds (across session averages)

Table 4

Number of Thresholds (and Curve-Fit Estimates) for  
 Each Duration Contributing to the Averages Presented in  
 Figures 17 (Experiment 1) and 18 (Experiment 2)

Duration (msec)	Experiment			
	1		2	
	Subjects			
	RP	GB	AL	GB
4.1	16	16	8	8
14	16	16	8	8
30	16	16	8	8
40	16	16	8	8
46	15	16	8	8
54	15	16	7	8
62	14	16	4	7
70	11	11	3	6
78	9	10	1	5
92	4	5	0	1

Figure 19. Experiment 1, Q:RP and Q:GB. Threshold energy (in log mL-msec) of one-pulse and two-pulse stimuli plotted as a function of total stimulus duration (spaced logarithmically in msec). Each point is the average of 64 threshold determinations from 16 sessions. For clarity, the thresholds of Q:RP have been displaced downward by 0.1 log mL-msec.



were previously presented separately in Figures 5 (one pulse) and 12 (two pulse).

Figure 19 shows that one-pulse and two-pulse thresholds are about the same (within the limits of calibration error) for the briefest durations. As stimulus duration is increased, the two-pulse thresholds deviate from complete integration ( $E = C$ ) at briefer durations than the one-pulse thresholds. Thus, even if critical duration is defined as the initial departure from complete integration (rather than the intersection of two functions), the two-pulse critical duration is still briefer than the one-pulse critical duration.

The one-pulse and two-pulse thresholds presented in Figure 19 both show partial integration between 30 and 90 msec. Within this range of stimulus durations the one-pulse thresholds are lower than the two-pulse thresholds, and therefore closer to the energy level of complete luminance-time reciprocity ( $E = C$ ); the one-pulse thresholds display greater integration than the two-pulse thresholds at these durations.

Measures provided by the two-function curve fits. The two-function curve fits provided three measures for each day's thresholds: a brief-duration energy measure ( $C$ , in mL-msec), a long-duration luminance measure ( $K$ , in mL), and a critical duration measure (intercept- $CD$ , in msec). The measures  $C$  and  $K$  fully describe the two fitted functions, and the ratio  $C / K$  indicates the intersection of these functions and therefore estimate intercept- $CD$ .

The averages of the logarithmic estimates of these three measures (intercept- $CD$ ,  $C$ , and  $K$ ) for one-pulse and two-pulse thresholds are

listed by subject and experiment in Table 5. A comparison of one-pulse and two-pulse measures is most meaningful for the data of Experiment 1. For the two observers in Experiment 1, the estimates of  $C_1$  and  $C_2$  are similar, while  $K_2$  is about 0.3 log mL above  $K_1$ . Since intercept-CD (in log msec) is equal to log C minus log K for both one-pulse and two-pulse thresholds, intercept- $CD_2$  is 0.3 log msec less than intercept- $CD_1$ , i.e., it is half the duration of intercept- $CD_1$ . The arithmetic means (in msec) of intercept- $CD_2$  and intercept- $CD_1$  (previously presented in Tables 3 and 2, respectively) describe this same relationship: intercept- $CD_2$  (ca. 50 msec) is approximately half of intercept- $CD_1$  (ca. 100 msec).

The standard deviation of intercept-CD is taken as a rough estimate of day to day variability. When intercept-CD is expressed in msec, the standard deviation of intercept- $CD_1$  (ca. 15 msec) is greater than the standard deviation of intercept- $CD_2$  (ca. 8 msec). However, when intercept- $CD_1$  and intercept- $CD_2$  are expressed in log msec, the standard deviations of these measures are more comparable (ca. 0.07 log msec).

The variability of intercept- $CD_1$  and intercept- $CD_2$ , and the relationship between these two measures, can be visualized for the data of Experiment 1 in the plots of Figures 20 (O:RP) and 21 (O:GB). The scatter plots at the top of these figures show the relationship between intercept- $CD_2$  and intercept- $CD_1$ ; each of the 16 data points indicates the value of intercept- $CD_1$  and intercept- $CD_2$  for a single day's testing. The correlation between intercept- $CD_1$  and intercept- $CD_2$  was significant for O:GB,  $r(14) = .75$ ,  $p < .001$ ; for O:RP,  $r(14) =$

Table 5

Means Across Days of the Logarithmically Expressed Estimates  
of Intercept-CD and the Constants C and K From the  
Two-Function Curve Fits

Subj.	Exp.	Integration Measures <sup>a</sup>		
		Intercept-CD (log msec)	C <sup>b</sup> (log mL-msec)	K <sup>c</sup> (log mL)
One pulse				
RP	1	2.03 (.07)	-.62 (.04)	-2.65 (.07)
GB	1	1.96 (.08)	-.45 (.07)	-2.41 (.10)
RP	2	2.09 (.05)	-.60 (.06)	-2.69 (.09)
GB	2	2.03 (.05)	-.43 (.05)	-2.46 (.04)
Two pulse				
RP	1	1.67 (.12)	-.63 (.07)	-2.31 (.08)
GB	1	1.69 (.06)	-.45 (.07)	-2.13 (.08)
AL	2	1.60 (.09)	-.34 (.08)	-1.94 (.11)
GB	2	1.68 (.05)	-.42 (.03)	-2.10 (.04)

<sup>a</sup>Numbers in parentheses indicate the standard deviations.

<sup>b</sup>Relative energy of the brief-duration function.

<sup>c</sup>Asymptote luminance for one-pulse stimuli beyond intercept-CD<sub>1</sub>,  
and average-luminance for two-pulse stimuli beyond intercept-CD<sub>2</sub>.

Figure 20. Experiment 1, O:RP. On top, a scatter plot shows the relationship between intercept- $CD_2$  (ordinate) and intercept- $CD_1$  (abscissa). Each of the 16 data points indicates the values of these measures for a single testing day. The solid line depicts the regression equation  $CD_2 = .26 CD_1 + 21$ . On bottom, intercept- $CD_1$  and intercept- $CD_2$  are plotted as a function of the day of testing.

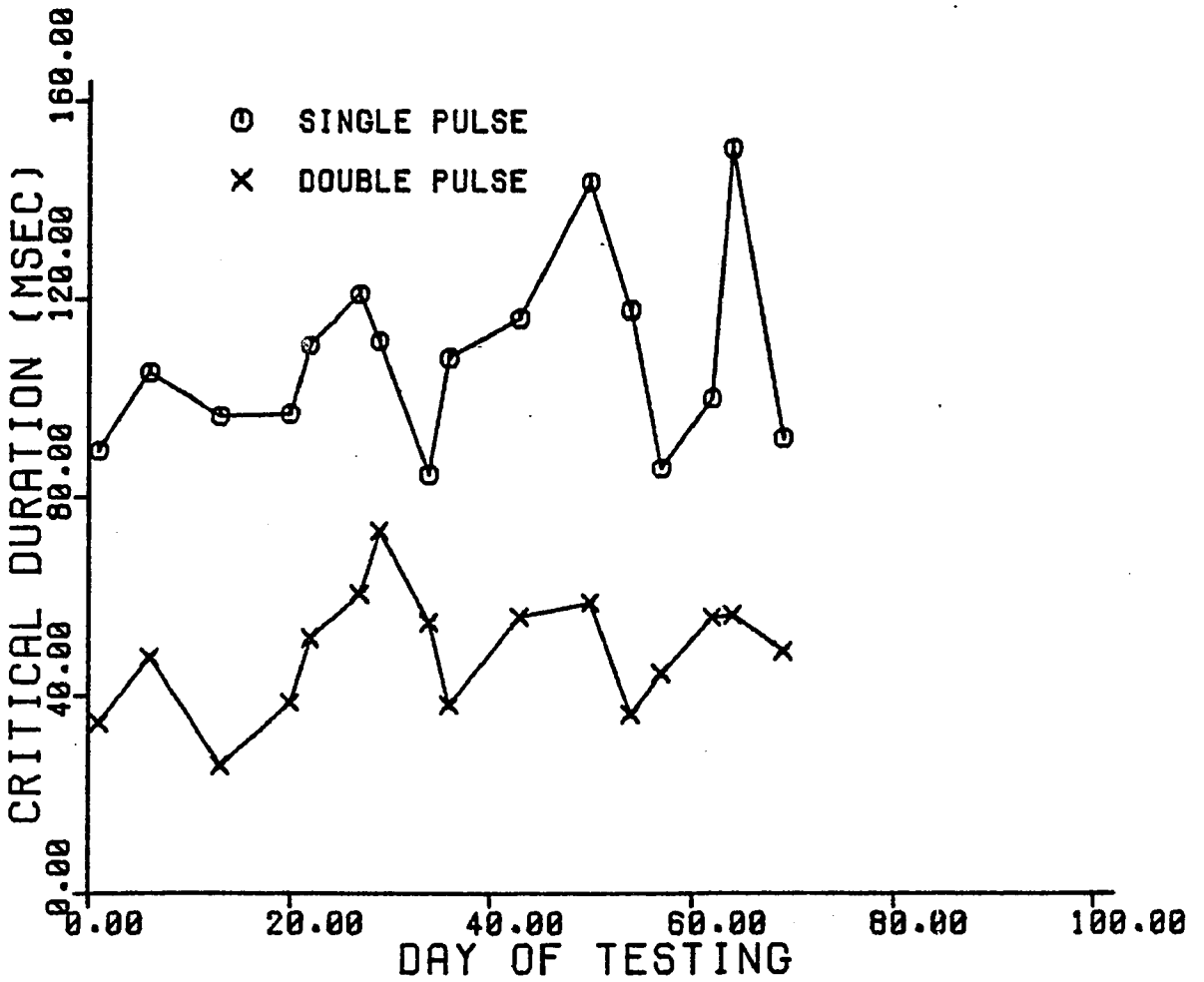
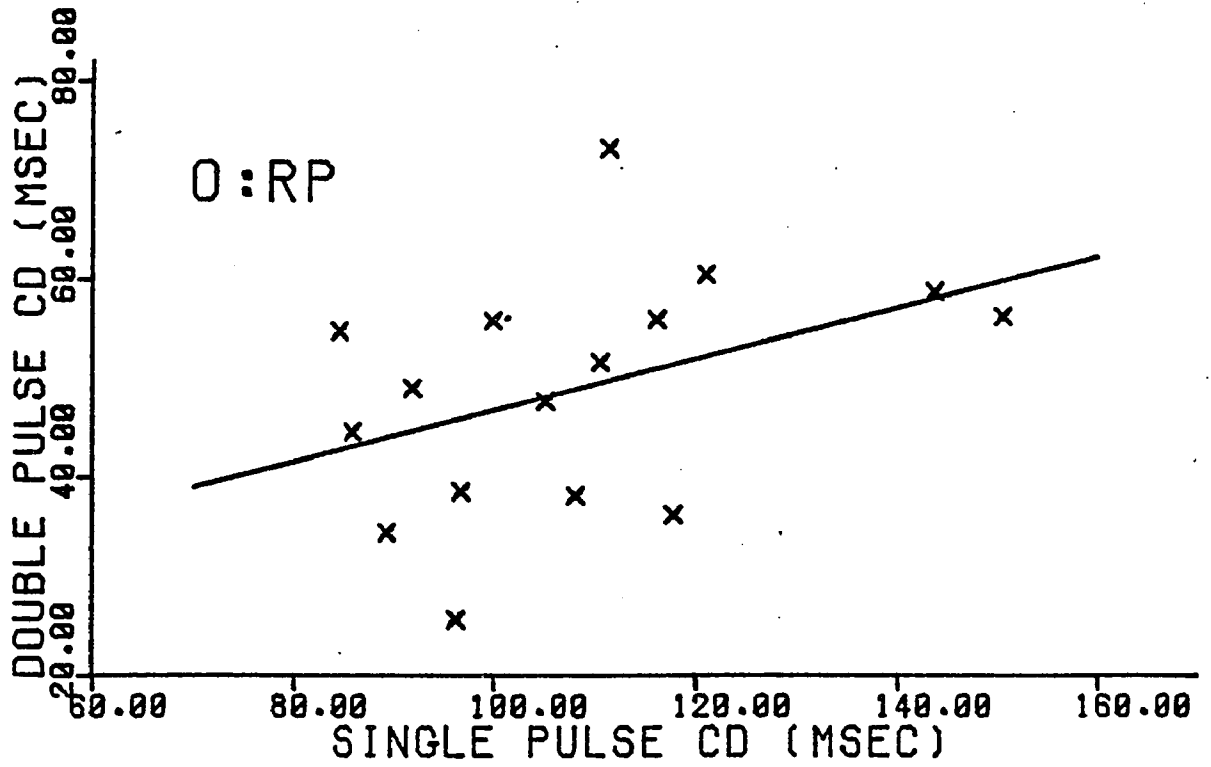
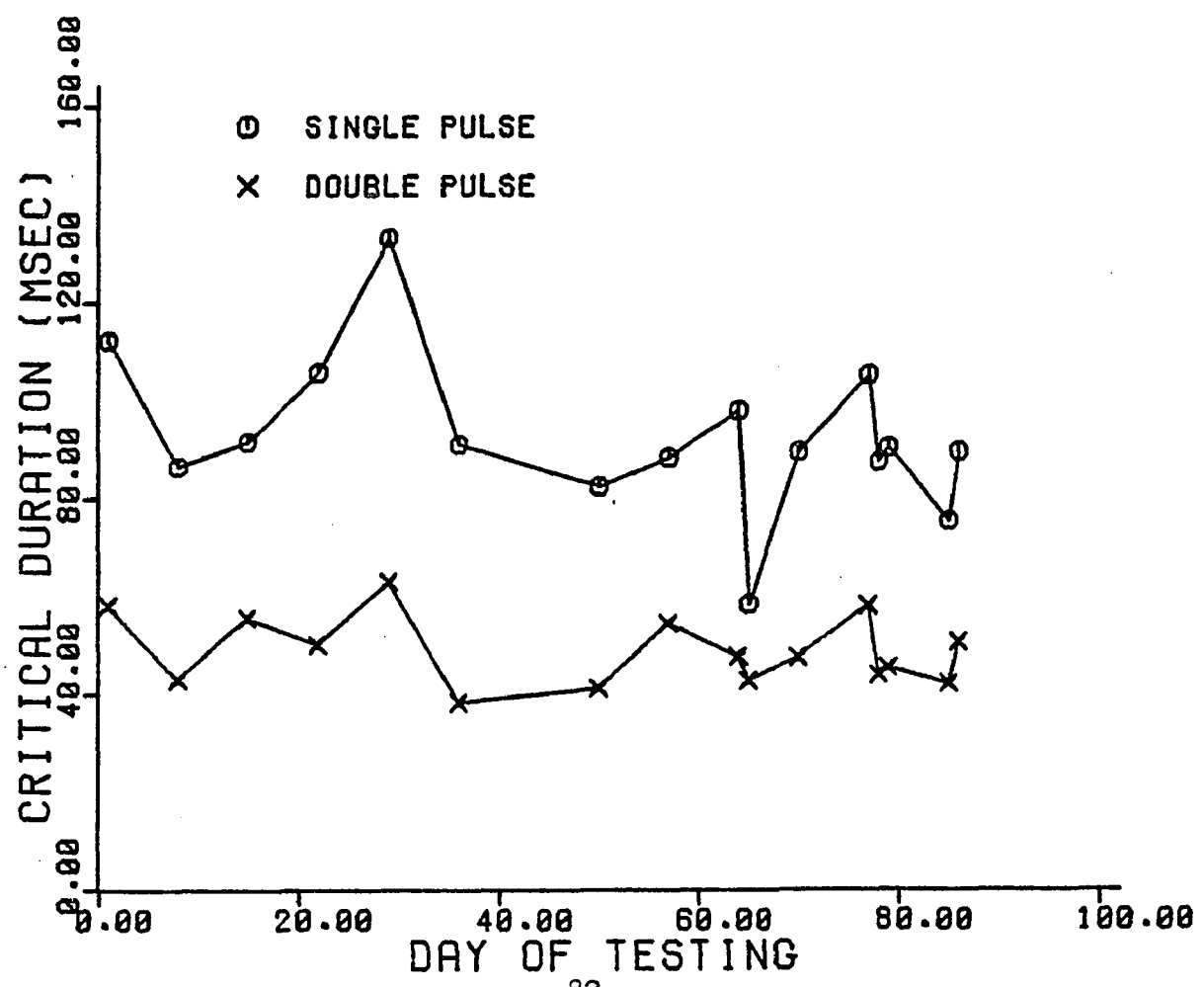
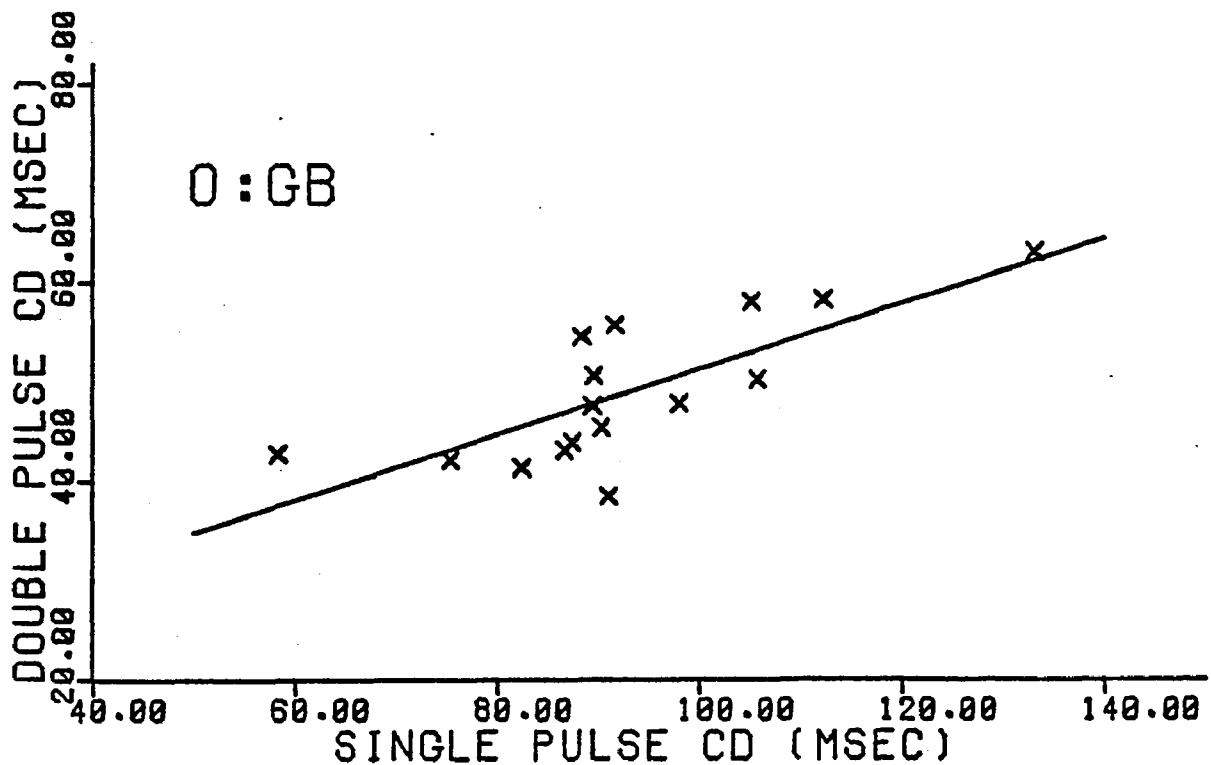


Figure 21. Experiment 1, Q:GB. On top, a scatter plot shows the relationship between intercept- $CD_2$  (ordinate) and intercept- $CD_1$  (abscissa). The solid line depicts the regression equation  $CD_2 = .33 CD_1 + 18$ . On bottom, intercept- $CD_1$  and intercept- $CD_2$  are plotted as a function of the day of testing.



.41,  $p > .05$ .<sup>15</sup> A positive correlation between these measures suggests that both are influenced by the same organismic (subject) variables which change from day to day.

On the bottom of Figures 20 and 21, intercept- $CD_1$  and intercept- $CD_2$  are both plotted as a function of the day of testing. O:RP completed Experiment 1 in 69 days, and O:GB in 86 days. There were no systematic changes in critical duration that would suggest practice (learning) or fatigue (boredom) effects. For O:GB, who demonstrated the higher correlation of intercept- $CD_1$  and intercept- $CD_2$ , concomitant changes across days of the magnitudes of these measures is more clearly observable.

## CHAPTER V

### Discussion

The results of the present study indicate for the dark-adapted fovea that: (1) intercept- $CD_2$  (ca. 50 msec) is approximately half the magnitude of intercept- $CD_1$  (ca. 100 msec), (2) the standard deviations of intercept- $CD_1$  and intercept- $CD_2$  (across days) are both about 0.07 log msec, or about 15 per cent of the mean when these measures are expressed in linear units (msec), and (3) while the relationship  $E / T = K$  of Herrick's TEpee effect describes two-pulse partial integration for individual session data, the slope of partial integration appears shallower than specified by the relationship (shallower than 1 on log-log coordinates) when the data of different sessions are combined.

The measures of intercept- $CD_1$  and intercept- $CD_2$  that were determined in the present study are conceptually different. Intercept- $CD_2$  is the break between complete integration ( $E = C$ ) and partial integration (described by the function  $E / T = K$ ), while intercept- $CD_1$  is the break between complete integration ( $L \times T = C$ ) and no integration ( $L = K$ ), thus ignoring partial integration. These are Herrick's definitions of critical duration.

The present results confirm for the dark-adapted fovea the relationship between  $CD_1$  and  $CD_2$  described by Herrick (1973a) for the light-adapted fovea. Using number of pulses as the independent variable, Herrick determined that the relationship between  $CD_n$

and the quantity  $\frac{n-1}{n}$  (where  $n$  is the number of pulses) has a slope equal to  $CD_1$  and a y-intercept equal to the duration of each pulse (2 msec in the present study). For the two-pulse condition, this relationship can be specified as follows:  $CD_2 = \frac{1}{2} CD_1 + 2$ . This relationship indicates, as do the results of the present study, that  $CD_2$  is approximately half the magnitude of  $CD_1$ .

Contrary to the present results, Clark and Blackwell (1959) reported that  $CD_1$  and  $CD_2$  were similar in magnitude for both their dark-adapted condition (CDs were 85 msec) and their light-adapted condition (CDs were 20 msec). They defined critical duration as the initial departure from complete integration. Even using this definition of critical duration, the present results show that two-pulse CD is briefer than one-pulse CD (see Figure 19). A close inspection of Clark and Blackwell's dark-adapted data indicates that  $CD_1$  was longer (the average of five observers is 100 msec) and  $CD_2$  shorter (the average of five observers is 75 msec) than the 85 msec estimate reported in the text. Thus, upon recalculation of CDs, the data of Clark and Blackwell also suggest that  $CD_2$  is briefer than  $CD_1$ .<sup>16</sup>

Threshold variability can be attributed to quantum fluctuations in the output of the light source (Hecht, Schlaer, & Pirenne, 1942), changes that occur within the observer (Cornsweet, 1970), or both. One organismic (observer) variable that can influence threshold detection is the time limit of temporal integration, i.e., critical duration. The present study indicates that critical duration varies from day to day; the standard deviations (across days) of intercept- $CD_1$  and intercept- $CD_2$  were about the same, 0.07 log msec or approximately

15 per cent of the mean.

One might suggest that the intercept-CD does not really change across days, and that the variability of this measure simply reflects sampling error. However, in Experiment 1, the measures of intercept- $CD_1$  and intercept- $CD_2$  obtained each day (using stimuli of different temporal configurations) were found to covary (at least for O:GB). If changes in intercept- $CD_1$  and intercept- $CD_2$  were produced solely by chance variations, it is unlikely that these measures would covary across days. The covariation suggests that those factors which influence one of these measures also influence the other, and that changes in the magnitude of these measures across days reflect real variations in the temporal processing capacity of the visual system.

For a particular observer, the range of durations showing partial integration can also change from day to day (see Footnote 13), and consequently from experiment to experiment (as seen for the one-pulse thresholds presented in Figure 5). Other investigators have shown that the range of partial integration is influenced by stimulus factors such as target size (Barlow, 1958; Graham & Margaria, 1935; Karn, 1936), background luminance level (Barlow, 1958; Clark & Blackwell, 1959), wavelength (Saunders, 1975; Sperling & Jolliffe, 1965), and time in the dark (Stewart, 1972).<sup>17</sup> The present study shows that non-stimulus factors (that change within the observer) can also exert their influence on the range of durations which display partial integration.

For two-pulse thresholds, the slope of partial integration for combined data (averaged across sessions) appeared more shallow than

the slope specified by the relationship  $E / T = K$ , shallower than a slope of 1 when threshold energy and stimulus duration were plotted on logarithmic coordinates (Figure 12). However, since the thresholds and threshold estimates predicted by this relationship were found to closely correspond after averaging (Figures 17 and 18), this relationship is tenable for individual session thresholds. Had only the combined data been examined, the relationship  $E / T = K$  could not have been considered an adequate description of two-pulse partial integration.

The relationship  $E / T = K$  is the second straight-line function of Herrick's TEpee effect. It is a threshold analogue of the Talbot-Plateau law. The Talbot-Plateau law states that a flickering stimulus above critical flicker frequency threshold (i.e., that appears fused) matches in brightness a steady light having the same average-luminance. Two-pulse stimuli between  $CD_2$  and  $UT_2$  are seen as one flash of light, and stimuli of different durations (within this range) demonstrate the same average-luminance at threshold.

Herrick (1972, 1973a, 1974) has suggested that the relationship  $E / T = K$  describes two-pulse (and multiple-pulse) partial integration for the light-adapted fovea. The present study indicates (at least for individual session data) that this relationship also describes two-pulse partial integration for the dark-adapted fovea (see Footnote 14).

In general, the results of the present study indicate that the particular characteristic of the neural response that determines threshold (perhaps amplitude or frequency) is similar in magnitude

for the one-pulse and two-pulse stimuli only if they are both equal in energy and brief (less than 30 msec for the dark-adapted fovea). At longer durations (between 30 and 90 msec), the two-pulse stimulus requires more energy than the one-pulse stimulus to elicit threshold detection. In this respect, the present psychophysical finding agrees with the electrophysiological data of Levick and Zacks (1970) obtained from cat retinal ganglion cells. Levick and Zacks found for brief durations (less than 30 msec) that when luminous energy was delivered as a pair of flashes (2 msec each), the shape of the response (a post-stimulus time-histogram) was similar in form to the response elicited by a one-pulse flash that was of the same energy and the same duration. At longer durations, keeping energy constant, the two-pulse response became bimodal, and lower in amplitude than the one-pulse response (see Figure 7 of Levick and Zacks, 1970, p. 689).

For purposes of threshold detection, the visual system processes one-pulse and two-pulse stimuli of brief durations with equal efficiency. At longer durations (greater than 30 msec for the dark-adapted fovea), the luminous energy is more efficiently used when it is presented continuously without an intervening dark interval.

This investigation has led to several questions that might be fruitfully explored in further studies: Why is one-pulse CD longer than two-pulse CD? or relatedly, for durations longer than two-pulse CD, Why is more energy needed to detect the two-pulse stimulus (suggesting less partial integration) than the one-pulse stimulus,

even when the total durations of both types of stimuli are the same (Figure 19)? What organismic factors are responsible for the apparent shift in critical duration across days? What is the nature of two-pulse partial integration? Is it simply the empirical relationship  $E / T = K$  (a threshold analogue of the Talbot-Plateau law), or does it have some explanation or significance beyond its empirical description?

In addition to these derived questions, there are other questions that were not directly explored in this study but clearly can be related to the procedures used and/or the results obtained. For example, what is the relationship between one-pulse and two-pulse thresholds at durations longer than those investigated in the present study? At these longer durations both one-pulse and two-pulse thresholds are influenced by probability summation. In this study, emphasis was placed upon an intercept measure of critical duration (intercept-CD), but an alternative definition of critical duration would be the shortest stimulus duration displaying a deviation from complete integration--an "initial" critical duration. Are similar conclusions obtained for both of these critical duration estimates when the influencing factor is a stimulus variable such as background luminance level, target size, stimulus wavelength, or retinal location?

## APPENDIX I

Filter calibration. Calibration of the filter combinations provided by the intensity programmer and fixed filter holder were determined within the optical system using photomultipliers 1 and 2 (see Figure 4). Each photomultiplier was connected to its own decade resistor box (Shallcross) such that photomultiplier voltage gain was proportional to resistance. The resistance boxes provided inputs to an oscilloscope high-gain differential preamplifier (Tektronix, Type D).

The glow modulator tube was pulsed on for 10 msec every second. With no filters between the two photomultipliers, the resistance of photomultiplier 1 was set at 100 kilohms and the resistance of photomultiplier 2 was adjusted to "null" the voltage difference between the outputs of the photomultiplier resistor boxes. After filters were introduced between the photomultipliers, the resistance of photomultiplier 1 was reduced to again "null" the voltage difference. This procedure was repeated three times for each filter combination.

The ratio of final resistance of photomultiplier 1 to 100 kilohms (multiplied by 100) indicates per cent transmission for that filter combination. Per cent transmission was corrected for the input impedance of the oscilloscope preamplifier using the following formula (R equals resistance in ohms):

$$\text{per cent transmission} = \frac{1.0125}{\left(\frac{1}{R}\right) (10^5) + .0125} \times 100$$

$$\text{density} = \log ( 100 / \text{per cent transmission} )$$

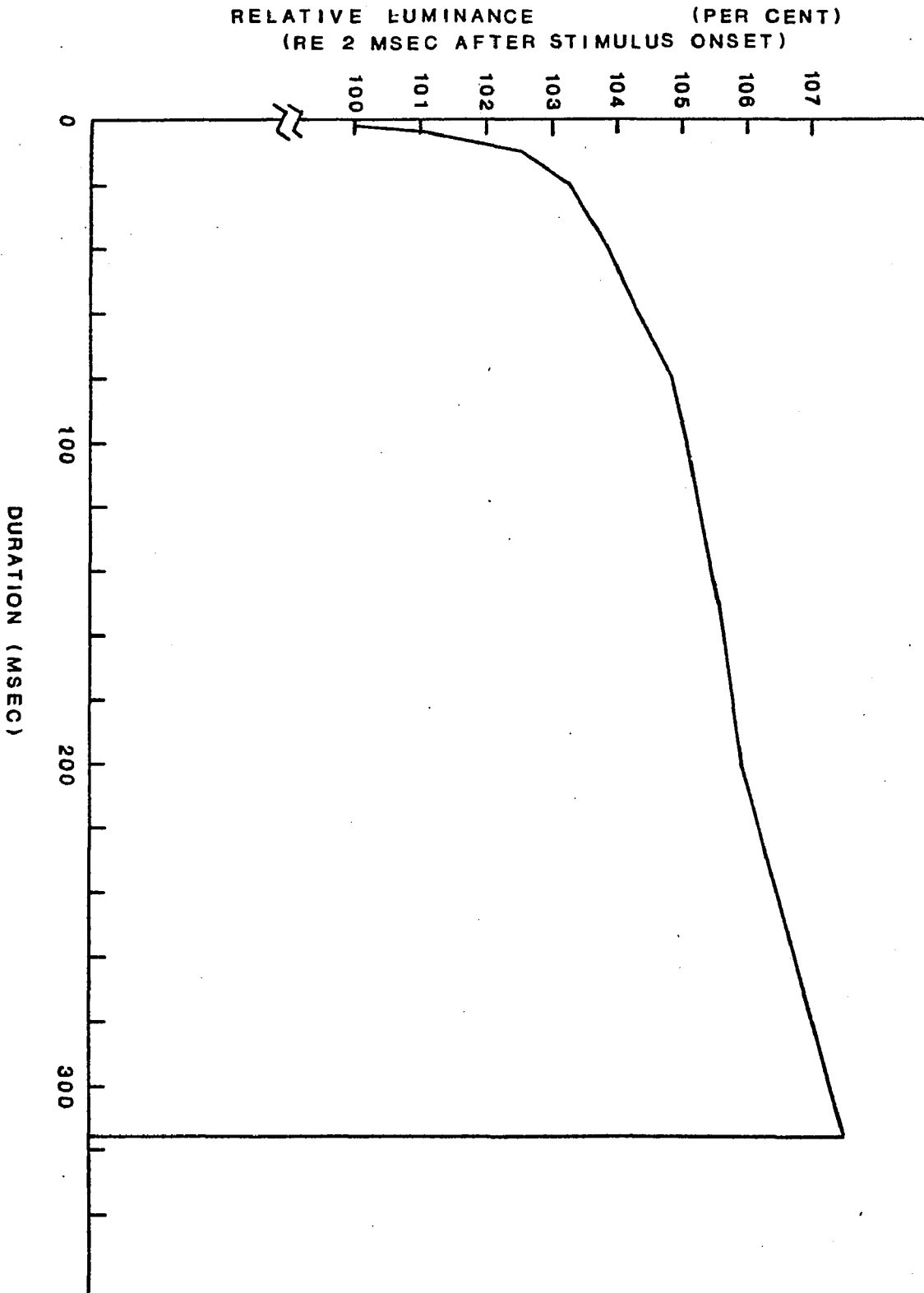
## APPENDIX II

Heat-up of the glow modulator tube. Photomultiplier voltage (which is proportional to stimulus luminance) was determined at ten sample times (from 4 to 300 msec) after light pulse onset. A standard oscilloscope was used to measure voltage at each of these sample times and also at 2 msec after light pulse onset. Voltage determinations at each sample time were counterbalanced with voltage determinations at 2 msec after light pulse onset; the relative light output at each sample time is the ratio of the means of these two voltage readings. Light pulses were presented and readings were taken once every 10 seconds.

Intensity growth was examined for light pulses of six different durations (from 20 to 316 msec); relative light output was determined for those of the ten sample times that were less than the duration of the light pulse being examined. Since the results at each sample time were similar for the different duration light pulses, the results were averaged. Relative luminance as a function of time after onset is shown in Figure 22. Light output increased in a negatively accelerated fashion up to seven per cent above onset level at 316 msec--the longest duration used in this study.

Luminance corrections for each stimulus duration were determined by graphically estimating increased luminous energy (area under the curve between stimulus onset and offset) using the trapezoidal rule,

Figure 22. Relative luminance as a function of time after light pulse onset.



and dividing this value by stimulus duration.

Per cent luminance increase and logarithmic corrections added to each threshold determination are presented in Table 6 for the one-pulse durations used in Experiments 1 and 2.

Table 6

Average Increase in Luminance Due to Glow Modulator Tube  
Heat-up for One-pulse Stimulus Durations

Duration (msec)	<u>Luminance Increase</u>	
	Per Cent	Log Units
20	2.06	.0089
30	2.51	.0108
40	2.81	.0120
54	3.12	.0133
78	3.54	.0151
100	3.85	.0164
126	4.13	.0176
158	4.40	.0187
200	4.69	.0199
316	5.43	.0230

### APPENDIX III

Influence of pupil changes on threshold. In the present study, observers viewed the stimulus target with their natural pupils. Two questions are raised: (1) Does the pupil respond to threshold level stimuli, and if so, are threshold determinations affected?, and (2) Do normal pupil changes appreciably contribute to threshold variability? To suggest answers to these questions, thresholds were determined both with natural pupils and 2 mm artificial pupils (binocular) for one subject (Q:GB).

Three durations were selected from the main experiment--a brief duration stimulus (20 msec) which is presumably always completely integrated, an intermediate duration stimulus (78 msec) which is sometimes partially integrated, and a long duration stimulus (200 msec) which is most often beyond utilization time. Control-stimulus (20 msec) thresholds were also determined in close temporal proximity to test-stimulus (varied duration) thresholds. During a session, four thresholds were determined (using the Random Method of Limits) for each test stimulus and each paired control stimulus under natural viewing conditions; four additional thresholds were determined for each stimulus (test and control) using 2 mm artificial pupils. Averages of test-stimulus thresholds, control-stimulus thresholds, and test-stimulus minus control-stimulus threshold differences are presented in Table 7; standard deviations are based on eight

Table 7

Thresholds Obtained With Natural Pupils and With  
2 mm Artificial Pupils for Q:GB

Condition	Duration (msec)	Average Luminance <sup>a</sup> (log mL)		Threshold Difference
		Stimulus		
		Test	Control <sup>b</sup>	
Artificial Pupils	20	-0.95 (.07)	-0.98 (.13)	+ .03
	78	-1.48 (.08)	-1.01 (.07)	-.47
	200	-1.66 (.09)	-0.97 (.06)	-.69
Natural Pupils	20	-1.88 (.06)	-1.86 (.11)	-.02
	78	-2.40 (.05)	-1.92 (.05)	-.48
	200	-2.55 (.07)	-1.91 (.09)	-.64

<sup>a</sup>Numbers in parentheses indicate the standard deviations (based on eight estimates, one from each session).

<sup>b</sup>Control-stimulus (20 msec) thresholds were determined in close temporal proximity to test-stimulus (20, 78, and 100 msec) thresholds.

estimates, one from each session, each the average of four threshold determinations.

Since the absolute levels of threshold luminance (in log mL) for the two viewing conditions are different, the test-stimulus minus control-stimulus threshold differences are compared. Threshold differences obtained with natural pupils were similar in magnitude to threshold differences obtained with artificial pupils for each duration. This suggests that pupil responses to threshold level stimuli exerted little influence on threshold measurement for these durations. Additionally, threshold variability across days (as reflected by standard deviations in Table 7) was no greater for natural pupils compared with artificial pupils.

Since 12 control-stimulus thresholds were determined for each pupil condition during each session, within session variability for the two viewing conditions could be compared. The average standard deviation (based on 12 thresholds per session) was 0.117 log mL for natural pupils and 0.104 log mL for artificial pupils; within session threshold variability did not significantly differ for the two viewing conditions,  $t(7) = 0.773$ ,  $p > .05$ .

The above cited evidence indicates that normal changes in pupil size did not appreciably influence the following: (1) relative threshold level (as reflected by test-stimulus minus control-stimulus threshold differences), (2) between session threshold variability, and (3) within session threshold variability.

Threshold retinal illuminance (which could be determined for

the artificial pupil condition) was 1.12 trolands for the 20 msec test stimulus, and 0.219 trolands for the 200 msec test stimulus. By comparing the threshold luminance obtained with natural pupils and the threshold luminance obtained with artificial pupils, it was possible to determine that the average diameter of Q:GB's natural pupils was 5.7 mm.

#### APPENDIX IV

False alarm rates. Observers were encouraged to provide a "yes" response only when they were quite certain they had seen the stimulus. Since false positive responses (false alarms) were infrequently obtained on blank trials, the three subjects were successful in maintaining a strict (or cautious) response criterion throughout the course of this study. False alarm rates for both experiments are listed in Table 8. The highest false alarm rate-- 1.3 per cent--was provided by Q:RP in Experiment 1, while Q:GB successfully avoided furnishing any false alarms in Experiment 2.

Table 8

Percentage of Blank Trials For Which  
False Alarms Were Provided

Subject	Experiment	Procedure	Per Cent False Alarms
RP	1	one pulse	1.3
RP	1	two pulse	1.0
RP	2	one pulse	0.7
GB	1	one pulse	0.5
GB	1	two pulse	0.2
GB	2	one pulse	0.0
GB	2	two pulse	0.0
AL	2	two pulse	0.2

## APPENDIX V

Hyperbolic functions fit to individual testing day one-pulse thresholds. Hyperbolic functions were fit to each day's one-pulse thresholds. Curve fits were determined for two hyperbolic functions: hyperbola 1,  $L T = C + D T$  (the relationship proposed by Blondel and Rey, 1911), and hyperbola 2,  $L = C T^B + D$ , where C, D, and B are constants, L is threshold luminance (in mL), and T is stimulus duration (in msec). Hyperbola 1 was fit using the reduction equation  $L = C T^{-1} + D$ , and hyperbola 2 was fit using the reduction equation  $\log (L - D) = B \log T + \log C$ . Hyperbola 2, by allowing exponent B to vary, adds an additional degree of freedom to hyperbola 1, for which the exponent is a constant -1.

The standard least squares approach (Lewis, 1960) was used to fit both hyperbolas. The solution for hyperbola 1 was straightforward and provided estimates of C and D. The solution for hyperbola 2 required the use of a computer program which first determined a rough estimate of asymptote D, then incremented around this value in nanolambert steps determining a solution for each value of D. Asymptote D assumed values between  $10^{-7}$  mL and the lowest threshold luminance obtained that day. (Higher values of D were not considered since the reduction equation ordinate value,  $\log (L - D)$ , is indeterminate for asymptotes higher than threshold luminance L.) The solution chosen demonstrated the smallest sum of squared deviations

between the threshold luminance (in mL) obtained and the threshold luminance (in mL) estimated by the function.

Hyperbola 1 curve fits to individual testing day thresholds are presented in Figures 23 (Experiment 1) and 27 (Experiment 2) for Q:RP, and in Figures 24 and 28 for Q:GB. Hyperbola 2 curve fits are presented in Figure 25 and 27 for Q:RP, and in Figures 26 and 28 for Q:GB. The same threshold data with two-function ( $L \times T = C$  and  $L = K$ ) curve fits were presented in Figures 6 and 8 for Q:RP, and in Figures 7 and 9 for Q:GB.

Figure 23. Experiment 1, O:RP. Hyperbola 1 functions,  
 $L T = C + D T$ , fit to individual session one-pulse thresholds.  
These same thresholds were presented in Figure 6 (with two-function  
curve fits) and Figure 25 (with hyperbola 2 curve fits).

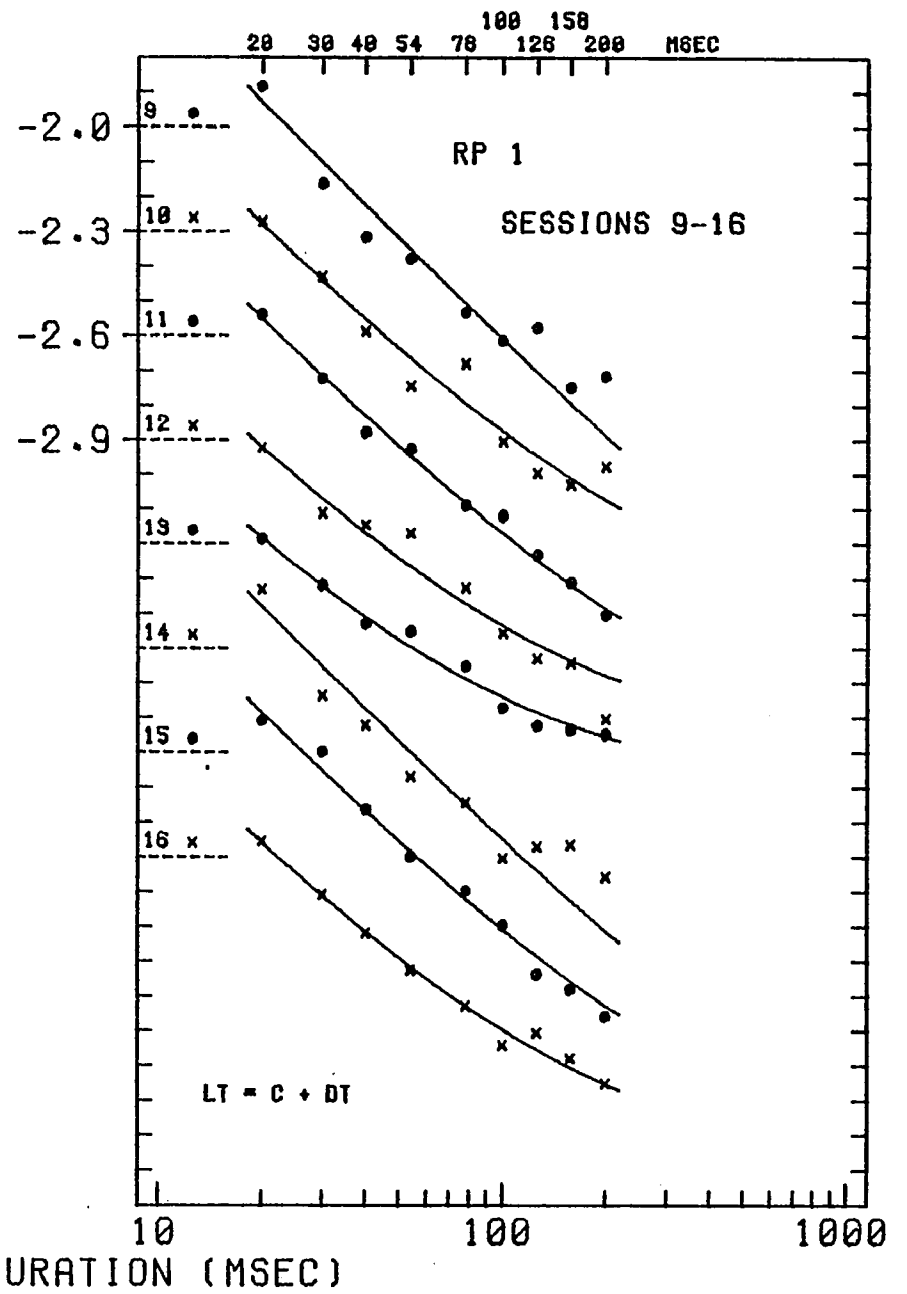
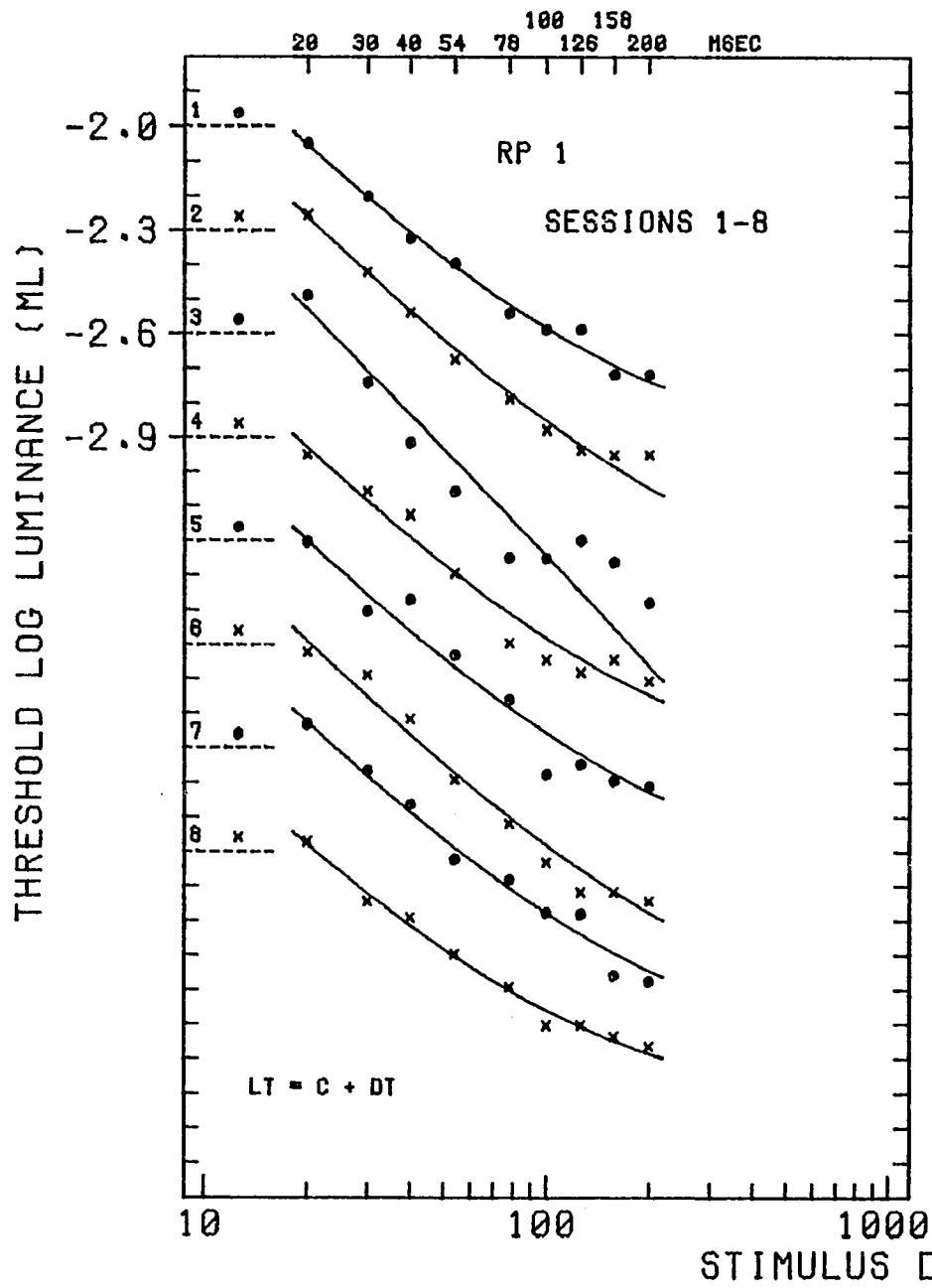


Figure 24. Experiment 1, Q:GB. Hyperbola 1 functions,  
 $L T = C + D T$ , fit to individual session one-pulse thresholds.  
These same thresholds were presented in Figure 7 (with two-function  
curve fits) and Figure 26 (with hyperbola 2 curve fits).

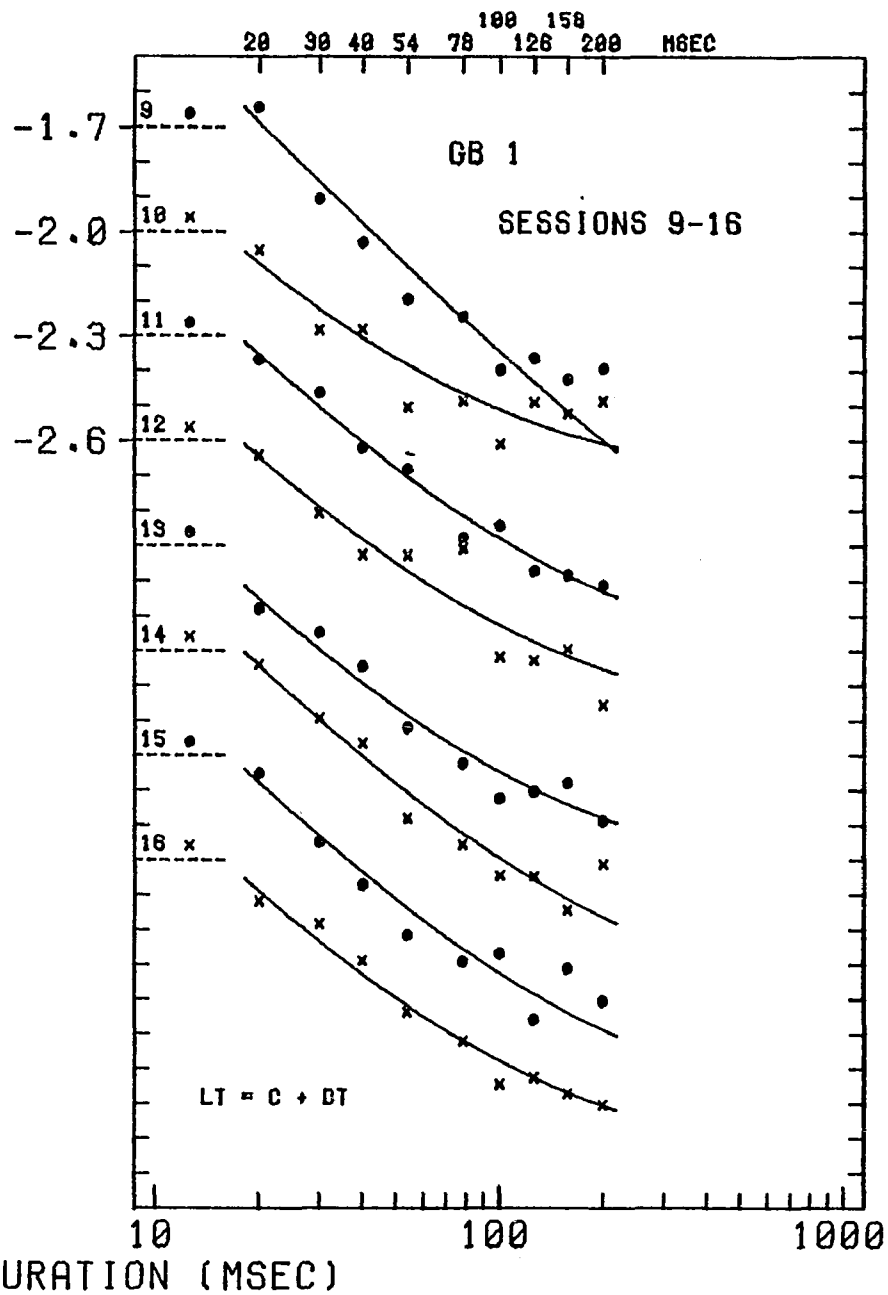
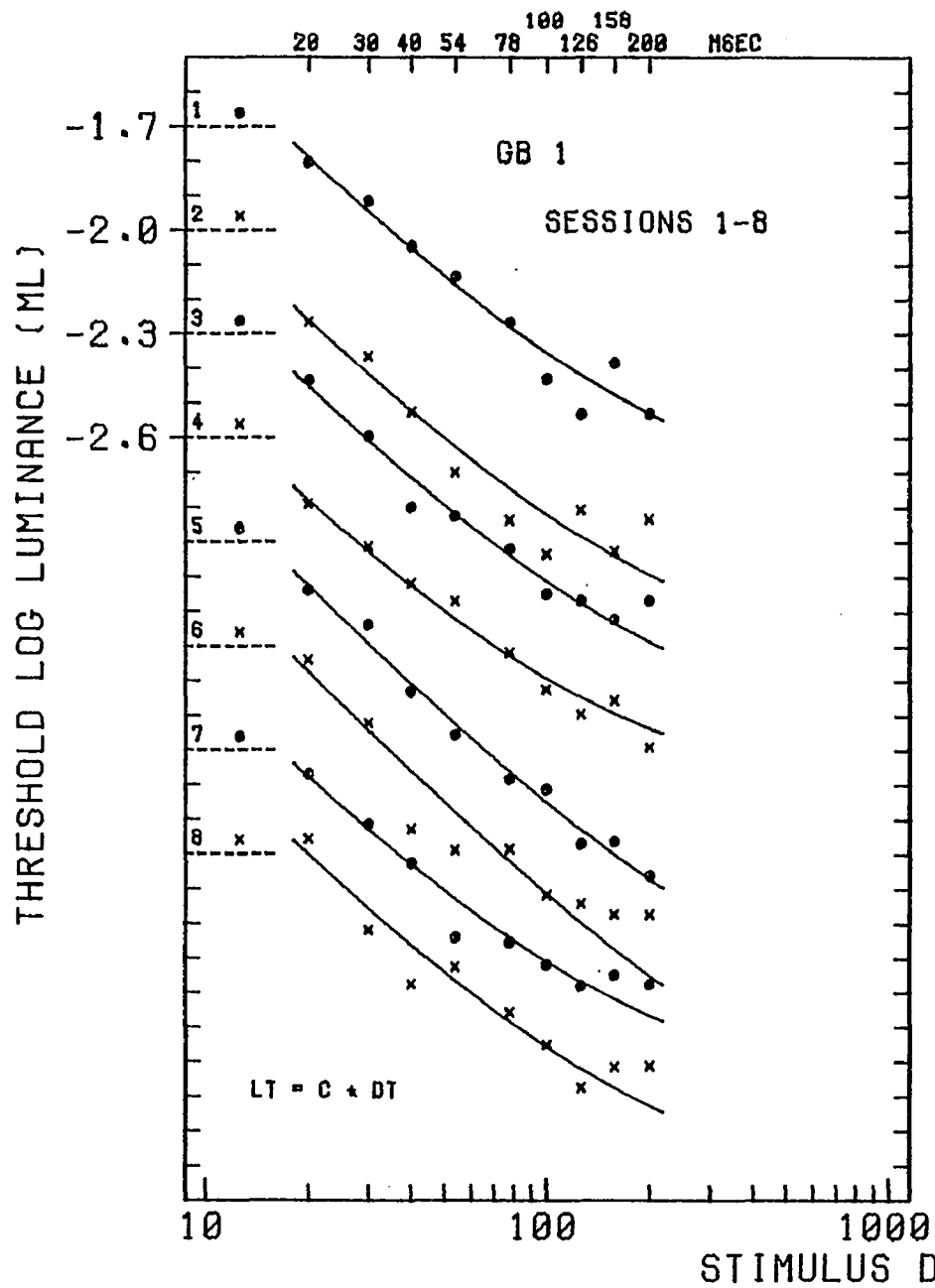


Figure 25. Experiment 1, O:RP. Hyperbola 2 functions,  
 $L = C T^B + D$ , fit to individual session one-pulse thresholds.  
These same thresholds were presented in Figure 6 (with two-function  
curve fits) and in Figure 23 (with hyperbola 1 curve fits).

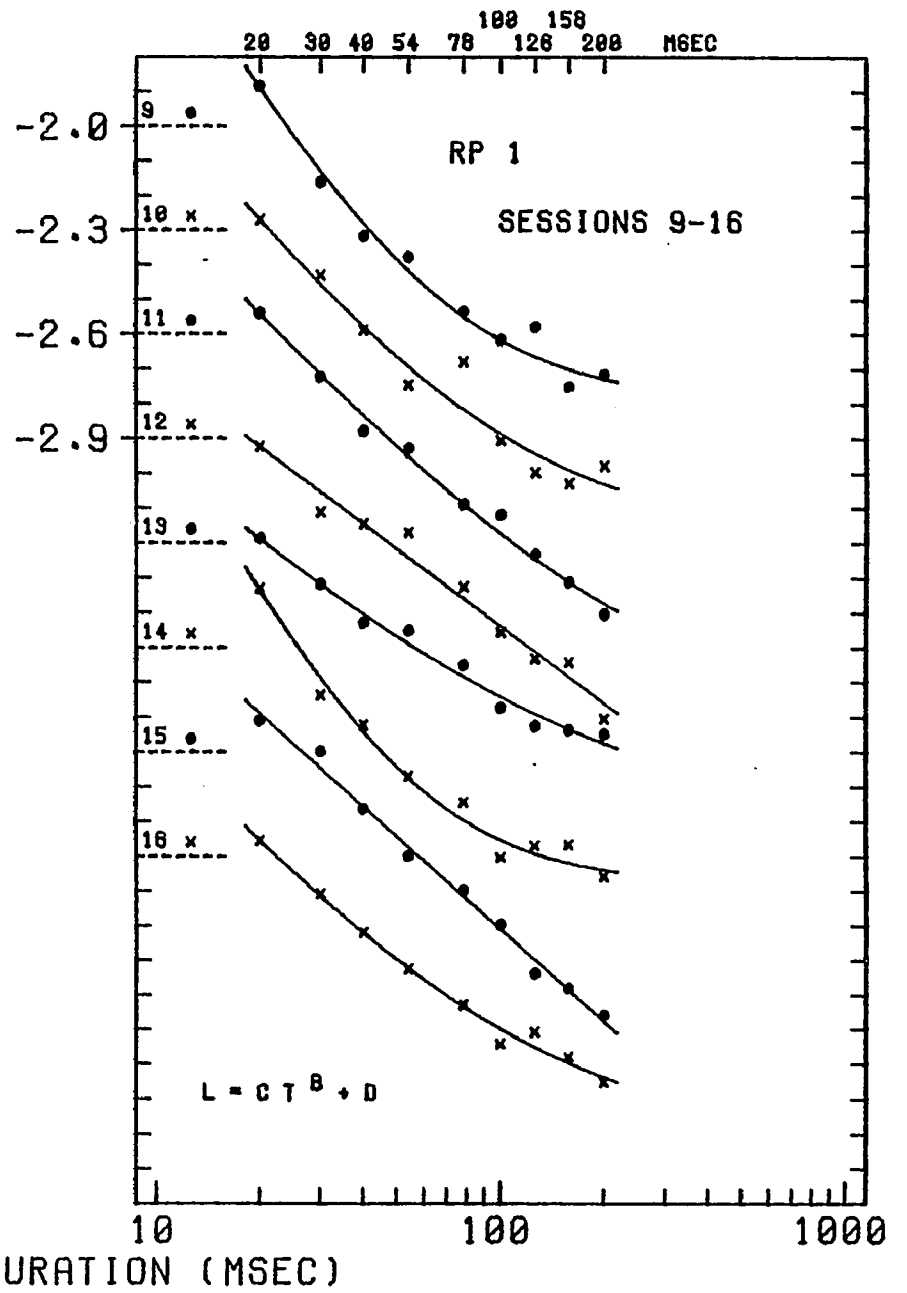
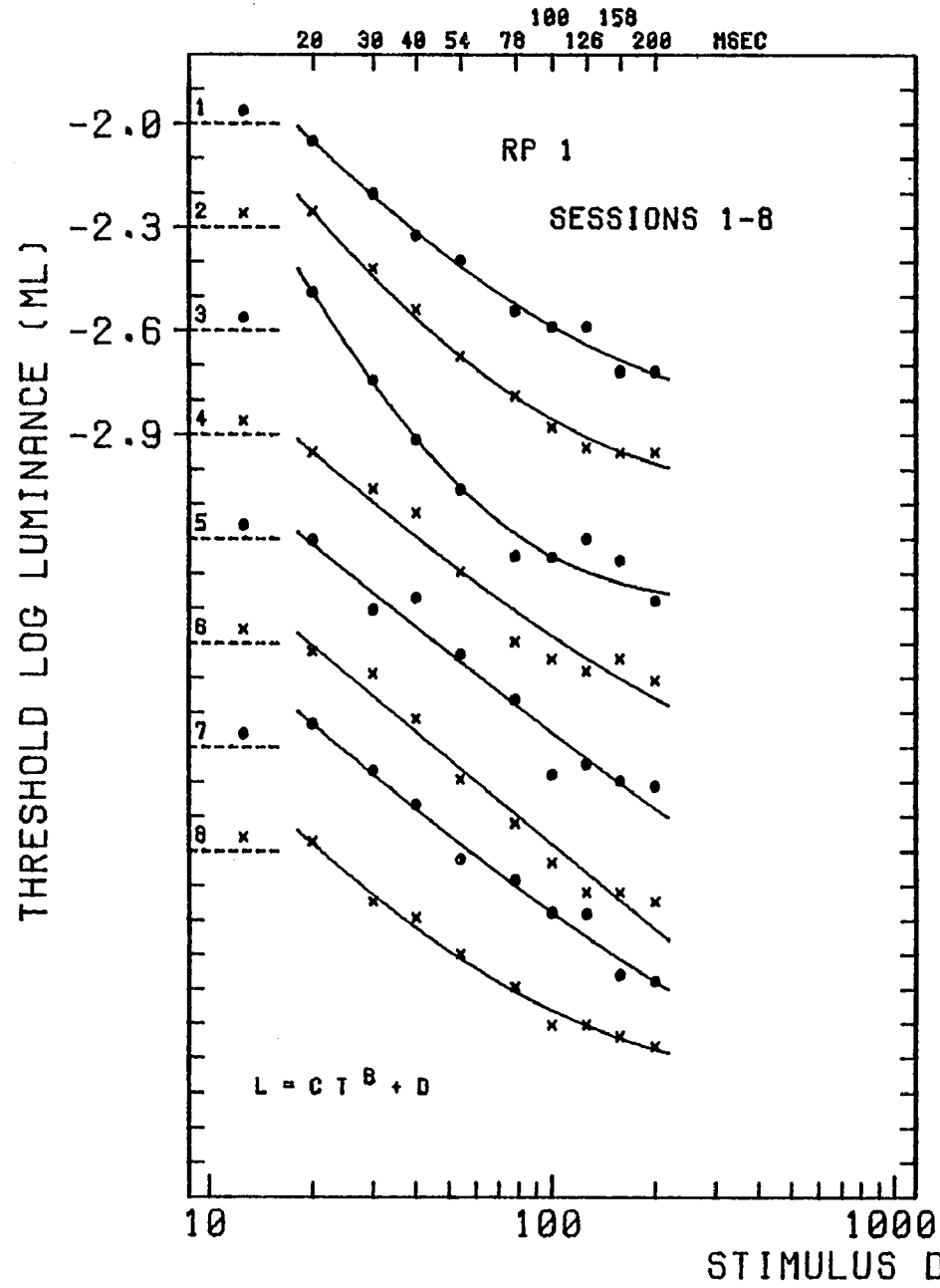


Figure 26. Experiment 1, O:GB. Hyperbola 2 functions,  
 $L = C T^B + D$ , fit to individual session one-pulse thresholds.  
These same thresholds were presented in Figure 7 (with two-function  
curve fits) and in Figure 24 (with hyperbola 1 curve fits).

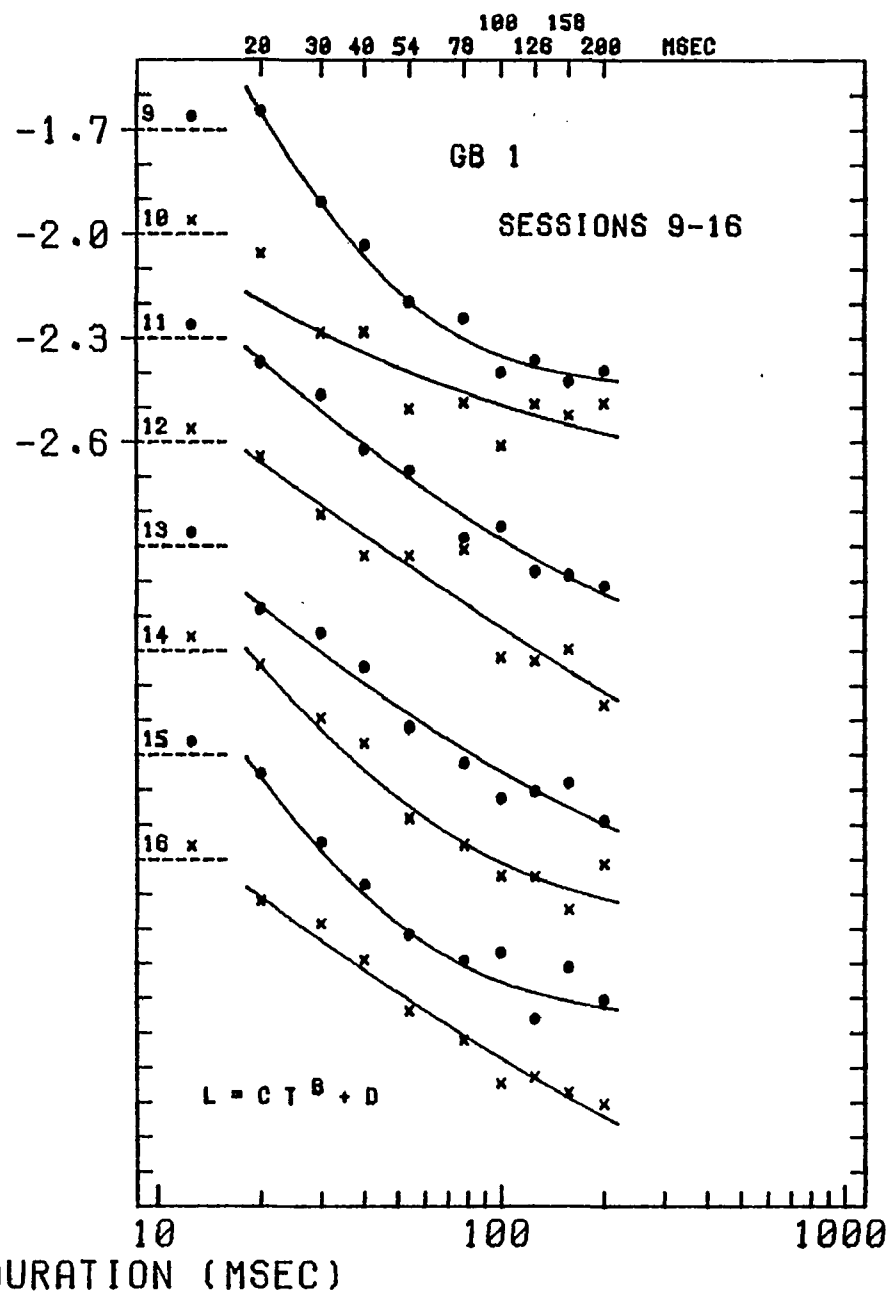
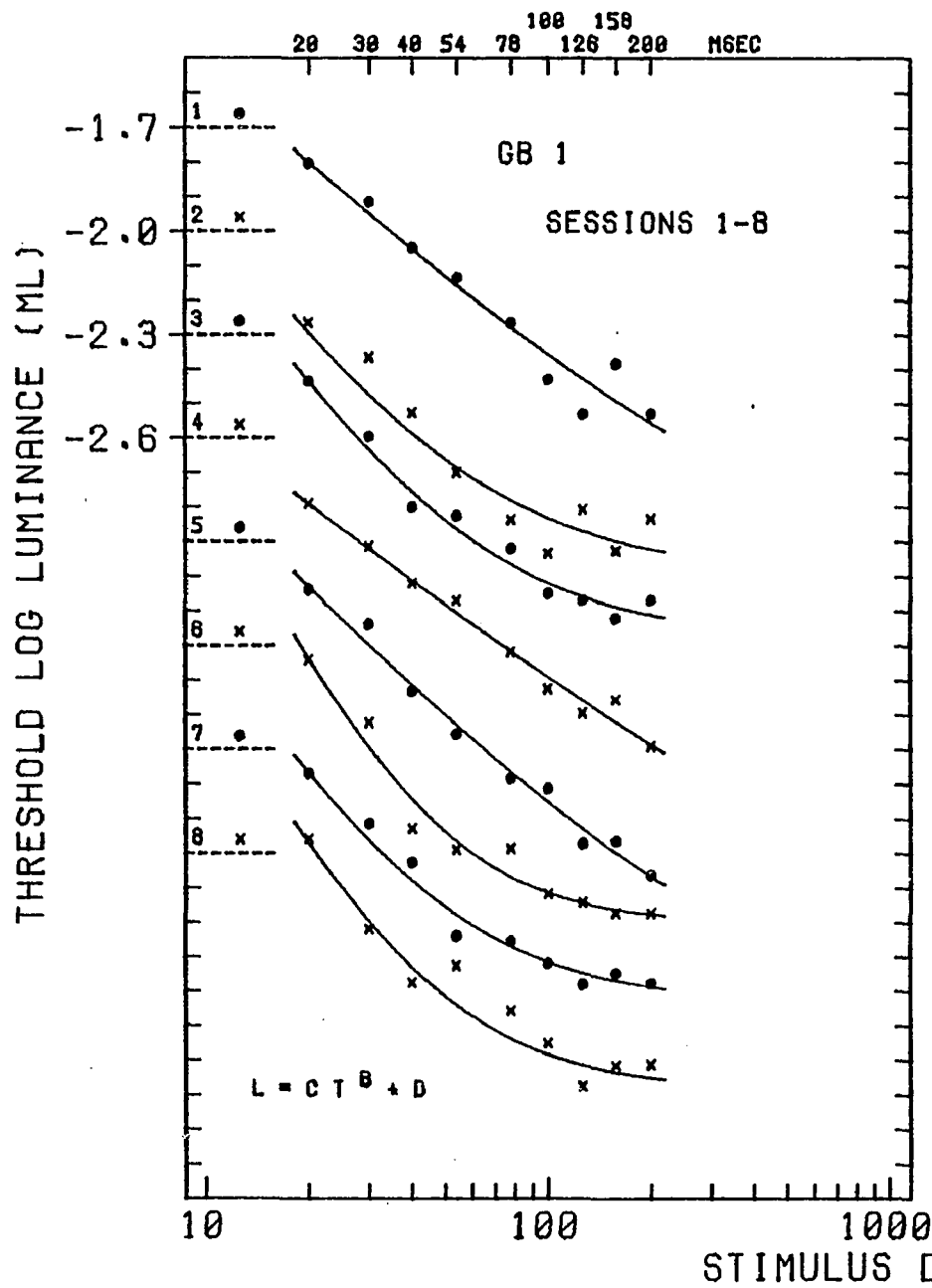


Figure 27. Experiment 2, Q:RP. On the left, hyperbola 1 functions fit to individual testing day one-pulse thresholds. On the right, hyperbola 2 functions fit to the same data. Two-function curve fits were presented in Figure 8.

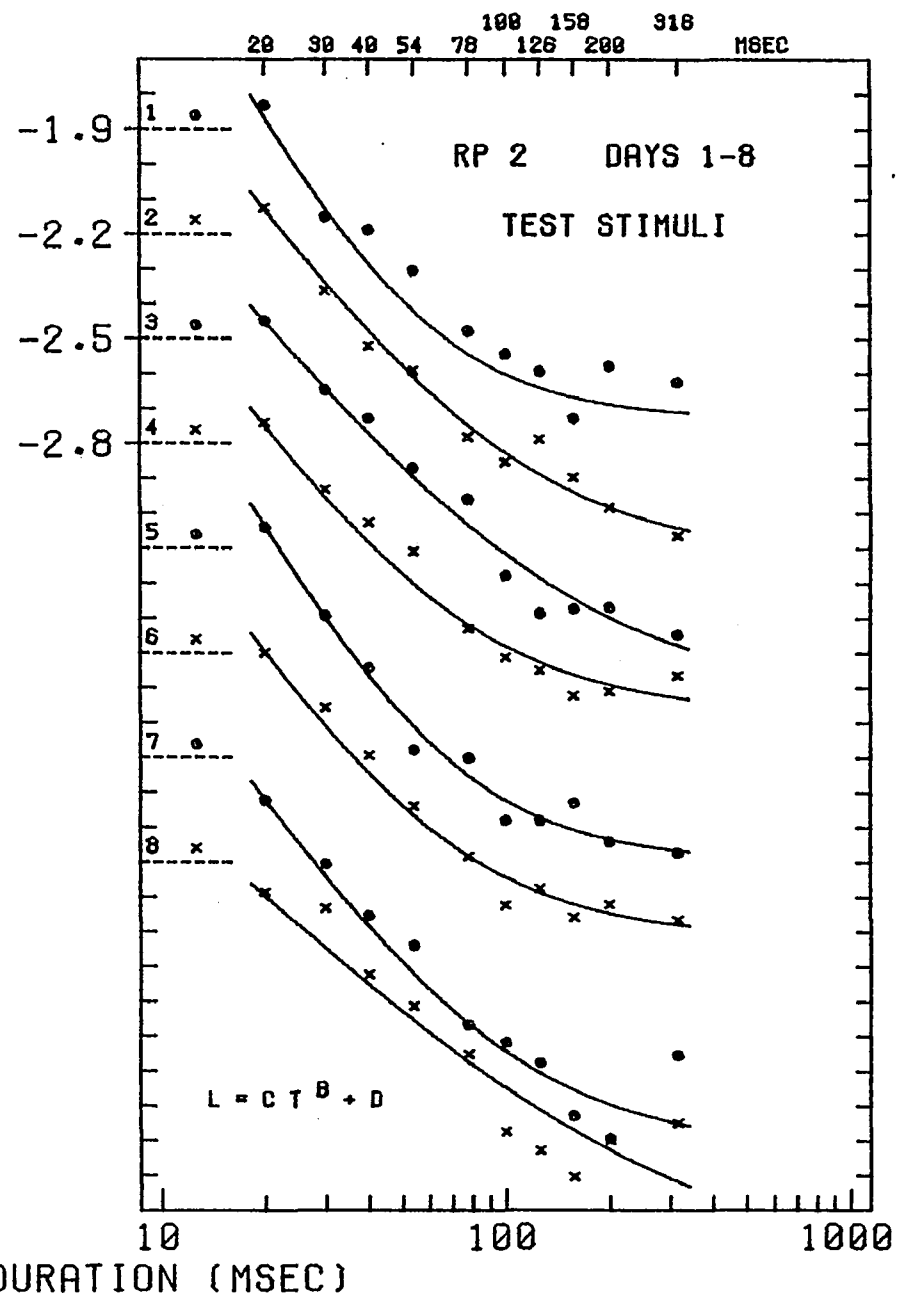
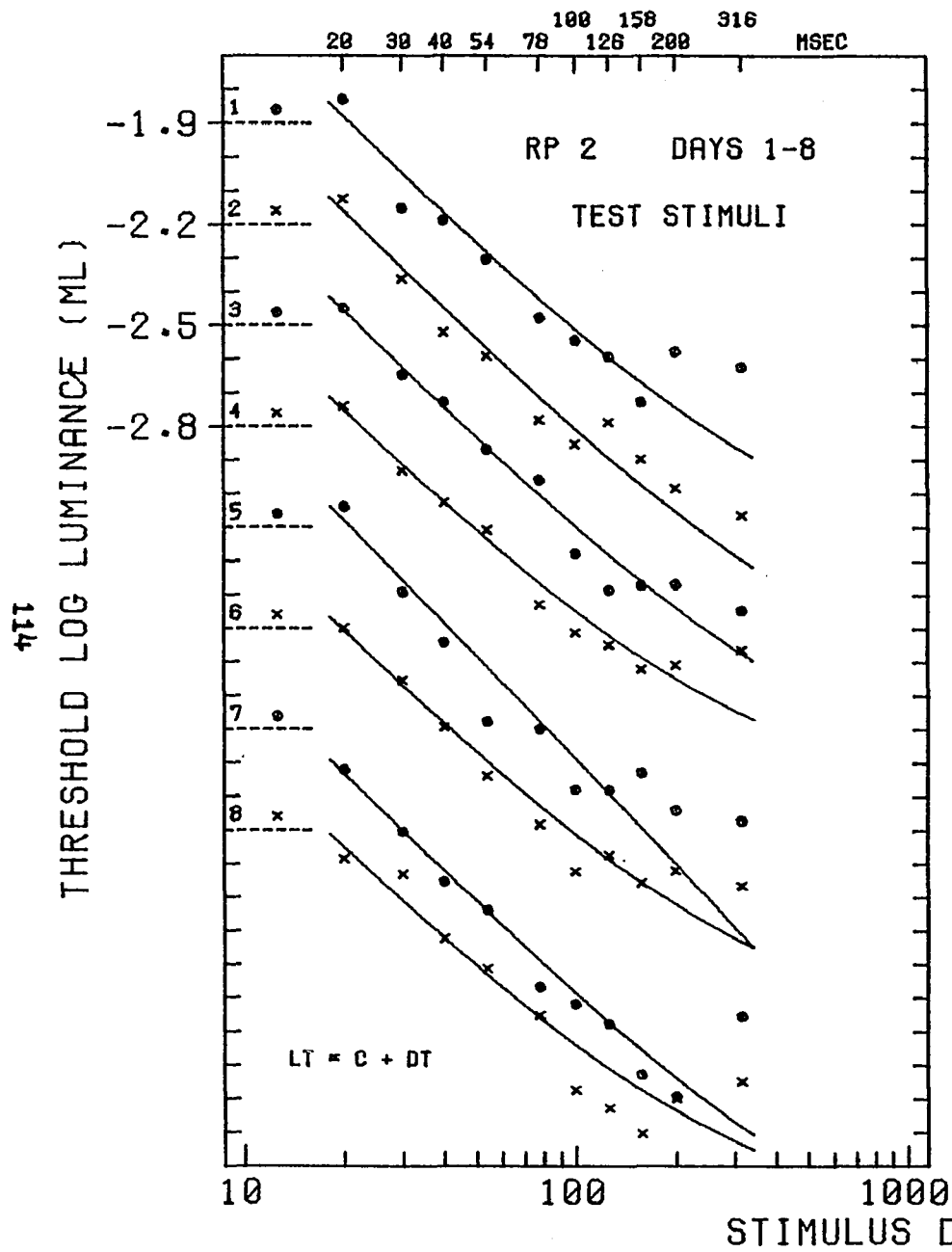
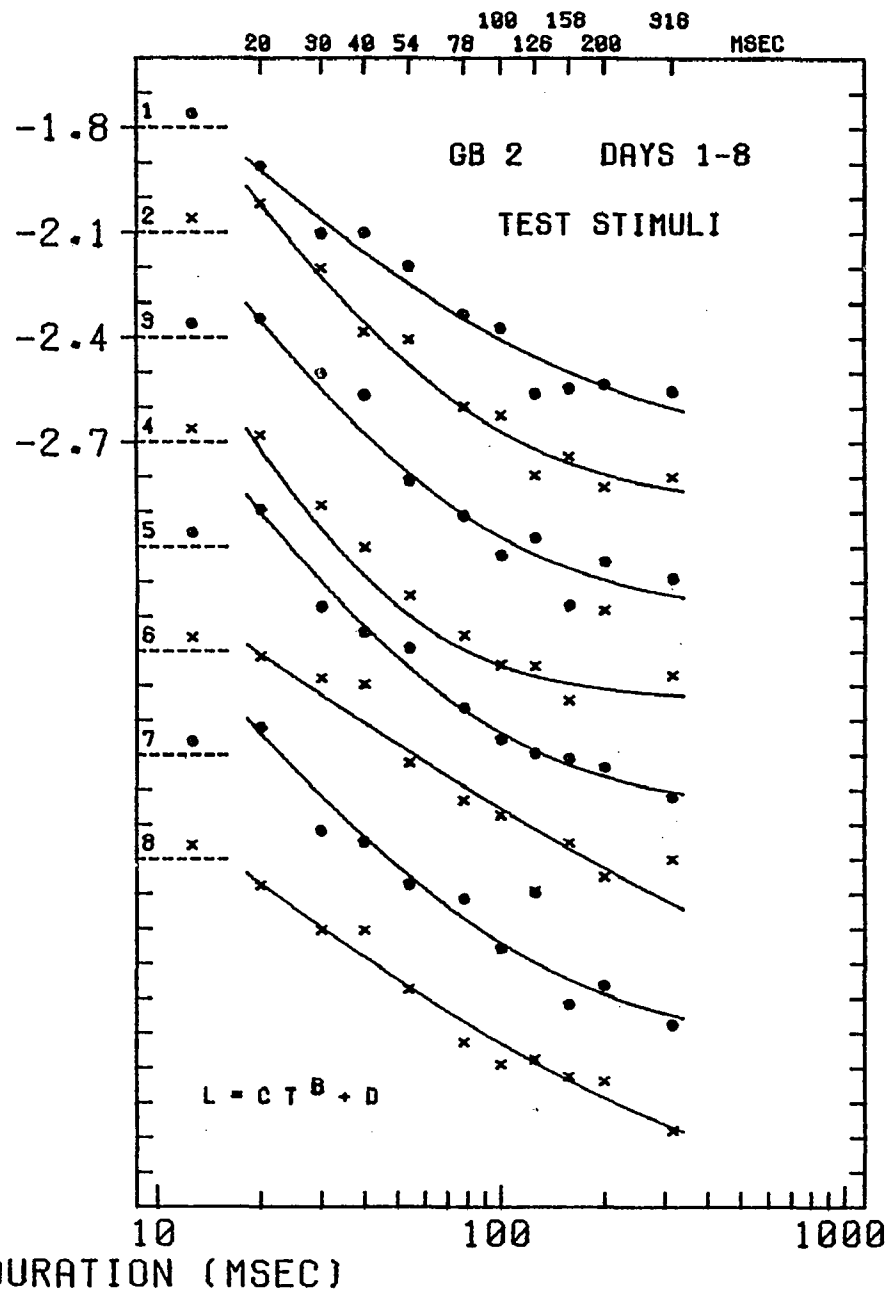
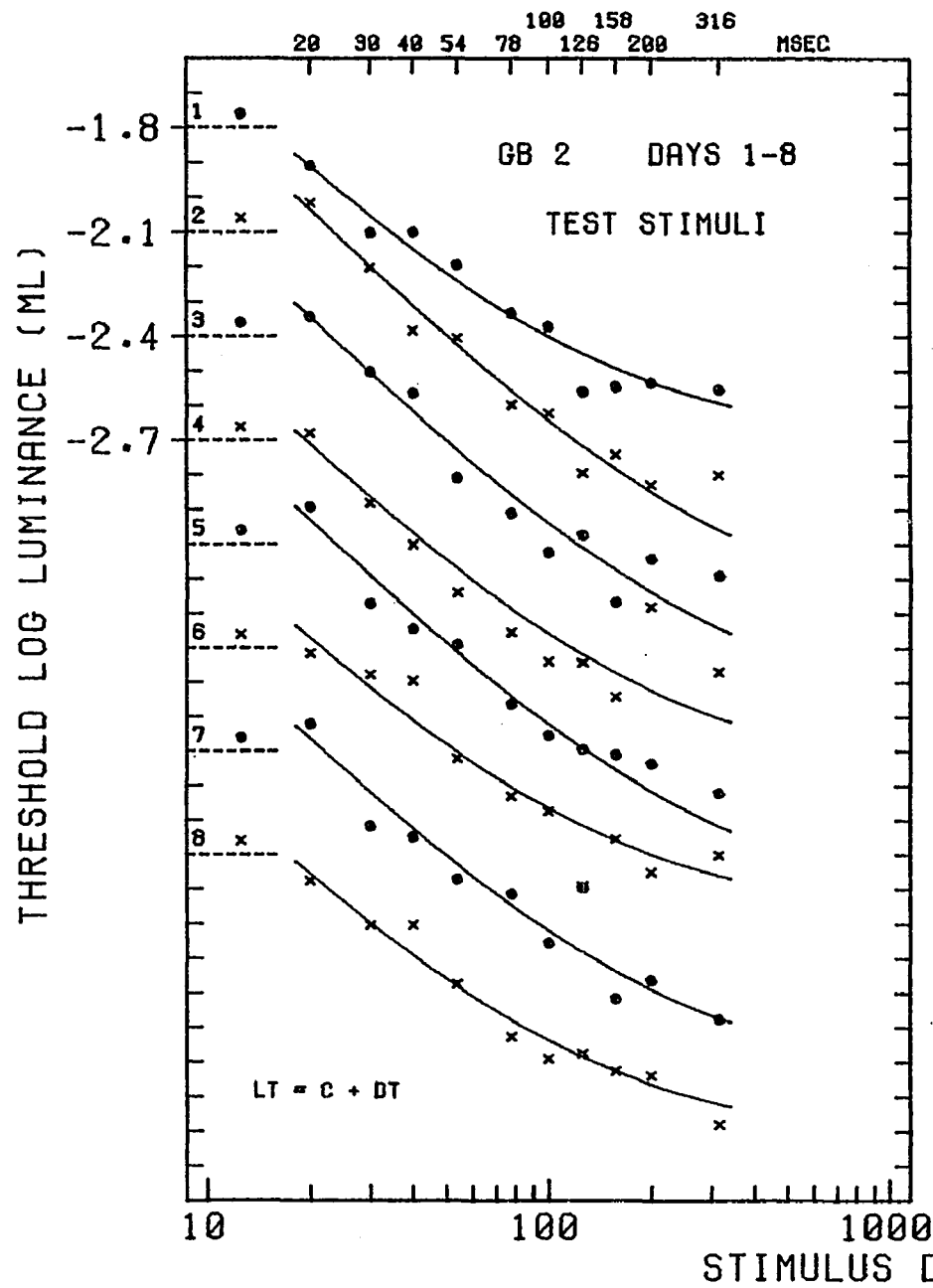


Figure 28. Experiment 2, Q:GB. On the left, hyperbola 1 functions fit to individual testing day one-pulse thresholds. On the right, hyperbola 2 functions fit to the same data. Two-function curve fits were presented in Figure 9.



### Footnotes

<sup>1</sup>The terms temporal integration and temporal summation have both been used with reference to Bloch's law. The present author prefers the term temporal integration which indicates that the threshold response is determined by the time integral of luminance.

<sup>2</sup>Clark and Blackwell (1959) found that threshold luminance was constant (after UT) only up to about 200 msec. Threshold luminance at longer durations was found to decrease, which they attributed to the observer having multiple opportunities to detect the stimulus.

<sup>3</sup>Two-pulse stimuli where the two light pulses differed either in luminance (Battersby & Defabough, 1968; Granit & Davis, 1931) or duration (Herrick & Theisen, 1972) have also been used to study temporal integration.

<sup>4</sup>In an equal-performance paradigm, the luminance necessary to obtain a fixed or equal performance level (e.g., threshold luminance) is determined as a function of stimulus duration. The change from complete integration to partial integration is indicated by an increase in the relative energy (in mL-msec) of the stimulus needed to maintain this constant response. In an equal-energy paradigm, the relative energy (in mL-msec) is kept constant for the different duration stimuli. The change from complete integration to partial integration is indicated by a change in the performance level (e.g., a decrease in per cent detection as stimulus duration is increased).

<sup>5</sup>Herrick (1972) found that the threshold luminance for the two-pulse stimulus elevated to about 0.04 log mL above the threshold luminance level expected for a one-pulse comparison stimulus. Other investigators found that under certain stimulus conditions, the two-pulse threshold asymptoted below the threshold level obtained for a one-pulse comparison stimulus (Clark & Blackwell, 1959; Gottlieb, 1979; Uetsuki & Ikeda, 1970). Stimulus factors which influence the two-pulse threshold level at these long stimulus durations are target size (Meijer, van der Wildt, & van den Brink, 1978), retinal location (Gottlieb, 1979; Herrick, 1973b), and background level (Clark & Blackwell, 1959; Uetsuki & Ikeda, 1970).

<sup>6</sup>Two-pulse  $UT_2$  can be more generally defined as that duration beyond which the two-pulse threshold either asymptotes or decreases (see Footnote 5). An inhibitory process rather than partial integration (or partial summation) has been inferred when the two-pulse threshold is above the threshold level attributed to probability summation (Ikeda, 1965; Meijer et al., 1978).

<sup>7</sup>The data presented by Clark and Blackwell (1959) were those obtained by Clark (1958).

<sup>8</sup>Herrick (1972) suggested that the averaging of data from different sessions distorts the shape of the TEpee function in the following ways: (1) abrupt changes at  $CD_2$  and  $UT_2$  become rounded, (2) the difference between threshold energy at  $CD_2$  and  $UT_2$  is reduced from 0.34 log mL-msec to 0.30 log mL-msec or less, and (3) the threshold drop after  $UT_2$  (attributable to probability

summation) is decreased.

<sup>9</sup>A modification of the standard method of least squares was used to fit these functions since the slopes of the fitted lines were constants (either -1, 0, or +1). When the slope (a) is a constant, the y-intercept (b) equals  $\bar{Y} - \underline{a} \bar{X}$ , where  $\bar{Y}$  is the mean of the dependent values and  $\bar{X}$  is the mean of the independent values.

<sup>10</sup>The variance of residuals is the sum of the squared deviations (points to the fitted line) divided by the number of points used for the curve fit (Lewis, 1960, p. 29).

<sup>11</sup>Two different hyperbolic functions were also fitted to each day's thresholds:  $L = C T^{-1} + D$  and  $L = C T^B + D$ , where L is luminance (in mL), T is stimulus duration (in msec), and C, D, and B are constants. The thresholds presented in Figures 6, 7, 8, and 9 are shown with these hyperbolic curve fits in Appendix V.

<sup>12</sup>The means and standard deviations of intercept-CD logarithmically expressed are presented in Table 5. Arithmetic means and geometric means were within 2 msec of one another.

<sup>13</sup>In addition to changes in the magnitude of intercept-CD<sub>1</sub> across days, the range of durations displaying one-pulse partial integration appears to change from day to day. Listed below are those sessions for which the transition between complete integration and no integration appears gradual (showing partial integration) and those sessions for which the transition appears abrupt (not showing partial integration). Individual testing day plots that show partial integration are: in Figure 6, sessions 1, 7, 8, 12, and

13; in Figure 7, sessions 4 and 12; and in Figure 9, days 1 and 7. Individual testing day plots that show an abrupt transition from complete integration to no integration are: in Figure 6, sessions 2, 3, 6, and 14; in Figure 7, sessions 2, 9, 10, and 14; in Figure 8, days 1, 3, 4, 5, 6, 7, and 8; and in Figure 9, days 2, 3, and 4.

<sup>14</sup>The transition between  $E = C$  and  $E / T = K$  is probably gradual (rather than abrupt as the TEpee effect would suggest) for at least some of the individual testing day plots. This is indicated in Figures 17 and 18 by average thresholds for brief durations (4.1 and 14 msec) that are slightly below their curve fit estimates, and average thresholds for intermediate durations (ca. 40 msec) that are slightly above their curve fit estimates. Individual testing day plots that appear to show such a gradual transition are: in Figure 13, sessions 8, 10, and 16; in Figure 14, sessions 12 and 14; and in Figure 15, days 5, 6, and 7.

<sup>15</sup>The correlations between intercept- $CD_1$  and intercept- $CD_2$  are similar when these measures are expressed in log msec,  $\underline{r}(14) = .70$ ,  $p < .005$  for  $\underline{Q:GB}$ , and  $\underline{r}(14) = .40$ ,  $p > .10$  for  $\underline{Q:RP}$ . The relatively low correlation for  $\underline{Q:RP}$  is in part attributable to the extremely low correlation across days of  $\log K_1$  and  $\log K_2$ ,  $\underline{r}(14) = .14$ ,  $p > .10$ ; there was, however, for  $\underline{Q:RP}$ , a significant correlation between  $\log C_1$  and  $\log C_2$ ,  $\underline{r}(14) = .67$ ,  $p < .005$ . For  $\underline{Q:GB}$ , these correlations were both significant,  $\underline{r}(14) = .74$ ,  $p < .001$  ( $\log K_1$  and  $\log K_2$ ), and  $\underline{r}(14) = .86$ ,  $p < .001$  ( $\log C_1$  and  $\log C_2$ ).

<sup>16</sup>Clark and Blackwell (1959) found the transition between

complete integration and no integration for the one-pulse thresholds to be abrupt for their dark-adapted condition. The initial departure from complete integration and intercept- $CD_1$  (as defined in the present study) were therefore the same. They also reported for their dark-adapted condition that the range of durations showing two-pulse partial integration was very limited;  $CD_2$  and  $UT_2$  were considered to be almost identical. Had they determined two-pulse thresholds for more durations between 40 and 90 msec, it is more likely that a range of durations showing two-pulse partial integration would have been found. In addition to the present investigation, Gottlieb (1979), Uetsuki and Ikeda (1970), and van den Brink and Bouman (1954) all found a range of durations showing two-pulse partial integration for the dark-adapted fovea.

<sup>17</sup>Conflicting results have been obtained from studies that have examined the effects of stimulus variables on the range of durations showing partial integration. For example, Barlow (1958) found that when target size was increased, the range of partial integration was decreased, while other investigators (Graham & Margaria, 1935; Karn, 1936) found just the opposite. Barlow also found that an increase in background luminance decreased the range of partial integration, while Clark and Blackwell (1959) reported the opposite effect. In contrast to the studies cited above, Biersdorf (1955) reported that changes in target size and background luminance had no effect on the range of durations showing partial integration.

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