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THE EFFECT OF THE TEMPORAL AND SPATIAL SEPARATION BETWEEN TWO VISUAL FIELDS ON THE DIFFERENCE THRESHOLD FOR LUMINANCE

by

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date — Chairman of Examining Committee

date — Executive Officer

David H R

Supervisory Committee

The City University of New York

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Table of Contents

List of Tables

List of Figures

List of Figures (Continued)

The general purpose of the present investigation is to study the influence of spatial and temporal interaction effects in the human visual system upon the luminance difference threshold.

In the case where there is a mutual influence of the effects of one stimulus on the effects of another, it may be said that an interaction exists. This mutual influence can be appraised by any one of a number of dependent variables, as, apparent brightness or the luminance difference threshold.

For example, investigation of the apparent brightness of a test field in the presence of an inducing field indicates that the apparent brightness of the test field is decreased by inducing fields whose luminance is equal to or greater than that of the test field (Diamond, 1953; Heinemann, 1955). This depression of the apparent brightness of the test field by a simultaneously presented inducing field is usually called "simultaneous contrast."

Light adaptation offers an example of visual interaction between the effects of two successively presented stimuli. Whereas in simultaneous contrast the depression of the apparent brightness of a test field occurs when both the test and inducing fields are presented simultaneously, in light adaptation experiments the interaction occurs when the two stimuli are presented successively, either to the same or to overlapping retinal areas. Two dependent variables frequently studied in experiments on light adaptation are the increment threshold (Crawford, 1947; Baker, 1949; and Battersby and Wagman, 1959), and the apparent brightness of a test stimulus (Wallace, 1937; Craik, 1940). In the increment threshold situation an increment of luminance is added to an already ongoing luminance at various times after the onset of the latter (Baker, 1949). The task of the subject, in this case, is the detection of the luminance increment.

Baker (1949) has studied the long term changes in the increment threshold during the course of light adaptation (from five to 1000 seconds after the onset of the adapting field). Crawford (1947), Boynton and Triedman (1953), and Battersby and Wagman (1959) have obtained data on the rapid rise in the luminance required for threshold detection of an increment flash during the first second of exposure to the adapting field.

Studies of light adaptation using the apparent brightness of a test field as a dependent variable (Craik, 1940), indicate that the effect of adapting the eye to light is to lower the apparent brightness of the test field which is subsequently presented. This latter instance, in which the apparent brightness of a second test field is decreased by previously presenting another luminous field, has also been called "successive contrast."

Another example of a visual interaction between the effects of two successively presented stimuli is the phenomenon of retroactive or backward masking. Crawford (1947), and subsequently Battersby and Wagman (1959), have demonstrated that the luminance required for a test flash to be detected starts to increase 100 msec before a subsequent conditioning field is presented. This increase in test field threshold occuring before the onset of the conditioning stimulus has been termed "backward" or "retroactive masking", while light adaptation has been referred to as "forward masking" or "simultaneous masking."[1] In forward masking the stimulus presented first acts to "mask" or decrease the effectiveness of a subsequent stimulus. In retroactive or backward masking the sequence is reversed; the second stimulus acts to reduce or "mask" the effectiveness of the first. The retroactive effect has been found to increase with decreasing temporal separation between the two stimuli (Crawford, 1947; Boynton and Triedman, 1953; Battersby and Wagman, 1959).

When two fields which differ in luminance are presented to the same retinal area in succession, a brightness difference may be detected between the two flashes. Under such circumstances the difference in the apparent brightness of the two fields may reflect the effects of light adaptation and backward masking. When measured psychophysically backward masking and light adaptation refer to changes in the apparent brightness of a test field presented before or after a conditioning field. As both light adaptation and backward masking depend upon the temporal interval between the two flashes, it is to be expected that the temporal separation between the two fields will affect the apparent brightness difference between the two fields. If a luminance difference threshold were determined on the basis of judgments of the relative brightness of the two fields, it would be expected that the luminance difference threshold would also be affected

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[1] In this thesis simultaneous masking will not be investigated. In simultaneous masking the presentation of both the conditioning stimulus and test stimulus overlap in time.

by the temporal separation between the two successively presented fields.

The investigations cited above have addressed themselves to the assessment of apparent brightness, and the increment difference threshold under successive presentation conditions. It appears that there has been no systematic investigation of the effect of varying the temporal separation between the two suprathreshold flashes of the same size presented successively to the same retinal area, upon an S's ability to detect a difference in brightness between the two fields.

Durup and Fessard (1938) have reviewed the literature concerning "successive" difference thresholds and have placed all the studies done to that date into three general categories. The categories are based on the nature of the temporal transition between the two fields to be discriminated.

The first category is called by the authors the "instantaneous" method, and corresponds to what is currently called the "increment" method. What distinguishes this method from the others to follow is that the transition from one luminance to the other is abrupt, and no dark interval intervenes between the two stimuli. This has been a very popular method and has been used in many studies (Stiles, 1929; 1949; Battersby and Wagman, 1959).

A second method of successively presenting two stimulus fields is with a gradual transition from the first luminance to the second, so that various luminance gradients exist in time. This condition has been most thoroughly studied by Drew (1937).

The third method of successively presenting two stimuli whose apparent brightness is to be compared is with a dark interval intervening between the two fields. This condition has not been subjected to much systematic analysis and appears to have been introduced by MacDougall (1904) for making apparent brightness matches between successively presented fields. No investigations using this method seem to have been made using the difference threshold as the dependent variable. It will be the purpose of the first study in the present investigation to study the temporal interaction between two successively presented fields between which a brightness difference is to be determined. The temporal interval separating the cessation of the first flash and the onset of the second flash will be varied, when the two flashes are of the same size and delivered to the same retinal area. Since the apparent brightness of either a first or a second successive flash is dependent on the ISI separating the two flashes, it is possible that the luminance difference threshold (if governed by differences in the apparent brightness between the flashes) will be a complex function of the ISI rather than independent of the time between the flashes.

Not only is the temporal separation between two successively presented fields likely to have an effect on the luminance difference threshold, but also studies of simultaneous contrast indicate that the apparent brightness of the test field is influenced by spatially separating the inducing field from the test field (Leibowitz, Mote, and Thurlow, 1953). As the measurement of a brightness difference threshold between the halves of a bipartite field presents a retinal configuration identical to the simultaneous contrast situation, it seems likely that spatial separations introduced between the half fields will influence the luminance difference thresholds.

Le Grand (1933) addressed himself to the question of assessing the influence of spatial separations between semi-circular fields on the precision with which judgments of brightness equality were made. His findings are reviewed at a later point in this thesis, but generally he found that the precision of the judgments decreased as the separation between the fields increased.

As Le Grand (1933) has demonstrated that the difference threshold is affect by varying the spatial separation between the halves of a simultaneously presented bipartite field then, of course, the Weber fraction as a function of luminance will also be displaced due to spatial separations between the fields.

Two investigations which have been principally concerned with the Weber fraction as a function of luminance are those of Bartlett (1942) and Cornsweet and Pinsker (1965).

Bartlett (1942) determined ΔI/I versus I curves for a simultaneously presented bipartite field separated by 13', using fixed adaptation and various exposure durations. These functions ascend rapidly to an asymptotic level. Cornsweet and Pinsker (1965), however, have described a situation in which they simultaneously presented two disc-shaped fields separated by 1°10' between which a luminance difference threshold was to be determined. They obtained a function in which Weber's Law holds over a five log-unit range. Both of these functions depart from the curve obtained by Konig and Brodhun (1889) in spite of the fact that the latter investigators used a bipartite field between which a discrimination had to be made. However, Le Grand (1957) has pointed out that, "In the measurements of Aubert (1865) and those of Konig and Brodhun (1889), the units of luminance used were too uncertain to enable the value of their results to be assessed" (pg. 260). In spite of this obvious limitation a comparison of the Konig and Brodhun results with those obtained by Bartlett and Cornsweet and Pinsker will be undertaken in the discussion section of this thesis.

One of the major differences between the experimental arrangement under which a difference threshold was obtained by Bartlett and by Cornsweet and Pinsker was the spatial separation between the two halves to be discriminated. It is possible that the differences in the results obtained by these authors are due to the spatial separations used between the fields, and that the form of the function relating the Weber fraction to luminance depends in some way on the spatial separation or interaction between the two simultaneously presented fields.

The purpose of the second study of this thesis, therefore, was to investigate the variations of the brightness difference threshold as a function of variations in the spatial separations between two simultaneously presented fields which differed in luminance.

Apparatus

A schematic diagram of the apparatus used in both experiments is shown in Figure 1. The system[1] is arranged for monocular viewing by the right eye of the subject. The light source (S) is a projection lamp with a horizontal ribbon filament (Westinghouse EDW T10 SR6A). The source was run at a constant current of 17.5 amps supplied by an Electro Model H Filtered DC power supply.

Lenses L1, 2, collimated the light emitted through an aperture in the lamp housing which covered the source. The aperture was at the height of the ribbon filament. The forward part of the ribbon filament acted as the source for channel I while the left side filament acted as the source in channel II. The channels were identical except where indicated.

The collimated light passed by an adjustable stop (ST). The stop could serve to block out either the right or left part of the field leaving only one half of each field illuminated. Beyond the stop, L3, 4, formed an image of the filament in the plane of the neutral density wedge. The mounting for this wedge included a holder for neutral density filters. From this image filament, light passed to the front surface mirror (M1) and from there was reflected through L6 and L7. Lens L7 formed a second image filament in the plane of a small stop behind which was an electromagnetic shutter (SH). The

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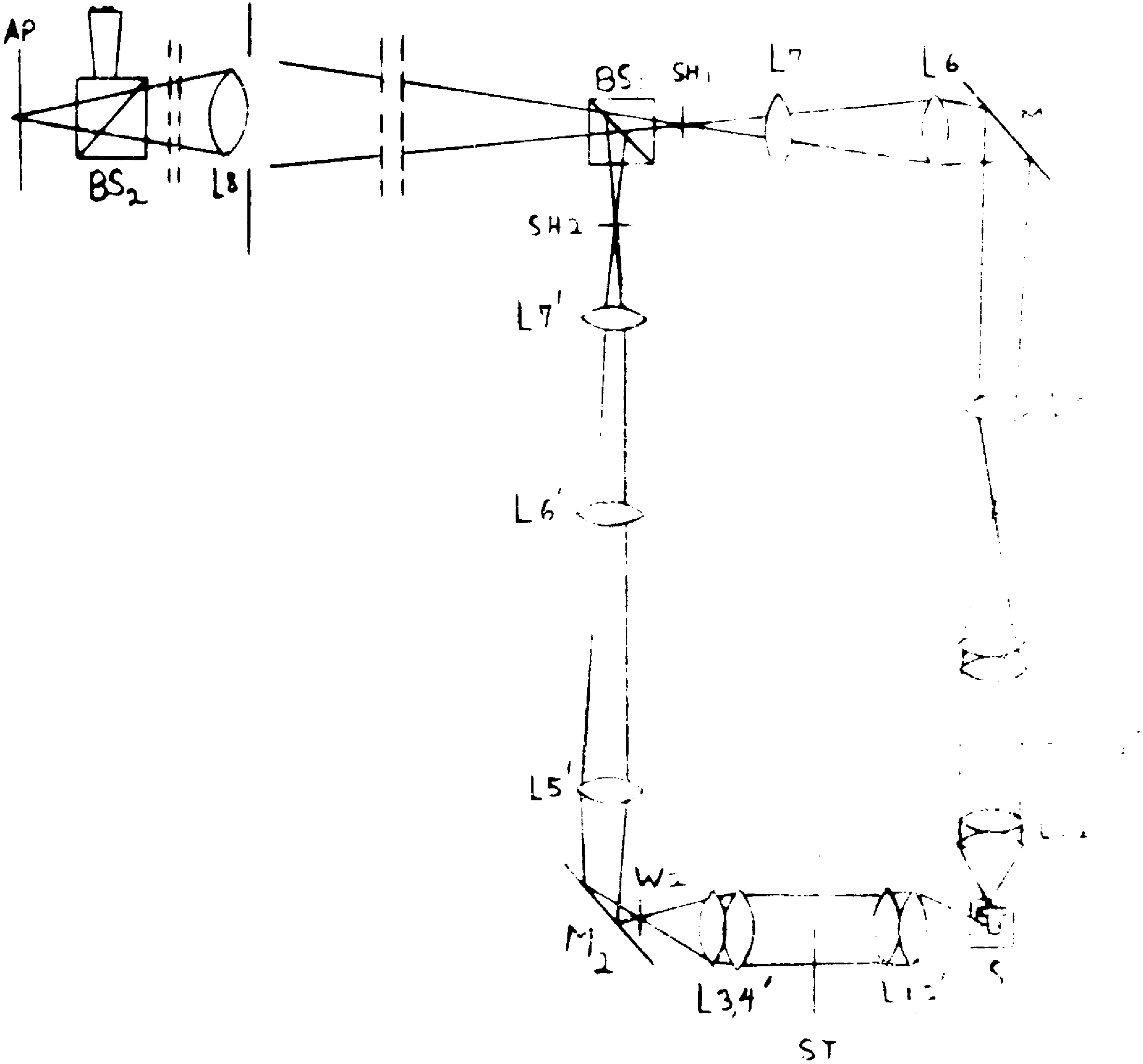
[1] The system to be described had a semi-Maxwellian view since the adapting field and stimulus fields were at different distances from S's eye.

Figure 1. Diagram of optical apparatus used in both experiments.


AP
BS2
L8
BS1
SH1
L7
L6
M
SH2
L7'
L6'
L5'
W2
M2
L3,4'
ST
L1,2'
S

exposure durations of the flashes were controlled by means of a modified Gerbrands tachistoscope timer which activated the shutter.

The rays passing through the aperture from channel I were transmitted ant those from channel II were reflected through a beam splitting cube (BS1), where both of the two beams were subsequently superimposed and in focus in the field lens, L8. In front of the field lens was a diaphragm (O) which contained an opening into which could be inserted stops of various diameters. The characteristics of the stops determined the size and shape of the field as seen by the subject. The field lens, L8, then formed an image of the filament in the plane of the subject's pupil after the single beam from both channels had been transmitted through anoterh beam splitting cube (BS2) and through a 2.75 mm artificial pupil. The distance from the field lens to S's pupil was 300 cm. L8, a telescopic achromat, had a diameter of 14 cm. All other lenses were 10 diopter and 3.8 cm in diameter. To the side of BS2 a 9°36' adapting field was illuminated at a level near the photopic threshold. This adapting field was circular with a two-inch diameter at a distance of 30.5 cm from the subject's eye.[1] Light from this adapting field passed through a 4.0 neutral density filter and was then reflected through BS2 into S's pupil. The adapting field consisted of a flashed opal glass evenly illuminated from behind by a 40-watt bulb ron on line voltage.

S thus had a Maxwellian view of the opening in the diaphragm (O) which was superimposed on a fixed adapting luminance. The S's

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[1] This circular opening acted as the field stop for the adapting field.

eye was accomodated on the fixation points located above and below the diaphragm (0) at a distance of 300 cm. S sat in the dark and his head was held in place by a dental impression biting board. In the absence of the stimulus, S's gaze was directed to the dimly lit adapting field. Within the field were placed two red fixation points located one above the other. These fixation points were placed on an imaginary vertical line above and below the field lens, L3, and were in the plane of focus of the stimulus array. S was instructed to fixate between them.

In Experiment II the stimulus arrangement consisted of a bipartite rectangular field, each half subtending 0.5° in the vertical dimension under all conditions. In the center of the bipartite field was a septum. The widths of the septa were: (in visual angle) 30", 45", 1', 3', 7', 10', 20', and 30'. All field sizes and separations were within a 2° area. Each of these stimuli formed one condition in Experiment II. Table 1 gives the visual angle and sizes of separations and the fields used in the study.

The exposure duration of each field was kept constant at 10 msec throughout all experimental conditions while the interval between the presentations of each of the fields was varied by changing the setting of the timer. The arrangement was such that S could deliver the stimuli to himself when he felt ready by pressing a button (microswitch) which activated the timer and hence the electromagnetic shutter.

When monitored by a phototube and oscilloscope the rise and fall times for the 10 msec flashes fell within 2 to 3 msec and a close approximation to a rectangular pulse was obtained. The reliability

Table 1. Separations and total field sizes used in Experiment II. All fields at a distance of 300 cm. Size of field is given in cm and visual angles.

Separation (θ)	Size of Separation in cm	Visual Angle of Total Field	Size of Total Field in cm
30" = .5'	0.04	1° 30"	5.3
45" = .75'	0.07	1° 45"	5.3
1'	0.09	1° 1'	5.3
3'	0.26	1° 3'	5.5
7'	0.61	1° 7'	5.9
10'	0.87	1° 10'	6.1
20'	1.75	1° 20'	7.0
30'	2.62	1° 30'	7.9

of repeated pulses was within ±1 msec. The pulses could be set to appear simultaneously or in succession. In Experiment II they were set for simultaneity.

In the experiment (II) S saw an adapting screen, the area upon which the stimulus was to be flashed being marked by the fixation points. By positioning the adjustable stops in each of the channels, the $I + \Delta I$ field could be made to appear either to the right or the left while the I field appeared on the converse side of the bipartite field. The apparatus, then, presents to the S two rectangular fields in Experiment II which appear side by side with a black separation of variable width separating the fields. Either side could be given a higher luminance than the other.

In Experiment I the arrangement differed somewhat. The fields were also presented to S's right eye and in the absence of the stimulus fields, fixation points were seen on the adapting screen. In this experiment, only one diaphragm (0) subtending 1° was used for all stimulus presentations. The adjustable stop was removed from the optical path and each of the channels could successively and independently illuminate the stimulus array. S saw a square field of 1° which contained the $I + \Delta I$ luminance (channel I) followed, after a preset interstimulus interval, by another field, subtending 1°, of luminance I throughout its entire extent.

Procedure

1. Experiment I - Temporal Separation

In this experiment two stimuli that differed only in luminance were presented in succession to the same area of the retina and the S's basic task was to report which one appeared brighter. The principal variables studied were the length of the dark interval separating the flashes and the luminance at which the measurements were made.

The stimuli used were evenly illuminated square fields subtending 1° at S's eye. S dark adapted for 15 minutes by wearing an eye patch over his right eye and then looked at the adapting field for another five minutes. After removing the eye patch E determined a DL (difference threshold) by the Method of Limits with an ascending and descending series at each of four luminance levels one logarithmic unit apart from each other and at each of nine inter-stimulus temporal intervals (ISI). During each of the daily sessions, a luminance value was haphazardly selected by E and one ascending and one descending series of measurements were made for each of the nine inter-stimulus intervals. A session lasted for 4½ to five hours with frequent rest periods. During each session, and for each fixed value of luminance and of ISI, two upper and two lower threshold transitions were obtained.

E waited thirty seconds before giving S the ready signal for re-exposure.

For each presentation of the pair of pulses, the second of the pair was set at a standard value (one of the four luminances used) on channel II in the optical system and the S's task was to indicate whether the first of the pair appeared brighter, equal, or dimmer than the second. In order to eliminate any effects due to knowledge of the series, E occasionally repeated a presentation and accepted the second of the two responses if a difference existed. The step size was kept at a constant ratio of the standard throughout the course of the first study (25%). That is, if the standard was 700 mlam, the optimal step size to determine the threshold was found to be 175 mlam, while for a standard of 7.0 mlam the step size used was 1.75 mlam.

Each series yields two transition points. Each transition point is a mean of two luminance values; $(I_1 + I_2)/2$.

In a descending series for the upper transition value, I_2 is the last luminance at which a "brighter" response occurred while I_1 is the first luminance to which an "equal" response was given. For the lower transition value I_1 is the luminance to which the first member of a consecutive pair of "dimmer" responses was given (with the further restriction that this be the first consecutive pair of "dimmer" responses occurring in the series). I_2 is the luminance which preceeded I_1.

In an ascending series for the lower transition value, I_1 is the last luminance at which a "dimmer" response occurred while I_2 is the first luminance to which an "equal" response was given. For the upper transition value in the ascending series, I_2 is the luminance to which the first member of a consecutive pair of "brighter" responses was given (with the restriction that this be the first consecutive pair of "brighter" responses occurring in the series). I_1 is the luminance which preceeded I_2.

In both studies the difference threshold (DL) was calculated in the same way. The DL is given by:

$$\frac{M_u - M_b}{2}$$

where, M_u is the mean of the upper transitions for all of the series and M_b is the mean of the lower transitions for all of the series for a given separation and luminance of the standard.

Between twenty and twenty-eight such threshold determinations at each luminance and ISI were undertaken in Experiment I.

2. Experiment II - Spatial Separation

In Experiment II two adjustable rectangular fields differing only in luminance and shown simultaneously were presented for 10 msec to S's right eye. The basic task of the S was to indicate which side appeared brighter. The principle variables studied were the width of the spatial separation between the fields and the luminance value of the standard at which the measurements were made.

In this study a DL was determined using the Method of Limits as outlined in the temporal study for five levels of luminance in log unit setps and for eight spatial separations between the fields. The S sat, as in the temporal study, dark adapted and with head held in position by a dental biting board. The exposure of the stimuli was done by S after a ready signal was given by E. S waited thirty seconds between presentations.

In this experiment S saw a rectangular field, the two halves of which were illuminated. Adjustments for the various septa were made by moving the adjustable stops which were mounted on a microscope stage. This stage advanced in mm units in two dimensions thus allowing proper focus of the stop. A razor blade was mounted on the stage. When poroperly positioned, this blade could eliminate any portion of the channel from view and could be precisely aligned with an edge of the field.

The lighted halves were separated in space by various angular subtenses. On half the trials the standard (I) was presented on the S's left, while the variable (I +ΔI) field was on the right. On the other half of the trials the situation was reversed. S was instructed to report whether the variable field appeared brighter, equal, or dimmer than the standard which was placed along side of it. The orders of ascending or descending, repetition of exposure, standard on left or right and the angular subtense of the separation between the 0.5° halves were all randomized.

In a given session the luminance of the standard was set and the DL was determined for each of the eight separations used. In each session, two ascending and two descending series for each of the eight spatial separations were run. A daily session lasted for three to four hours and was interrupted by frequent rest periods. A total of eight such threshold determinations was made. Each of the series terminated when S gave two changed brighter or dimmer responses in a row. The starting point of the next series was selected haphazardly. The optimal step size was found to be about 4% of the standard and was kept constant at this value.

E changed the separation between the fields by inserting a premade stimulus array into the diaphragm in front of the field lens. For two values of spatial separation, two additonal sessions were carried out in a slightly different manner. The same procedure as before was followed throughout, except that now E did not change the separation in the daily session, but changed the luminance level instead to new values. These values were also randomized. This procedure determined directly the variation of the DL as a function of luminance for a fixed spatial separation between the two halves of a bipartite field.

Calibration Procedure

1. Relative Calibrations

a. Filters

Light from one of the optical paths of the Maxwellian system was used to illuminate a piece of milk glass and the various filters were inserted into the path in front of the milk glass screen. An illuminometer was fastened into place and repeated measurements of the luminance on the milk glass screen were made with and without the filters in place.

The density of each of the filters was given by:

$$D = \log 1/T \text{ where,}$$

$$T = \frac{\text{luminance on milk glass with filter inserted}}{\text{luminance on milk glass without filter}}$$

As the density was already given for the filters the transmission was obtained by:

$$T = 1/\text{antilog } D \times 100$$

and this was the value which was assessed.

Within the error of measurement the filters were found to correspond to their nominal values and to be off by at most ± 1%.

b. Wedges

Three procedures were used to measure the variation in the density of the wedge with angular position:

(1.) A phototube (RCA-929) corrected by a Kodak Wratten filter (No. 106) was placed in the position of the observer's eye and wedge positions were determined for which the output of the phototube was equal to that produced by interposing in the light beam a series of calibrated neutral density filters.

(2.) The light, after passing through the wedge was diffused by a milk glass screen. The luminance of this screen was measured with a Macbeth Illuminometer, for a series of angular positions of the wedge.

(3.) The same optical arrangement as (2.) was used but the luminance measurements were made with a Spectra Pritchard Photometer (model number 1970-PR). Figure 2 shows the Spectra readings for each angular position of the wedge for each of the two wedges used in the studies. The departure from linearity is almost non-existent.

2. Absolute Luminance Calibrations

The basic method used to measure the absolute luminance levels was to measure the luminance of the adapting field with the Macbeth Illuminometer and then to match visually each of the fields used in the experiments to the adapting field. The details are as follows:

The Macbeth Illuminometer was held securely up against BS2 with the reflected adapting field in view. Numerous measurements were made, with the artificial pupil moved aside, of the luminance of the adapting field. The mean for a large number of Macbeth settings gave a value of the adapting field equal to 76.12 mlam when no filter was inserted in front of the screen. For both series of studies a 4.0 neutral density filter was inserted in front of the adapting field before it entered through the artificial pupil into S's eye. Measurements made at the beginning and end of the experiments gave values of 76.12 mlam and 68.44 mlam respectively. This is a difference of about 10%.

In order to obtain the luminance of the Maxwellian fields, the

Figure 2a. Calibration of density of Wedge No. 1. Arbitrary readings on the Spectra Pritchard Photometer for various angular positions of Wedge No. 1.

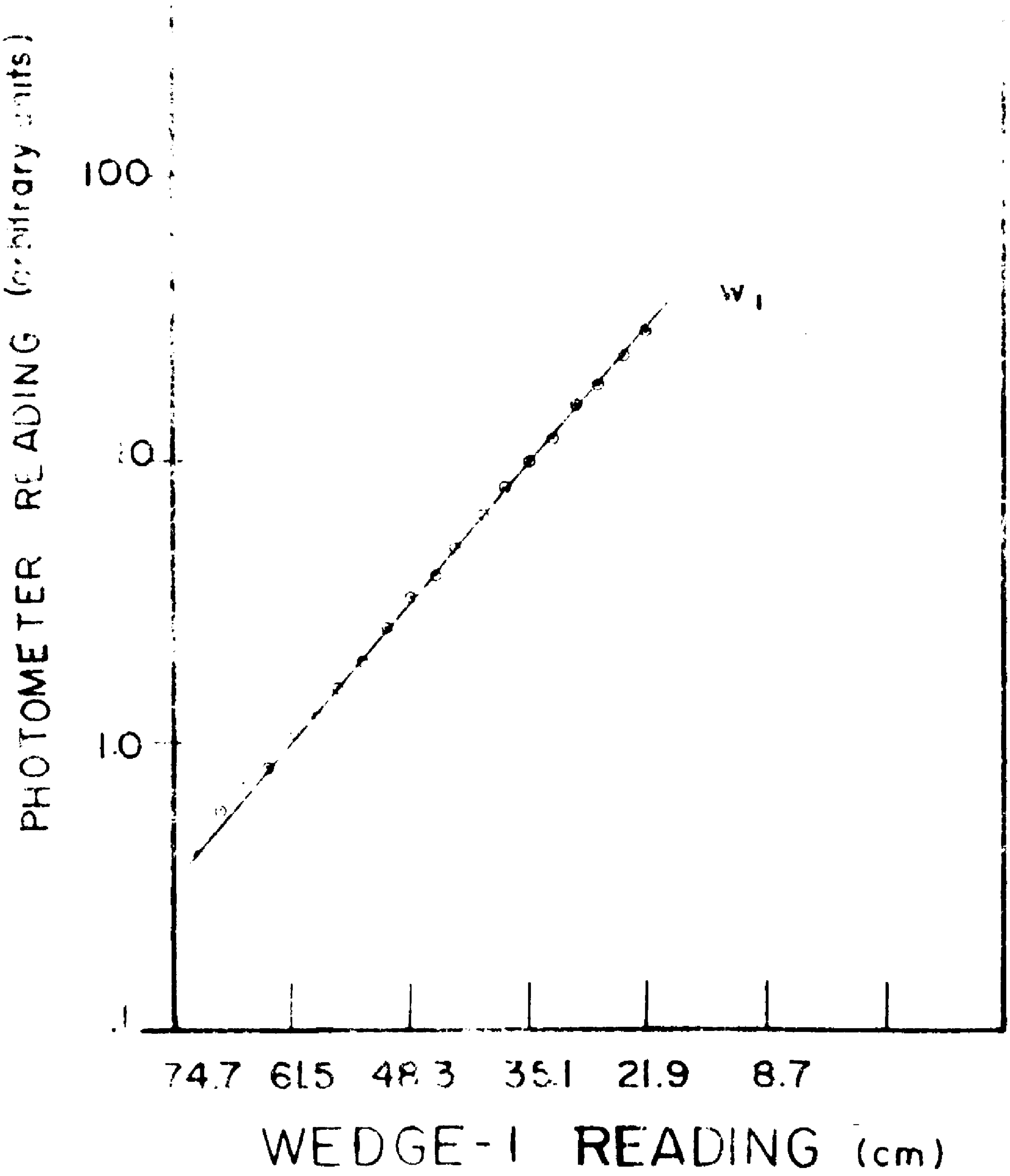
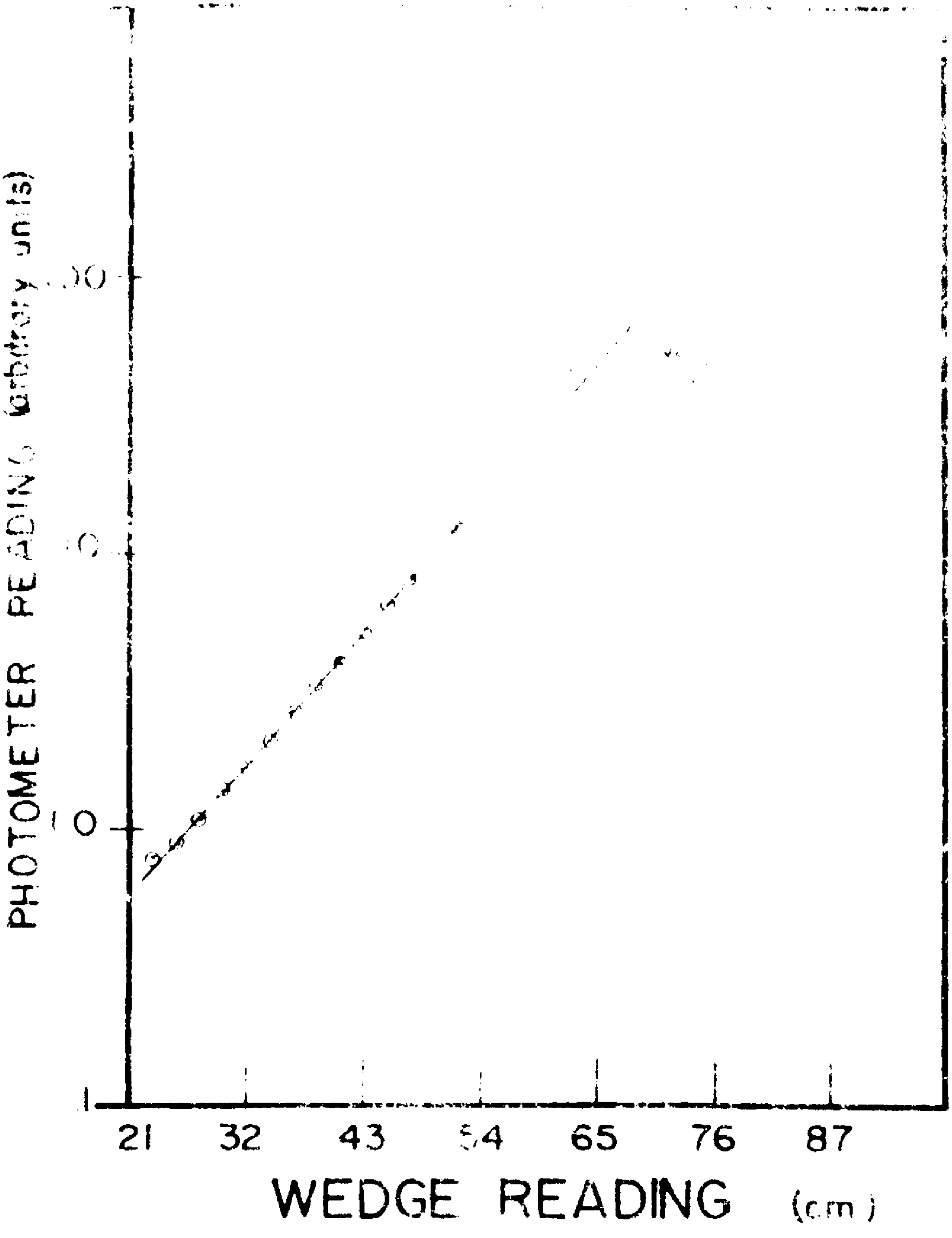

PHOTOMETER READING (arbitrary units)
100
10
1.0
.1
W1
74.7
61.5
48.3
35.1
21.9
8.7
WEDGE-1 READING (cm)

Figure 2b. Calibration of density of Wedge No. 2. Arbitrary readings on the Spectra Pritchard Photometer for various angular positions of Wedge No. 2.


PHOTOMETER READING (arbitrary units)
1
10
100
1000
21
32
43
54
65
76
87
WEDGE READING (cm)

optical channels were independently matched to the adapting field, with both fields seen through the artificial pupil. Care was taken to ensure that the image filaments from each of the channels completely filled the artificial pupil. The effective pupil size was the same, therefore, for both the Maxwellian and non-Maxwellian fields. Care was also taken to align the Maxwellian view so that the two channels were in focus in the plane of the artificial pupil. While no measurements were made as to the centering of the pupil, both Maxwellian fields were well focused, and no color frignes or blurring was evident. A check on the homogeneity of the Maxwellian fields was obtained by exposing each of the fields for a long period of time and covering the field lens entirely except for a small aperture which permitted light to pass when placed over the field lens. By moving this aperture over the entire lens in small steps a reading of relative luminance was obtained on the CRO. This reading showed only minor fluctuations from position to position on the lens and for each of the fields.

Before the matches of the adapting field to the wedges were made one half of the adapting field was eliminated from view by a stop so placed that the Maxwellian field appeared in the dark adjacent to the adapting field. With S anchored to the biting board, E moved the wedge in small steps until S indicated a match between the fields. A large number of such measurements were made and a mean of the measurements was taken as that density at which the test fields had a luminance equal to that of the adapting field.

When a reading was obtained for each of the wedge settings which corresponded to the adapting field luminance a check on the accuracy of these difficult matches was made by matching each of the wedges to the other when one was set equal to the adapting field. A large number of such matches were made throughout the study to check on the stability of the matching judgments of wedges to the adapting field. Since the matches of the wedges to the adapting field were very difficult to make because of the heterochromatic nature of the two fields, an attempt was made by using neutral density filters in front of the adapting and channel fields to decrease such differences. Therefore, in order to eliminate the color differences as much as possible, all matches between the adapting field and wedges and between the wedges themselves were made at a luminance of 0.7612 mlam. All other luminance values were calculated.

The matches of the two wedges to each other when one was set as a standard equal to its adapting field match and the other as a variable luminance were a little less stable. Under this condition one half of each field was exposed such that the two fields when seen, each projected as a semi-circle, the two being adjacent and viewed for an extended period of time (until S was sure of a match). For well over 150 matches obtained in this manner, the means of the matches always fell within 15% of each other. Therefore, for precise values, 15% should be allowed for in errors due to photometric settings of the wedges to equality.

An absolute threshold for each of the wedges was measured on subject MG using the Method of Limits. The threshold for wedge No. 1 was equal to 0.14 mlam and for wedge No. 2, 0.19 mlam. This is equal to 2.66 and 3.60 trolands respectively for each of the channels. The adapting field, with a 4.0 neutral density filter inserted in front of it was equal to 0.144 trolands and the retinal luminance range covered was from 13.239 to 132,390.58 trolands.

The pulse duration was locked into the Gerbrands timer at the beginning of the study and remained the same (10 msec) throughout the course of both investigations. The pulses were periodically monitored by using a CRO and a phototube. The asynchronies were also periodically monitored and were found to be reliable to within one to two msec.

Results

I. Experiment I - Temporal Separation

In Experiment I differential brightness sensitivity as a function of luminance and temporal separation between two 10 msec flashes was investigated. The results are shown in Figure 3-7 and Tables 2-5.

The shortest temporal separation used (95msec) was chosen on the basis of some preliminary measurements made on subject SS. These measurements showed that at this temporal separation the S reported seeing two flashes about 85% to 95% of the time. All figures and tables refer to subject SS except where indicated.

Figure 3 shows the relationship between the DL and the temporal separation (ISI) between the cessation of flash one and the onset of flash two for four luminance levels separated by log unit intervals for subject SS. In this study the standard flash always came second and S had to indicate whether the first was brighter than, equal to or dimmer than the second. He was instructed to say "equal" if uncertain of his judgments. All values are given in log millilamberts. No attempt was made to correct S's behavior to a luminance criterion. That is, S was not told when he was objectively correct.

Table 2 shows the DL obtained for each of the luminances and for each ISI investigated.

At short ISI's, DL is large and as the ISI is increased, DL decreases. The smallest DL occurs between 120-180 msec ISI, the exact position of the minimum depending on the luminance level. Thereafter, as the ISI is increased, the DL becomes larger once again. This rise stops in the neightborhood of 250 msec. Beyond 250 msec there may be

Figure 3. Logarithm of the difference threshold as a function of the inter-stimulus interval between two flashes for four luminance values of the second standard flash.

All functions have been displaced from obtained values in order to facilitate comparison as follows: 0.70 mlam decreased by 0.82 logarithmic units; 7 mlam decreased by 1.32 logarithmic units; 70 mlam decreased by 2.02 logarithmic units and 700 mlam is decreased by 2.48 logarithmic units.

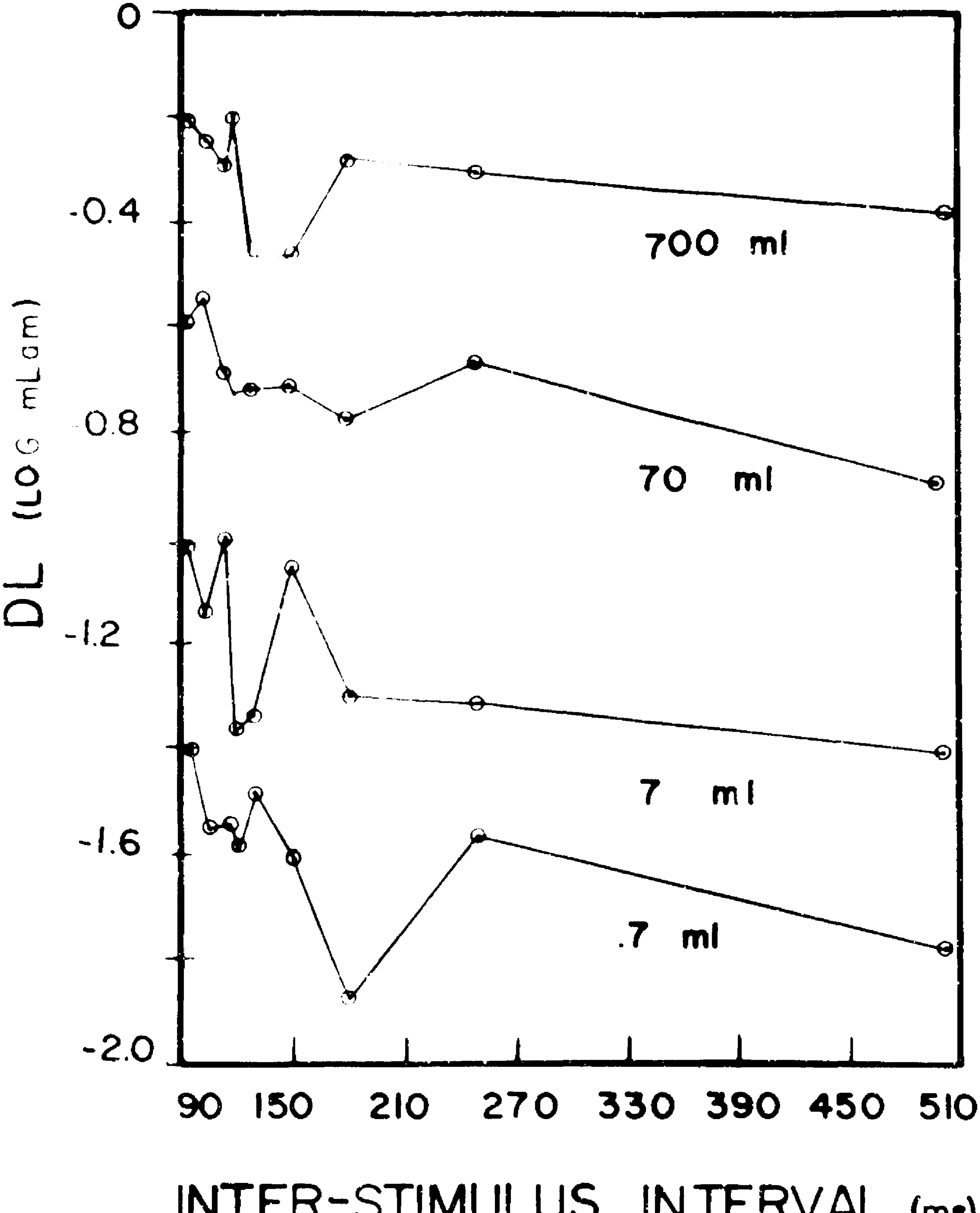

0
-0.4
-0.8
-1.2
-1.6
-2.0
DL (LOG mLam)
700 ml
70 ml
7 ml
.7 ml
90
150
210
270
330
390
450
510
INTER-STIMULUS INTERVAL (ms)

Table 2. Values of DL obtained for nine different ISI's and four luminance levels of the standard

Standard in mlam	ISI (msec) 95	105	115	120	130	150	180	250	500
700	191	174	152	191	100	100	161	151	126
70	27	28	21	19	19	19	17	22	13
7	2.1	1.5	2.1	0.9	1.0	1.9	1.1	1.2	0.8
0.7	0.27	0.19	0.19	0.17	0.21	0.16	0.09	0.18	0.11

Table 3. PSE values obtained for nine ISI's and four luminance values of the standard

Standard in mlam	ISI (msec) 95	105	115	120	130	150	180	250	500
700	517	413	469	535	382	409	530	563	652
70	71	79	60	68	63	88	67	78	76
7	8.0	8.3	8.6	7.2	7.7	8.7	7.3	7.8	7.6
0.7	0.85	0.83	0.80	0.75	0.86	0.67	0.75	0.85	0.75

a decrease in the DL once again, until at ISI equal to 500 msec the DL is about as low as that found at the first minimum. This latter decrease, however, may have been due to variability and it may be reasonable to assume that the function is flat after 250 msec.

The characteristics described above are general; however, the curves obtained at different luminance levels may differ from each other in some respects. While the exact location of the minimum as a function of luminance could not be ascertained with any degree of confidence, there is a strong suggestion that, as luminance decreases, the ISI at which the minimum DL is found increases. Greater precision in the measurements is needed to establish this.

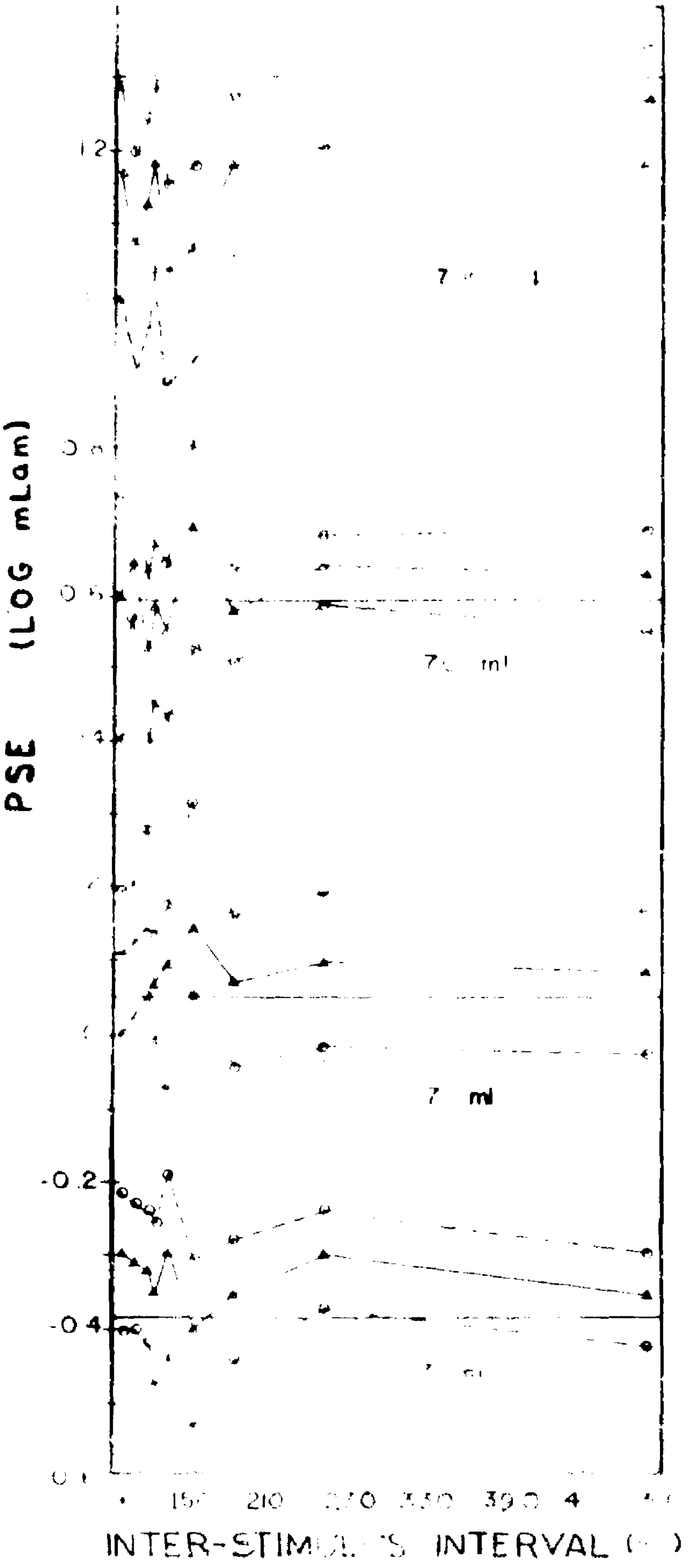
In Figure 4 the log of the point of subjective equality (PSE) is plotted as a function of ISI for observer SS. The PSE is defined as the mean of the upper and lower threshold transitions. Each of the four curves is for a different fixed value of the luminance of the second (standard) flash. Table 3 presents the PSE values for each luminance of the standard and each ISI.

For the highest luminance, 700 mlam, of the second (standard) flash, the luminance of the variable at the PSE is always lower than the luminance of the standard. This is commonly referred to as a constant error or, if the matches are done successively, a time error. This time error is defined as the difference between the point of subjective equality (PSE) and the point of objective equality (POE) or the standard. For the highest luminance the time error is negative, and is greater than could be attributed to calibration errors.

A negative time error implies that in order for the first flash

Figure 4. Logarithm of the PSE (mean of upper and lower threshold crossings) for four luminance values of the standard as a function of the inter-stimulus interval. Each of the curves have been displaced in the coordinate system as follows: 700 mlam decreased by 1.55 logarithmic units; 70 mlam decreased by 1.25 logarithmic units; 7 mlam decreased by 0.8 logarithmic units; 0.7 mlam decreased by 0.23 logarithmic units.

The horizontal lines indicate the logarithm of the luminance of the standard (POE). The unbroken curves represent the logarithm of the PSE values for each standard. The broken line curves above and below the unbroken PSE curve represent the logarithm of one standard deviation unit above and below the PSE.



PSE (LOG mLam)
1.2
0.6
-0.2
-0.4
150
210
390
ml
ml
INTER-STIMULUS INTERVAL

to appear as bright as the second, the first must be of lower luminance than the second. Conversely, two flashes of equal luminance do not look equally bright. Rather the first of the two equal luminance flashes looks brighter than the second.

All of the PSE values at the 700 mlam level are less than the point of objective equality (POE). Furthermore, it appears that the PSE is not independent of ISI. That is, up to 180 msec of ISI, the PSE changes with changes in ISI. The nature of these changes in the PSE as ISI increases up to 180 msec is complex. Beyond 180 msec the PSE does appear to be independent of ISI. It appears, therefore, for the 700 mlam standard that up to 180 msec ISI both the PSE and DL change as ISI changes, whereas beyond 180 msec only the DL is affected by changes in ISI.

Figure 4 also shows the standard deviation of the PSE values for a given luminance and ISI (broken curves).

At a standard of 70 mlam and at lower luminances, the time error is no longer negative but becomes increasingly positive.

A measure of the relationship between the DL and the PSE as a function of ISI was obtained by a rank order correlation at each level of luminance. Table 4 shows the Rho values obtained for subject SS.

For any given level of the standard, the DL did not vary as a regular function of the PSE. In other words, as the PSE changed as a function of ISI, these changes were not correlated with the changes in

Table 4. Rank order correlation between the PSE and DL at each given luminance of the standard across ISI.

Standard	Rho
700 mlam	.11
70 mlam	.13
7 mlam	.53
0.7 mlam	.77

the DL as a function of ISI. A change in ISI affect, up to a certain point, both the PSE and DL but not necessarily in the same direction, since both are complex functions of ISI as previously described.

As the DL function contains all of the information which would be available in a plot of $\Delta I/I$ where ΔI is the DL and I is the standard, the traditional plot was not used in this study. Division of the DL by the standard on a log DL/I plot would simply move all of the functions down in the coordinate system by an amount equal to the log I.

Another measure, the co-efficient of concordance, was used as the "Weber fraction." This measure is a ratio of the DL to the PSE and is presented as an additional piece of information. This form of the fraction takes into account the time error and has been used on occasion by previous investigators (Blackwell, 1963). Where no time error exists the fraction is identical to the more traditional form of the Weber fraction.

Figure 5a shows the log of the ratio of the DL to the PSE plotted as a function of the temporal interval between the two flashes. The parameter of the curves is the luminance of the standard flash.

Figure 5b shows the same results for a second subject, MG, for the 700 mlam standard. The data were divided into a first and second half and the Weber fraction was determined for each half separately to check on reliability. The form of the function appears invariant over trials and appears highly similar to that obtained from subject SS.

Figure 5a. Logarithm of the Weber fraction (DL/PSE) as a function of the inter-stimulus interval (ISI) for four luminance values of the standard. All curves have been displaced in the coordinate system as follows: 700 mlam is increased by 0.03 logarithmic units; 70 mlam is decreased by 0.37 logarithmic units; 7 mlam is decreased by 0.61 logarithmic units and 0.7 mlam is decreased by 0.97 logarithmic units.

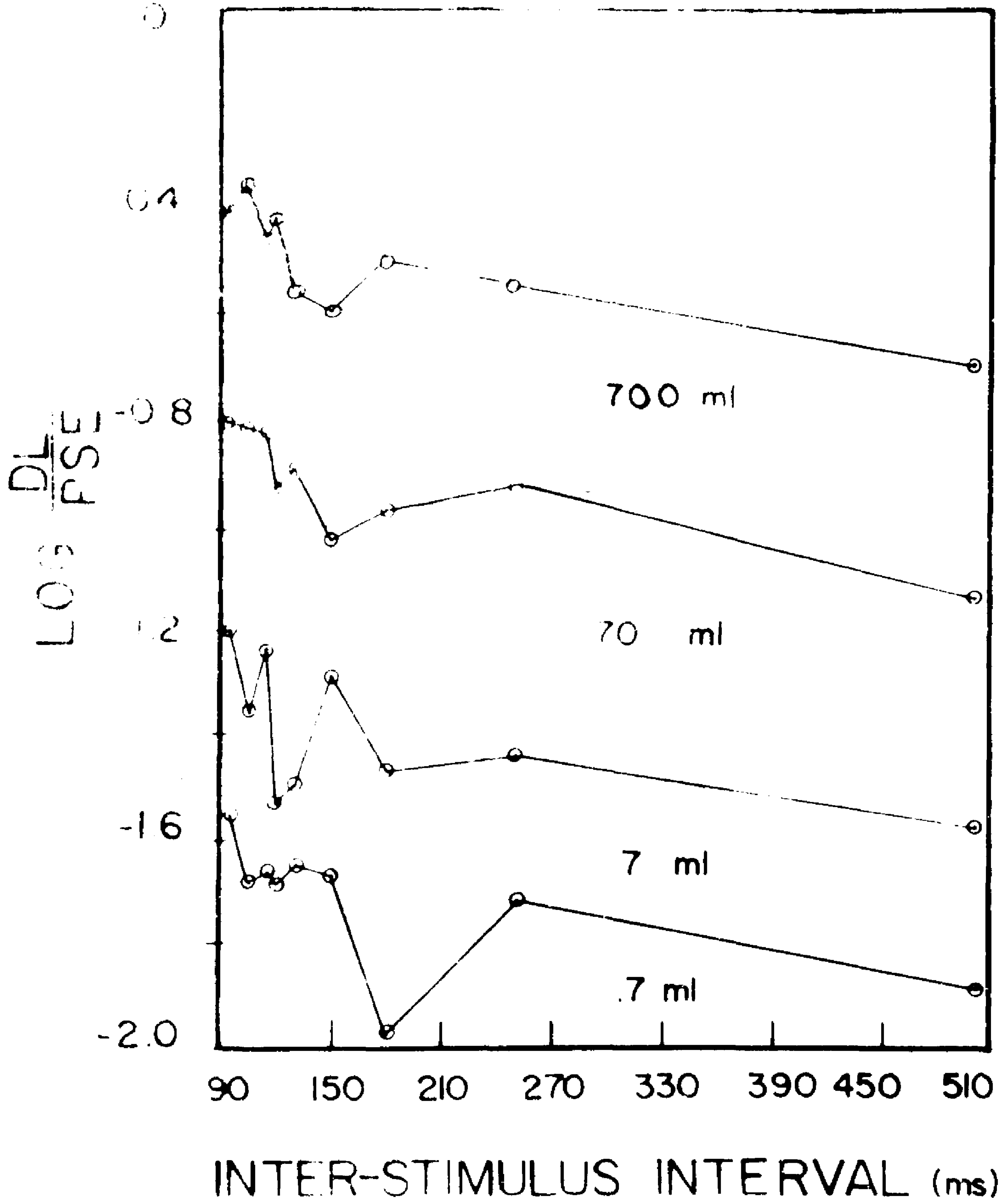
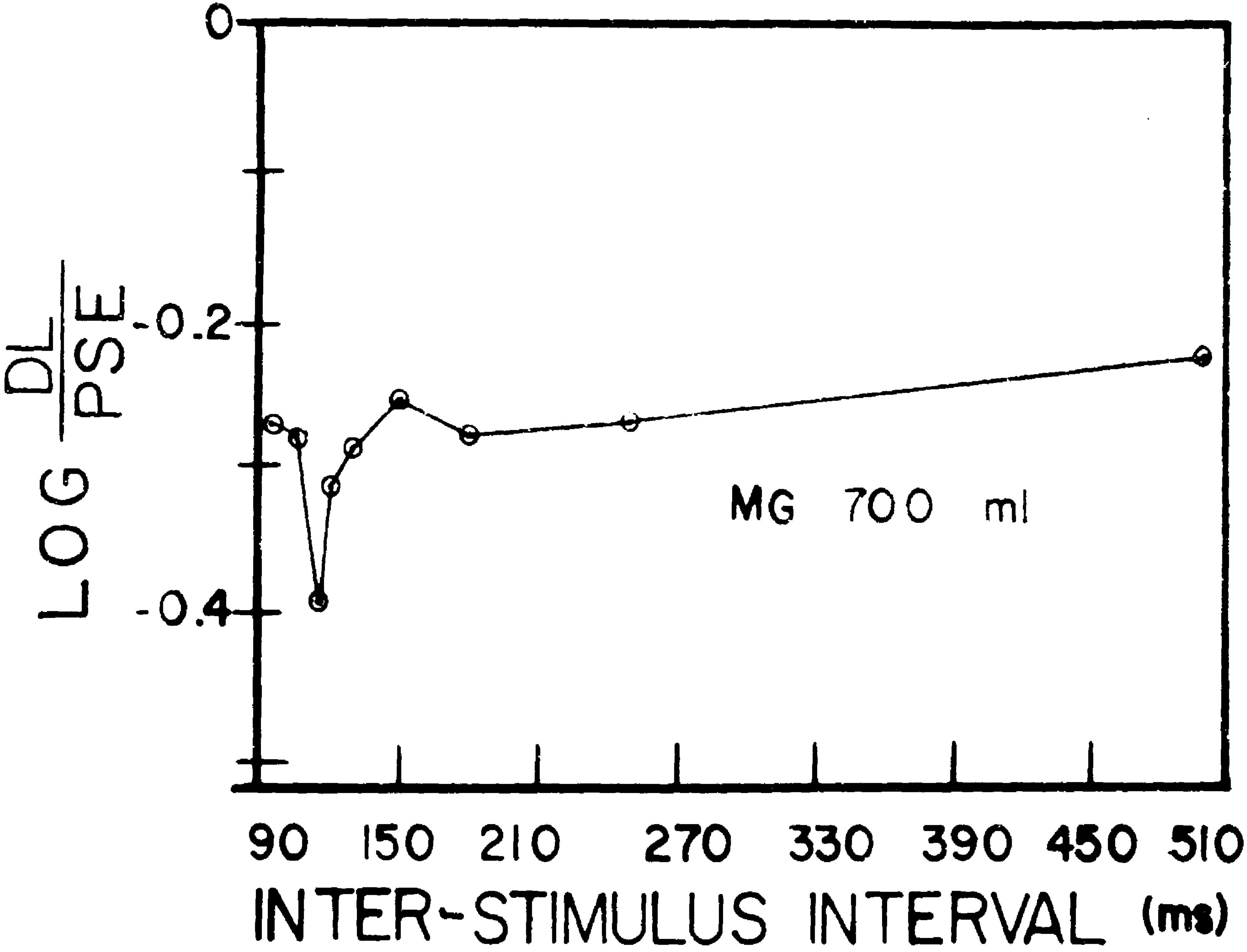

0
-0.4
-0.8
-1.2
-1.6
-2.0
LOG DL/PSE
700 ml
70 ml
7 ml
.7 ml
90
150
210
270
330
390
450
510
INTER-STIMULUS INTERVAL (ms)

Figure 5b. Logarithm of the Weber fraction (DL/PSE) for subject MG for each of nine inter-stimulus intervals using a standard flash equal to 700 mlam.


0
-0.2
-0.4
LOG DL/PSE
MG 700 ml
90
150
210
270
330
390
450
510
INTER-STIMULUS INTERVAL (ms)

For subject SS the general features of the functions are similar to those seen in Figure 3. At short ISI discrimination is poor and with increasing ISI the Weber fraction decreases to a minimum in the region between 120 and 180 msec and then rises once more to 250 msec. From 250 msec there is a gradual decrease until at ISI equal to 500 msec the value of the fraction is as low or lower than that found at the mimimum.

The location of the mimimum and the secondary maximum could not be fixed precisely as a function of luminance. The consistent features across luminance were:

1. A sharp decrease in log DL/PSE to a minimum between 120-180 msec.

2. A maximum (secondary) which followed the minimum.

3. A gradual tapering off to a value at 500 msec which equaled approximately, the value obtained at the minimum.

The third feature may, however, arise from variability of the judgments. The positions of the maximum and minimum were different for the different luminances used.

The curve for subject MG demonstrated the same general feature for the 700 mlam standard. A decrease to a minimum was observed at 115 msec with a rise at 150 msec. Subject MG did not display the same effect as SS at the end portion of the curve.

A third degree polynomial was fitted to the data of SS using a method of least squares, and a criterion that the smallest exponent account for the greater portion of the variance. A test of significance was made for deviations from regression for each component order individually and inclusive of each component order for each of the equations. Table 5 gives the summary analysis of variance and the regression equation for each function. Figure 6 shows a fit of the regression line and the

Table 5. Analysis of Variance and Regression Equations for the 3rd degree polynomial equation fitted to each of the functions.

a. Analysis of Variance

Source	df	Sum of Squares	% of Total Variance	F
Linear	1			
700		.057226	62%	$p < .01$
70		.067870	67%	$p < .01$
7		.048245	43%	$p < .05$
0.70		.047165	36%	$p < .05$
Quadratic	1			
700		.003992	4.3%	NS
70		.001946	1%	NS
7		.001356	1%	NS
0.70		.010404	7%	NS
Cubic	1			
700		.010921	11.8%	NS
70		.021371	21%	$p < .025$
7		.000539	5%	NS
0.70		.021474	17%	NS
Deviations from Regression	5			
700		.019969		
70		.009401		
7		.066189		
0.70		.048731		
Total	8			
700		.092103		
70		.100589		
7		.110328		
0.70		.127774		

Table 5 (Continued)

b. Regression Equations

Standard	Regression Equations
700	$\log \hat{Y} = .34707199 - .011685142X + .000045487483X^2 - .00000005287X^3$
70	$\log \hat{Y} = .55740333 - .015427026X + .000062435799X^2 - .000000073841090X^3$
7	$\log \hat{Y} = .46148573 - .003425089X + .0000107286X^2 - .000000011733556X^3$
0.7	$\log \hat{Y} = .51496927 - .016276141X + .000064149617X^2 - .000000074017128X^3$

obtained values about the regression line.

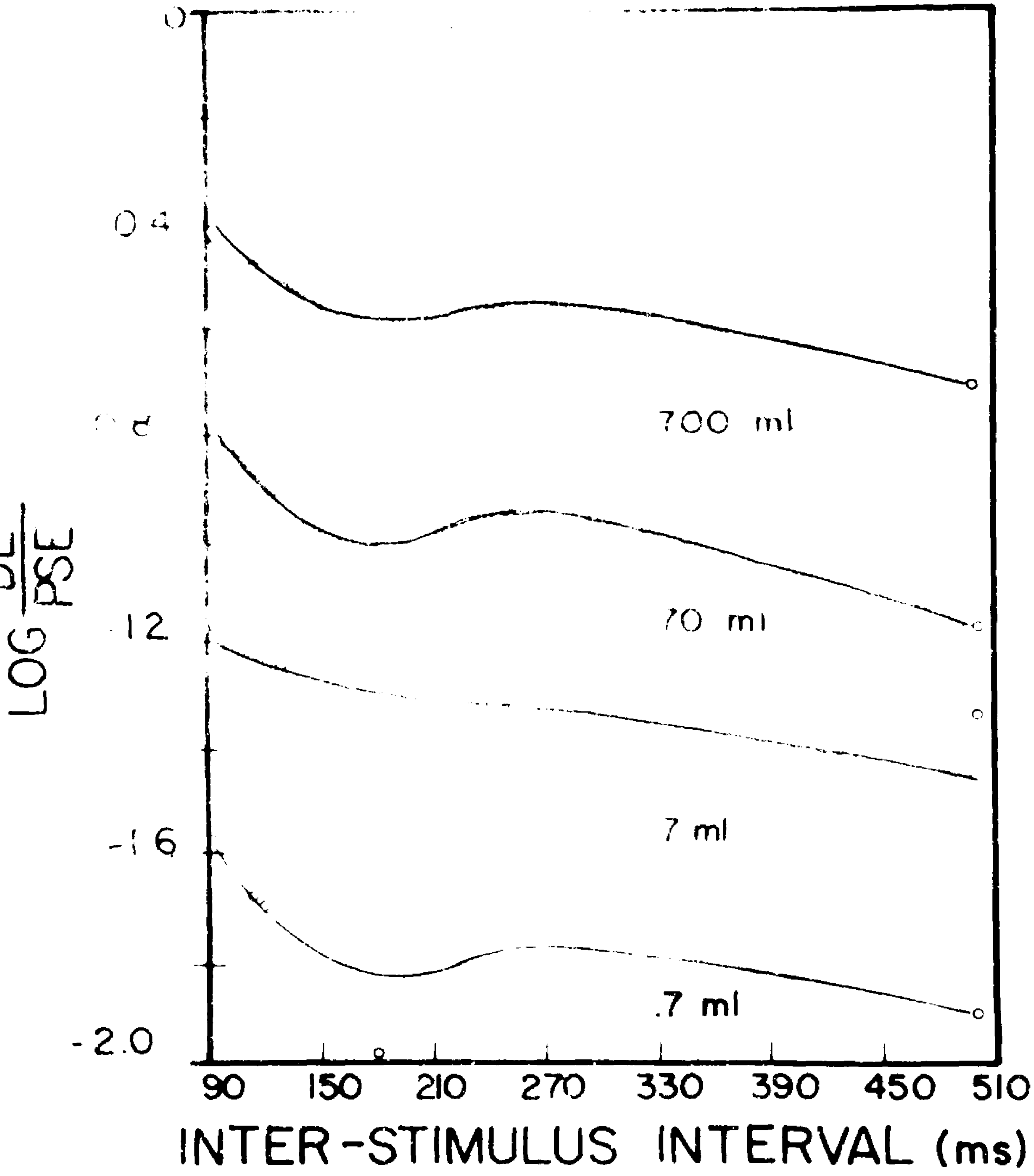
While a test of significance of each component indicated that a cubic order polynomial was significant for only the 70 mlam standard ($p <.025$) it should be pointed out that when all three degrees inclusive were considered (linear, quadratic and cubic) a large part of the variance was thereby explained. Thus, for the 700 mlam standard, the cubic order accounted for only 12% of the total variance by itself but when considered inclusive with the two previous orders it accounted for 78.1% of the total variance. Similarly for the 70 mlam standard, 21% was accounted for by the cubic component alone but 89% of the total variance was explained when the linear, quadratic and cubic orders were taken together. The 7 mlam function accounted for 49% of total variance when all three were taken together and 60% of the total variance was explained through the cubic order for the 0.7 mlam standard.

As can be seen from Figure 6, the fits to the data points by a third degree polynomial are very good in spite of the indicated nonsignificance. In one case, 7 mlam, perhaps a quartic or higher order function would have fitted better but since three of the four functions were well fit with a third degree to a least square criterion, this degree of polynomial was settled upon.

While the exact location of the minimum cannot be ascertained, the fitted functions all appear to have a secondary maximum at approximately 250 msec. There is some suggestion of a more pronounced minimum as luminance increases. In the fitted functions the minimum is approximately the same for all curves, being at 180 msec.

The quantity log DL/PSE represents the combined effects of variation

Figure 6. Logarithm of the Weber fraction as a function of inter-stimulus interval (ISI) for four luminance values of the standard fitted by a third degree polynomial equation ($\hat{Y} = a + bX + cX^2 + dX^3$). Plotted points are empirical values. Curves have all been displaced as in Figure 5a.



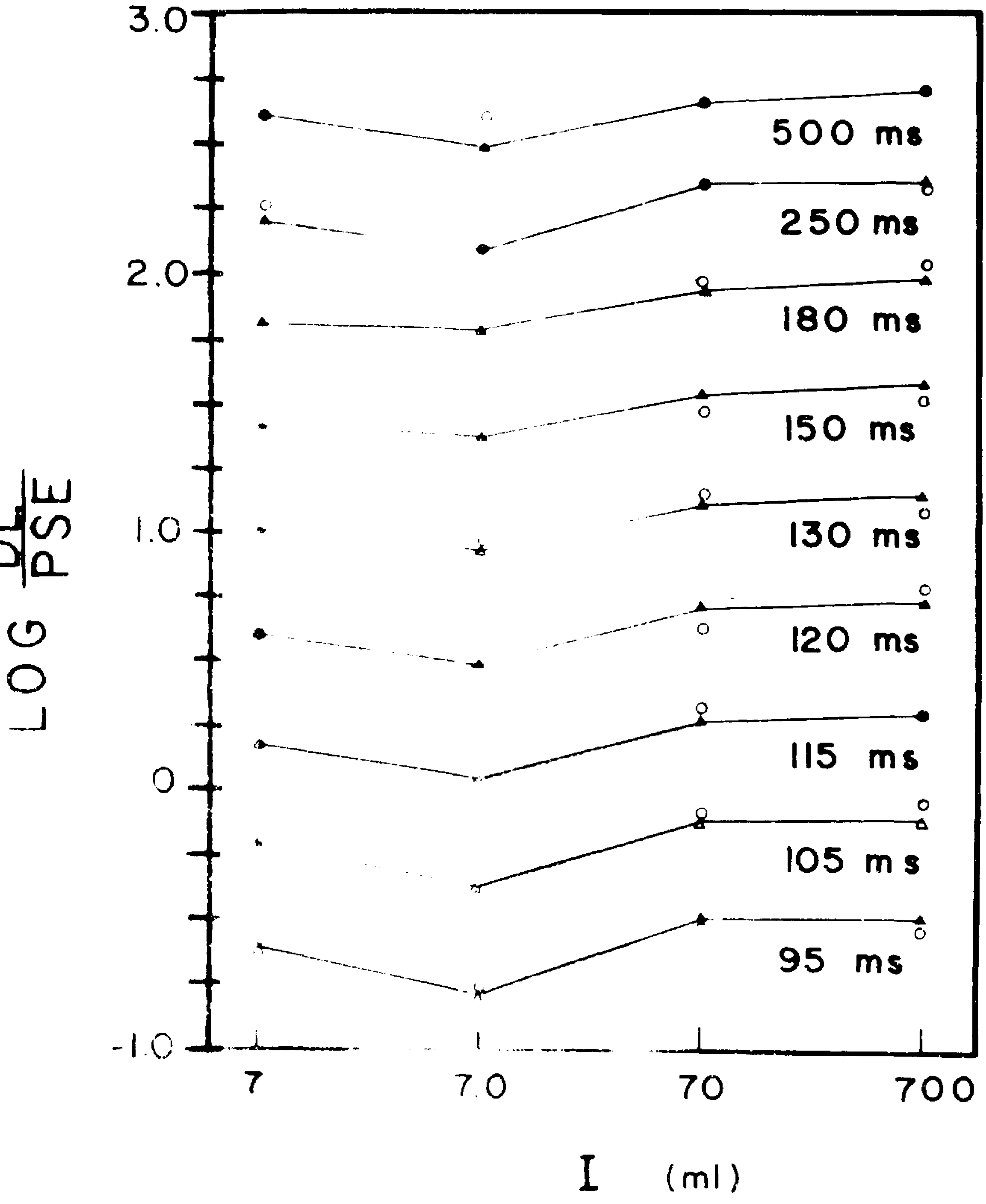
0
0.4
0.8
1.2
-1.6
-2.0
LOG DL/PSE
700 ml
70 ml
7 ml
.7 ml
90
150
210
270
330
390
450
510
INTER-STIMULUS INTERVAL (ms)

in PSE and DL for ISI values up to 180 msec, and the effects of variation in DL alone beyond 180 msec for the highest luminance. For the lower luminances, as the PSE is equal to the POE, within the limits of calibration errors, the variation in the function is due entirely to changes in the DL (e.g., minor variations in PSE change the function somewhat, but only slightly). Therefore, the secondary maximum found at 250 msec and the gradual decrease of the fraction to a minimal value at 500 msec are due to factors influencing the DL rather than to variations in the PSE at ISI more than 180 msec for the 700 mlam standard. At ISI less than 180 msec, even though the PSE is not independent of ISI, a comparison of Figures 3 and 4 indicates that the greater portion of the effect (i.e., minimum) is due to a decrease in the DL rather than to changes in PSE.

Figure 7 shows the log DL/PSE plotted against log I. The parameter of the curves is ISI. The crosses represent values read from the fitted curves; the circles are the empirical points. As can be seen here also, the cubic order polynomial gives a good fit to the empirical points.

All the functions show a very slight decrease in Weber's fraction to a minimum at 7 mlam except at an ISI of 150 msec. At 150 msec and perhaps at 180 msec the function shows no decrease and only a slight rise at the higher levels of luminance. This trend is the same for 115 msec, 105 msec, and 120 msec, except for the fact that the rises and falls become more gradual. It should be pointed out that all of the functions are relatively horizontal as all of the variation between the values fall within 1/10 of a log unit. Within this 1/10 of a log unit, Weber's Law is obtained for the luminance range investigated for all ISI's.

Figure 7. Logarithm of the Weber fraction (DL/PSE) as a function of luminance of the standard for nine inter-stimulus intervals (ISI). All functions have been displaced in the coordinate system to facilitate comparison. The displacements are: 95 msec decreased by 0.09 logarithmic units; 105 msec is increased by 0.45 logarithmic units; 115 msec increased by 0.82 logarithmic units; 120 msec increased by 1.24 logarithmic units; 130 msec increased by 1.6 logarithmic units; 150 msec increased by 2.02 logarithmic units; 180 msec increased by 2.72 logarithmic units; 250 msec increased by 2.87 logarithmic units and 500 msec is increased by 3.44 logarithmic units.


3.0
2.0
1.0
0
-1.0
LOG DL/PSE
500 ms
250 ms
180 ms
150 ms
130 ms
120 ms
115 ms
105 ms
95 ms
7
7.0
70
700
I (ml)

2. Experiment II - Spatial Separation

In Experiment II the spatial separation between two simultaneously presented 10 msec flashes was varied and the DL and PSE were determined over a four log unit range of photopic intensities (.7 to 7000 mlam).

Figure 8 shows the relationship between the log DL and angular separation (θ) between the fields. The parameter of the curves is the luminance of the standard to which the variable was compared in brightness. All values are given in millilamberts. Table 6 presents the DL values obtained for all luminance values of the standard at each value of θ.

It is apparent from inspection of the functions that the DL is smallest at very small separations (30"). As the separation between the fields is increased, the DL (in log units) rapidly increases and with further increases in separation beyond about 10' there is little further change in the DL.

The rate of rise in the DL does not appear to be directly related to luminance, but there is a suggestion that the value at which the function first begins to show little further change in DL with increases in separation may be related to luminance.

For the three highest luminances there appears to be, between 7' to 10' an "overshoot" in the DL before it settles down to a relatively steady level. This "overshoot" is not, however, found at the lower luminances and may simply reflect variability.

For the 7000 mlam standard the difference threshold is doubled at a separation of 1' as compared to that at 30", while at a separation of 3' it is more than quadrupled and is more than five times as great at

Figure 8. Logarithm of the difference threshold as a function of angular separation between the halves of a bipartite field for five luminance values of the standard. All curves have been displaced in the coordinate system as follows: 0.7 mlam is decreased by 0.30 logarithmic units; 7 mlam decreased by 1.00 logarithmic units; 70 mlam decreased by 1.48 logarithmic units; 700 mlam is decreased by 2.16 logarithmic units and 7000 mlam is decreased by 3.06 logarithmic units.

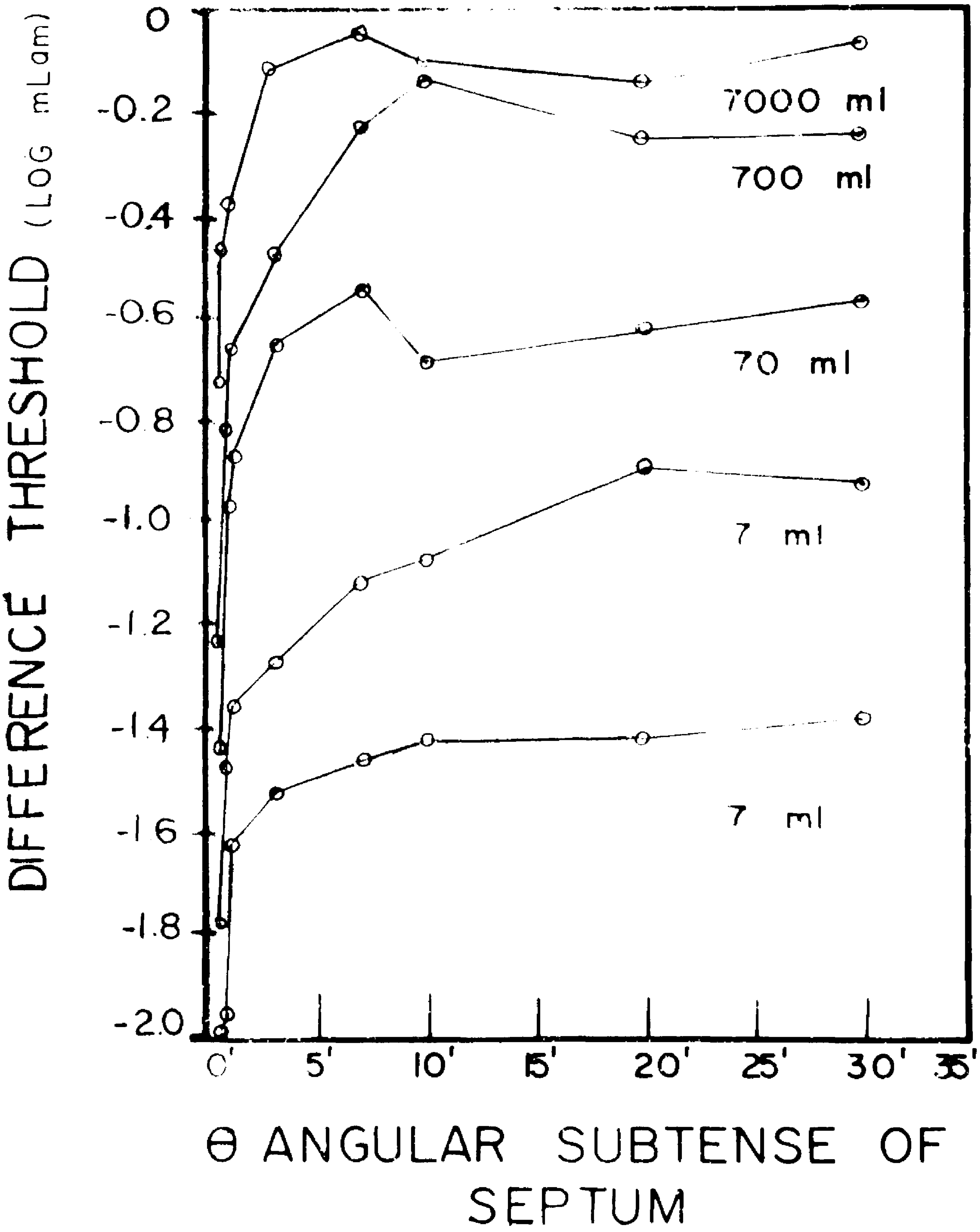

DIFFERENCE THRESHOLD (LOG mLam)
0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.4
-1.6
-1.8
-2.0
7000 ml
700 ml
70 ml
7 ml
7 ml
0'
5'
10'
15'
20'
25'
30'
35'
θ ANGULAR SUBTENSE OF SEPTUM

Table 6. <u>DL values obtained at five luminance levels of the standard and at eight different angular separations between the fields.</u>

Standard	θ							
	30"	45"	1'	3'	7'	10'	20'	30'
7000	219	391	492	891	1031	906	813	969
700	8.4	21.9	31.3	48.4	85.9	106.3	82.8	84.4
70	1.1	3.3	4.1	6.9	8.8	6.3	7.2	8.3
7	0.16	0.31	0.31	0.50	0.73	0.80	1.23	1.13
0.7	0.02	0.03	0.05	0.07	0.08	0.09	0.09	1.00

7'. With separation greater than 10' of arc at this luminance, there are no further changes in DL.

The 700 mlam function exhibited the most marked threshold changes in the DL as a function of spatial separation. Between 30" and 1' the DL is quadrupled. Beyond 10' separation, the DL remained at a level ten times as high as at 30".

Exactly where asymptote was reached as a function of luminance could not be ascertained from these data, although, it can be stated that beyond 3'-7' most of the change in the DL has already taken place no matter what the level of luminance.

Figure 9 shows PSE in log millilamberts as a function of θ for various luminance levels of the standard. Log PSE is independent of separation; the functions are all horizontal. All of the functions fall within the limits of our calibration error of ±15% and can be considered as objectively equal to the standard. Table 7 presents PSE values for all luminance values of the standard at each value of θ.

Table 8 presents a summary of the analysis of variance done on the log DL/PSE data as a function of luminance and separation. Five luminances versus the four largest separations (7' to 30') were subjected to an F-test. The obtained F for both the luminance and luminance x separation interaction were found to be highly significant ($p < .001$). The F obtained for the separations was not found to be significant at the 20% level of confidence. Thus, beyond 7' the effect of separation between the two fields was not significant, i.e., the functions are horizontal lines. On the other hand, for any given value of angular separation, values of the log DL/PSE vary significantly with luminance. This implies that Weber's Law does not hold within the range of separations subjected to analysis (7' through 30').

Figure 9. Logarithm of the PSE values obtained at each of five luminances of the standard and for each of eight angles of separation between the halves of a bipartite field. The PSE is the mean of the upper and lower threshold crossings using the Method of Limits. Horizontal lines indicate the value at which matches must be made in order to be objectively equal to the luminance of the standard.

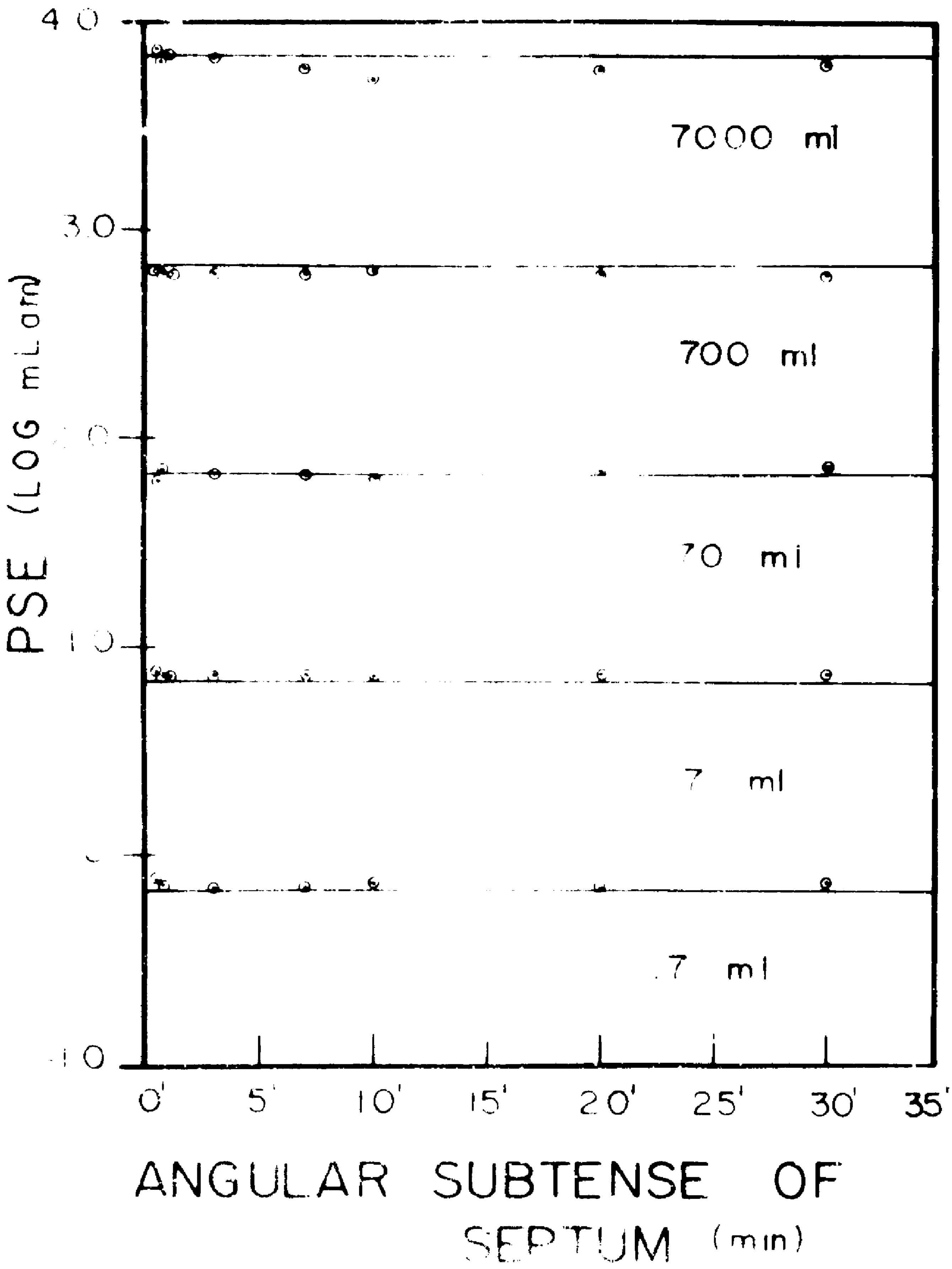

4.0
3.0
2.0
1.0
-1.0
PSE (LOG mLam)
7000 ml
700 ml
70 ml
7 ml
.7 ml
0'
5'
10'
15'
20'
25'
30'
35'
ANGULAR SUBTENSE OF SEPTUM (min)

Table 7. PSE values obtained at eight different angular separations between the fields for five different levels of luminance of the standard

Standard	θ							
	30"	45"	1'	3'	7'	10'	20'	30'
7000	7375	6672	7179	6734	5719	5219	5875	6281
700	635	634	633	628	611	663	627	606
70	65.8	73.3	69.4	69.1	66.3	72.5	61.6	74.5
7	7.7	7.5	7.4	7.4	7.4	7.2	7.6	7.4
0.7	0.77	0.75	0.67	0.71	0.70	0.75	0.70	0.77

Table 8. Analysis of Variance Summary Table for Experiment II.

Source	df	Sum of Squares	Mean Square	F
Luminance (C)	4	.5169	.1292	*10.01 ($p < .001$)
Separations (R)	3	.0356	.0119	.91 NS ($p <$ 20%)
(Cells)	(19)	(1.9852)		
Luminance X Separation interactions (R x C)	12	1.4327	.1192	*9.23 ($p < .001$)
Within Cells Variance	140	1.8109	.0129	
Total	159	3.7961		

* Indicates significance

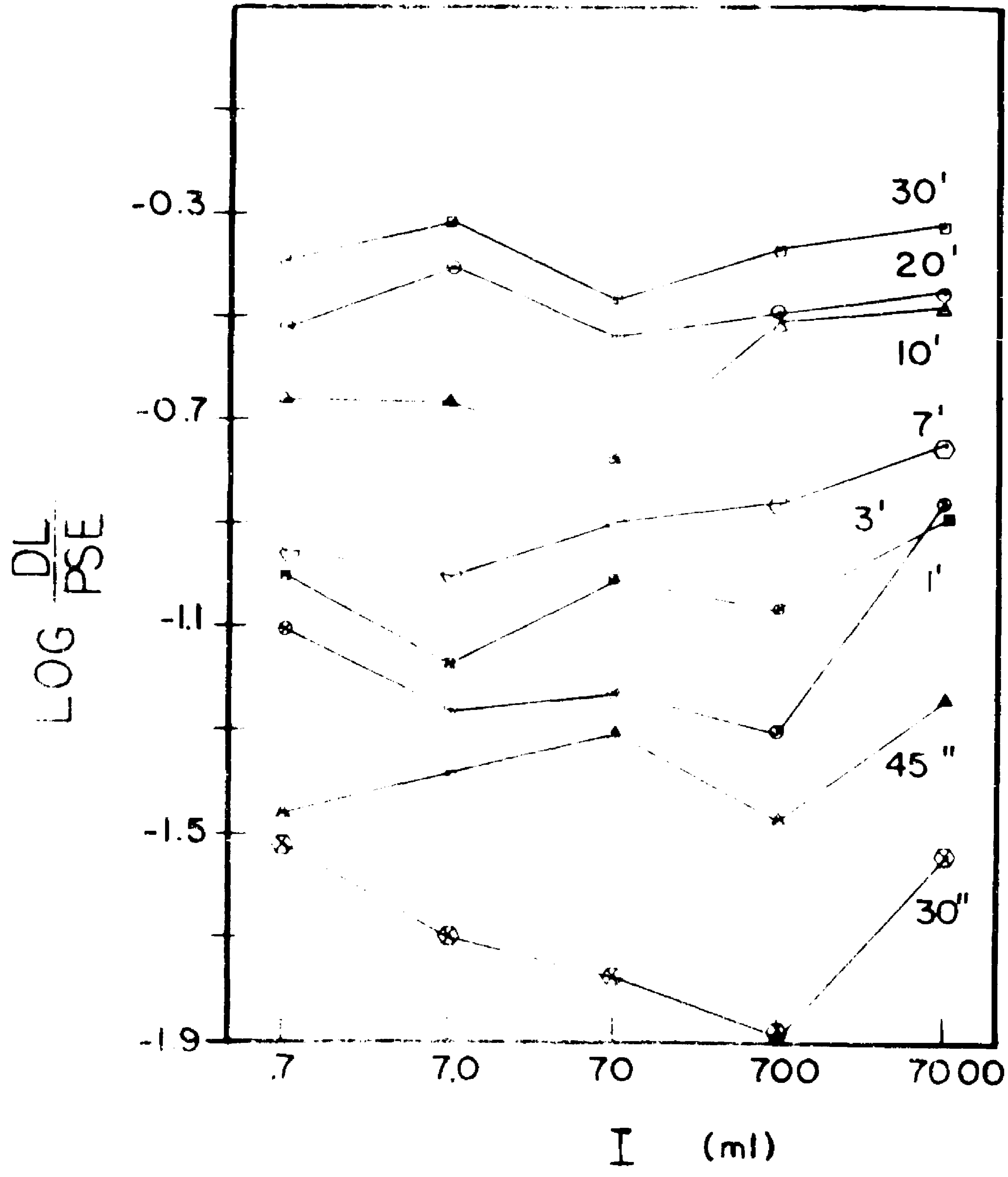
The significant interaction between luminance and separation implies that at different separations different log DL/PSE versus luminance functions will be obtained.

These results are illustrated in the derived functions shown in Figure 10. The parameter on these curves is θ and the plot is one of log DL/PSE against log I. The functions demonstrate a systematic order up to 7' beyond which their placement in the coordinate system is overlapped. In Figure 10 all functions up to and inclusive of 7' are in their proper (i.e., actual) locations.

For the four smallest separations used, the function descends to a minimum at 700 mlam. For the four larger separations this minimum is shifted to 70 mlam and the extent of the decline is reduced. For all functions log DL/PSE is highest at the highest luminance level. Comparison of the DL at high luminances for closely spaced versus widely spaced photometric fields indicates that the DL is smaller the closer the two fields lie to each other. This trend is found for all levels of luminance; the closer the fields, the smaller the DL.

While the functions obtained with a small separation between the halves show the smallest DL at all luminance levels, the 30" curve in particular, shows the greatest degree of departure from Weber's Law. The function is similar to that obtained by other investigators using a variety of other methods (Hecht, 1934; Craik, 1938; etc.) if the luminance range is taken into consideration. Another feature of the functions taken together is a progressive flattening as the separation is increased. At 20' and 30' the curvature is much less marked than at 30".

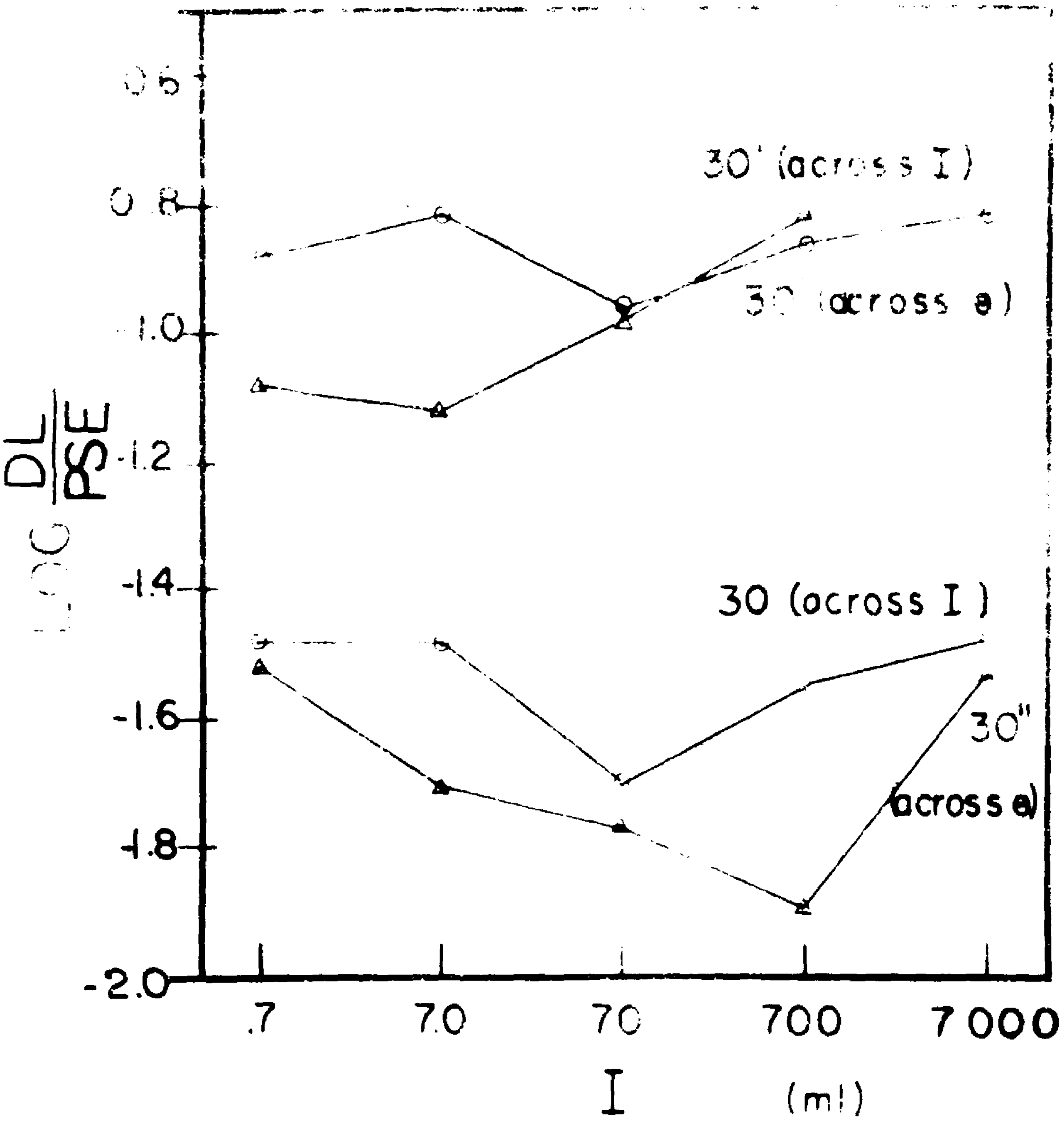
Figure 10. The logarithm of the Weber fraction (DL/PSE) as a function of luminance of the standard for eight spatial separations between a bipartite field. All functions are in their proper placement in the coordinate system except for the top three. The 10' curve has been displaced upward by 0.3 logarithmic units; 20' by 0.4 logarithmic units and 30' by 0.5 logarithmic units.


30'
20'
10'
7'
3'
1'
45 ''
30''
-0.3
-0.7
-1.1
-1.5
-1.9
LOG $\frac{DL}{PSE}$
.7
7.0
70
700
7000
I (ml)

It is also apparent that the shapes of the functions beyond 7', while roughly comparable, do exhibit differences. At 7' there is a marked increasing trend with increasing luminance, while at 20' and 30' this increase is no longer so apparent. Generally, the functions are ordered in reference to both sensitivity (placement in the coordinate system) and general shape (from marked curvature towards a relatively horizontal trend).

It has already been stated in the procedure section, that in Experiment II in each daily session a luminance value was fixed and the DL determined for each different θ. Since one object of the study was to obtain derived functions of log DL/PSE versus log I, each of two separations were set and the DL was determined for each of five luminance levels of the standard. Figure 11 compares the functions obtained for two separations obtained in these two different ways. The lower curve indicated by "across θ" was obtained by setting a luminance level and making measurements at different values of spatial separation. When this was done for the five levels of luminance used in the study, the θ value of interest was selected and the fraction plotted. The curve "across I" was obtained by setting a θ = 30" and changing the luminance. Measurements were made over a four day period changing the luminance rather than the separation. Comparison of these two curves shows a marked similarity of the general trend. Each of the curves decreases to a minimum and then shows a rise again. The same procedure was followed for θ = 30' yielding the top two functions. Again, the shapes are comparable although there are some differences. These differences are most likely due to day-to-day variability in sensitivity as well as criterion effects due to the method of obtaining the data.

<u>Figure 11.</u> Comparison of the logarithm of the Weber fraction (DL/PSE) obtained by two different methods of collecting the data for each of five luminance values of the standard. The curve obtained "across I" indicates that in each daily session, an angular separation was set between the halves of the bipartite field, and the luminance of the standard was changed. Values obtained "across θ" indicate that in each daily session, the luminance value of the standard was set, and the logarithm of DL/PSE was obtained for the various θ values used in the experiment.

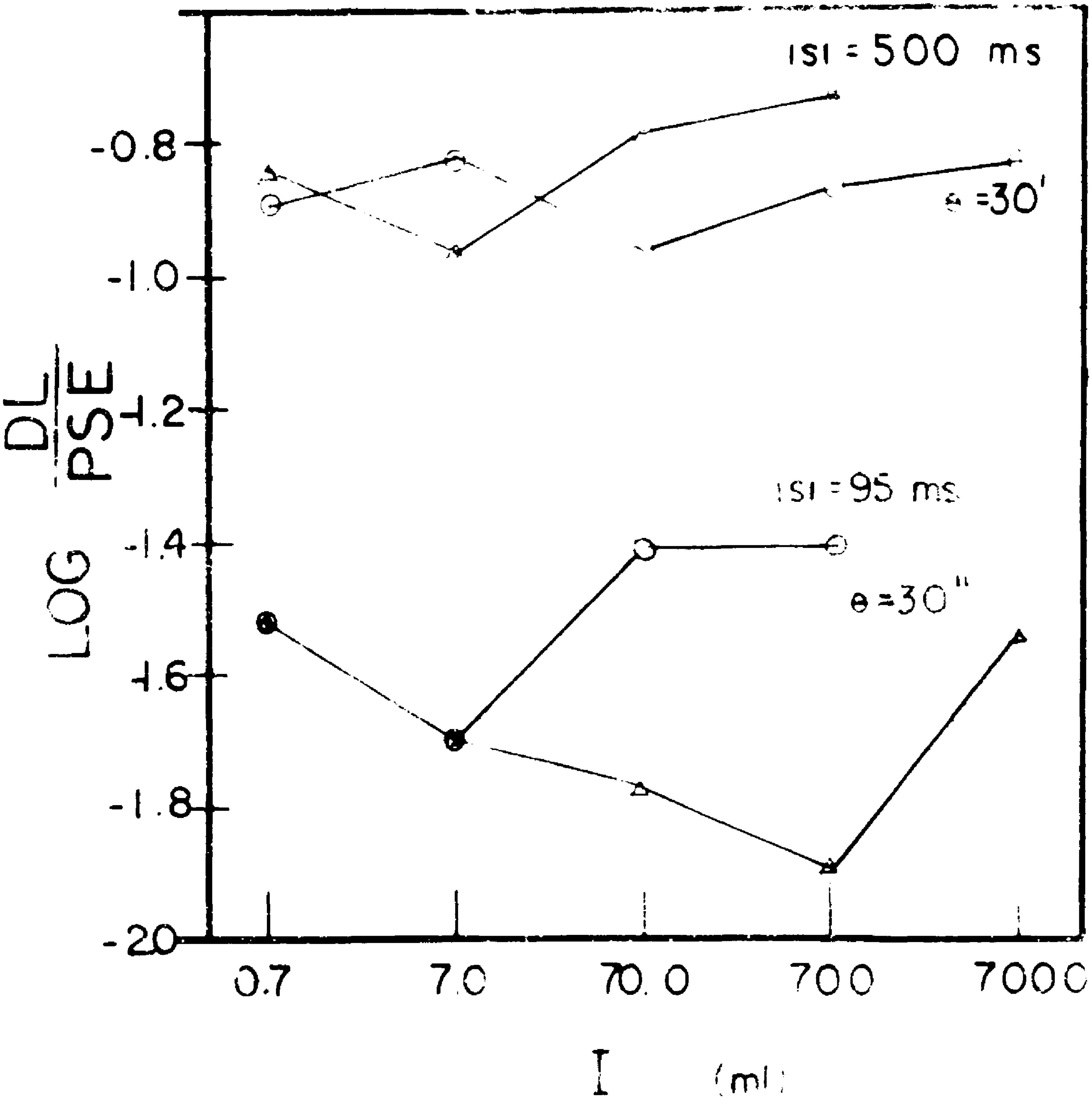


0.6
0.8
-1.0
-1.2
-1.4
-1.6
-1.8
-2.0
LOG DL/PSE
30' (across I)
30' (across e)
30 (across I)
30"
(across e)
.7
7.0
70
700
7000
I (ml)

Figure 12 shows the effect of spatial and temporal separation between the fields on log DL/PSE versus log I for two levels of separation. The separations chosen were **small** and **large**, temporal and spatial separations. In the lowest two curves a 95 msec temporal separation is compared to a 30" spatial separation. The 95 msec curve has been arbitrarily lowered in the coordinate system to facilitate comparison. The initial segments (from .7 to 7 mlam) of the two functions are identical insofar as their shape is concerned. Beyond this initial portion the functions appear entirely different. While the spatial function continues to decrease (sensitivity increases) to a minimum at 700 mlam, the temporal function exhibits poorer sensitivity at intermediate luminances. After 700 mlam the spatial curve rises and sensitivity becomes poor once again, although, never as poor as for the temporal situation. After reaching a maximum sensitivity at 7 mlam, the temporal function rises to an asymptotic level. With a small spatial separation, however, sensitivity continues to improve over a three log unit range and only at the highest luminance level does it become poor again.

The second set of curves are those obtained for a wide temporal and spatial separation. Here a 30' spatial separation was compared with a 500 msec temporal separation. The curves are roughly comparable in shape. The spatial function is leading the temporal function by one log unit. That is, if the temporal function had all of its values of log DL/PSE shifted up to the right, the two curves would be identical in shape. It appears that to a first approximation the form of the function is the same for large temporal and spatial separations. While

Figure 12. Comparison of the log Weber fraction obtained at each value of the standard for narrow (30", 95 msec) and wide (500 msec; 30") temporal and spatial separations between the fields to be discriminated. ISI refers to interstimulus interval; θ refers to the angular subtense of the septum between the halves of the bipartite field. The entire curve for ISI = 95 msec has been lowered by 0.97 logarithmic units in the coordinate system to facilitate comparison.

ISI = 500 ms
θ =30′
ISI = 95 ms
θ =30″
LOG DL/PSE
-0.8
-1.0
-1.2
-1.4
-1.6
-1.8
-2.0
0.7
7.0
70.0
700
7000
I (ml)

the temporal curve shows a decrease at 7 mlam, this decrease is shifted to 70 mlam in the spatial situation. After the minimum is attained for both functions there is a subsequent rise, but these differences may be due to variability.

Discussion

1. Experiment I - Temporal Separation

No investigations comparable to the present study appear to have been previously made. Although many investigators have been concerned with the temporal variable in vision, none have systematically varied the ICI as a parameter while noting its effects on luminance difference judgments between successively presented superimposed suprathreshold fields having no spatial overlap. It was found that the effect of inserting a variable dark interval between two fields on the luminance difference threshold is complex. Figure 3 illustrates the precise nature of this effect. It has already been indicated that the curve has at least two changes of direction. This complexity of form has immediate consequences for any interpretation of the data based on psychophysically determined effects which are monotonic functions of time such as light adaptation (forward masking) and backward masking.

Psychophysically determined effects can be distinguished from various processes which may underlie these effects. For example, the phenomenon of light adaptation may be understood in at least two ways. It may be understood as a photochemical and neural process. It may also be understood psychophysically as changes in the apparent brightness judgments of the second of two successively presented flashes or on the basis of changes in the luminance required to detect a flash which follows an adapting luminance at various times. This same relationship between "process" and "psychophysically determined effects" also applies to the phenomenon of backward masking.

Whereas the study of forward masking is usually concerned with the detection or the assessment of the apparent brightness of the second of two flashes presented successively, the study of backward masking is concerned with the detection of the first field when followed in time by another luminous field. Unfortunately, there appears to have been no investigations of the apparent brightness of the first flash when followed by another luminous field. Rather, the study of backward masking has been restricted to the situation where increments in luminance are to be detected. It should be stressed that although the psychophysical functions obtained for either forward or backward masking are monotonic, the various physiological processes resulting in such effects may be more complex.

The present analysis will be restricted to the "psychophysical" definition of these effects and will not deal with physiological processes. As any single monotonic psychophysical function cannot account for the nature of the results obtained, the question arises as to whether such a complex function as was obtained in the present study may be constructed out of the interaction of two different monotonic functions of ISI. It is a well documented fact in both vision and hearing that a stimulus can act both "backward" and "forward" in time and influence the detection or brightness of another stimulus (Wallace, 1937; Craik, 1938, 1940; Crawford, 1947; Baker, 1949; Battersby and Wagman, 1959, 1964). The former effect has been called "backward masking" while the latter has been referred to as "forward masking" or "light adaptation." Each of these psychophysical effects have been shown to be a different monotonic function of the time between the two stimuli. It is possible, however, that the interaction between both of these psychophysical effects was operative in the present experiments and is, in part, responsible for the complex non-monotonic nature of the results.

Two general types of arrangement in which forward masking has been investigated have used the detection of an increment (Battersby and Wagman, 1959; 1964) and apparent brightness (Wallace, 1937, Craik, 1938, 1940) as the dependent variables.

In the increment situation an increment is added to an already ongoing luminance and the task of the subject is to detect the presence of the increment. As no clear relationship exists between the detection of increments and the comparison of the brightnesses of successively presented fields, no predictions to the present results can be made for the data obtained using the increment method. This argument also applies to backward masking data obtained by the increment method.

Other investigators of forward masking have used apparent brightness as the dependent variable (Wallace, 1937; Craik, 1940). These investigations indicate that the effect of adapting the eye to light is to lower the apparent brightness of a field which is subsequently presented. In these studies, the brightness of the fields was assessed by matching a comparison field in one eye to a test field in the other eye. They appear to offer a basis for comparison to the present set of results, insofar as the task of brightness assessment in the present study was similar to the previous investigations. These comparisons, however, cannot be pursued too far as predictions based on the above results lead to the construction of monotonic functions. Neither forward nor backward masking effects, in and of themselves, are sufficient to account for the present set of results.

It should be remembered that the subject was instructed to assess the brightness difference between the two fields and on the basis of his judgments a luminance difference threshold was obtained. It has already been indicated that the present results may arise from an interaction between forward and backward masking effects. As both backward and forward masking when psychophysically measured refer to the apparent brightness of the first and second flashes respectively, it is possible that the luminance difference threshold may be related in some way to aspects of the apparent brightnesses of the two fields. In order to best evaluate the relationship between aspects of the apparent brightness of the fields and the luminance difference threshold an empirical approach is necessary.

In order to evaluate the apparent brightness of a test field a comparison luminance presented to one eye may be adjusted to measure the apparent brightness of the test field presented to the other eye (Diamond, 1955). This method avoids the difficulties inherent in presenting both the measuring instrument and test field to the same eye (Heinemann, 1955). It is also distinguished from various types of scaling methods used to measure apparent brightness as the operations involved in both types of methods are very different.

In the present study a luminance difference threshold was determined between two successively presented flashes of light. The two flashes were separated bya variable dark interval (ISI) and the task of the subject was to make a brightness assessment of the two fields. It is possible, under these same experimental conditions, to make apparent brightness measurements of each of the two successive flashes as a function of the luminance of each flash and the ISI between the flashes. These measurements are possible only if the ISI separating the two flashes is long enough so as to enable the subject to see two discrete flashes of light. These latter measurements, however, werenot made in the present investigation and what follows below is the outcome of a hypothetical experiment in which both luminance difference and apparent brightness judgments are made by the same observer. The purpose of such an analysis will be to show how the relationship between apparent brightness and the luminance difference threshold can be assessed.

While the luminance difference threshold is obtainable by the same procedures as have been detailed in the present investigation, the method of measuring the apparent brightness of the flashes requires considerable explanation. In order to measure the luminance difference threshold the second of two successive flashes was set at a standard luminance value (700ml) and the luminance of the first flash was varied in small luminance steps around the value of the standard. The first flash was designated the variable and the second was called the standard.

When apparent brightness measurements are to be made the comparison field, given to the left eye, must be placed binocularly adjacent to the test field delivered to the right eye. If both the comparison and test fields are presented to homotopic retinal areas, fusion of the fields occurs and the measurements can not be made.

If the second (standard) flash is set at a fixed luminance value (e.g. 700ml), the apparent brightness of the first flash can be measured (by a binocular brightness match) for the various fixed luminances of the first flash used previously to obtain the luminance difference threshold. These apparent brightness measurements can be made for all ISI at which the luminance difference threshold is determined. In this way a family of apparent brightness curves for each luminance of the first flash in the presence of a second fixed luminance flash as a function of the ISI can be obtained. In the same manner, a family of apparent brightness curves of the second flash for different luminance values of the second flash in the presence of a fixed luminance of the first flash at different ISI may be determined.

Figure 13

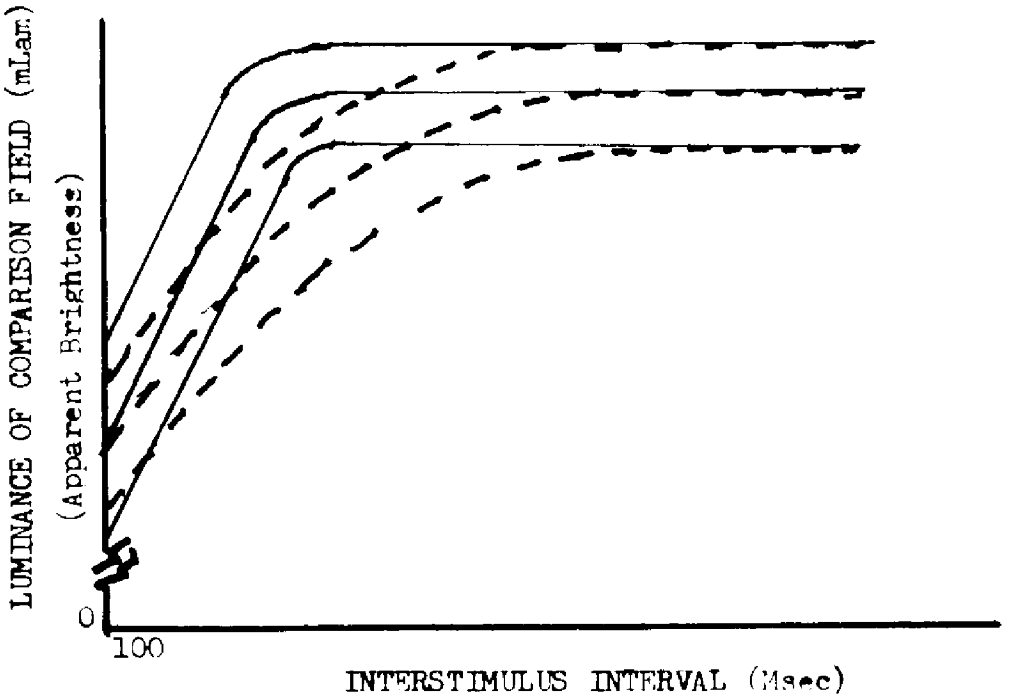
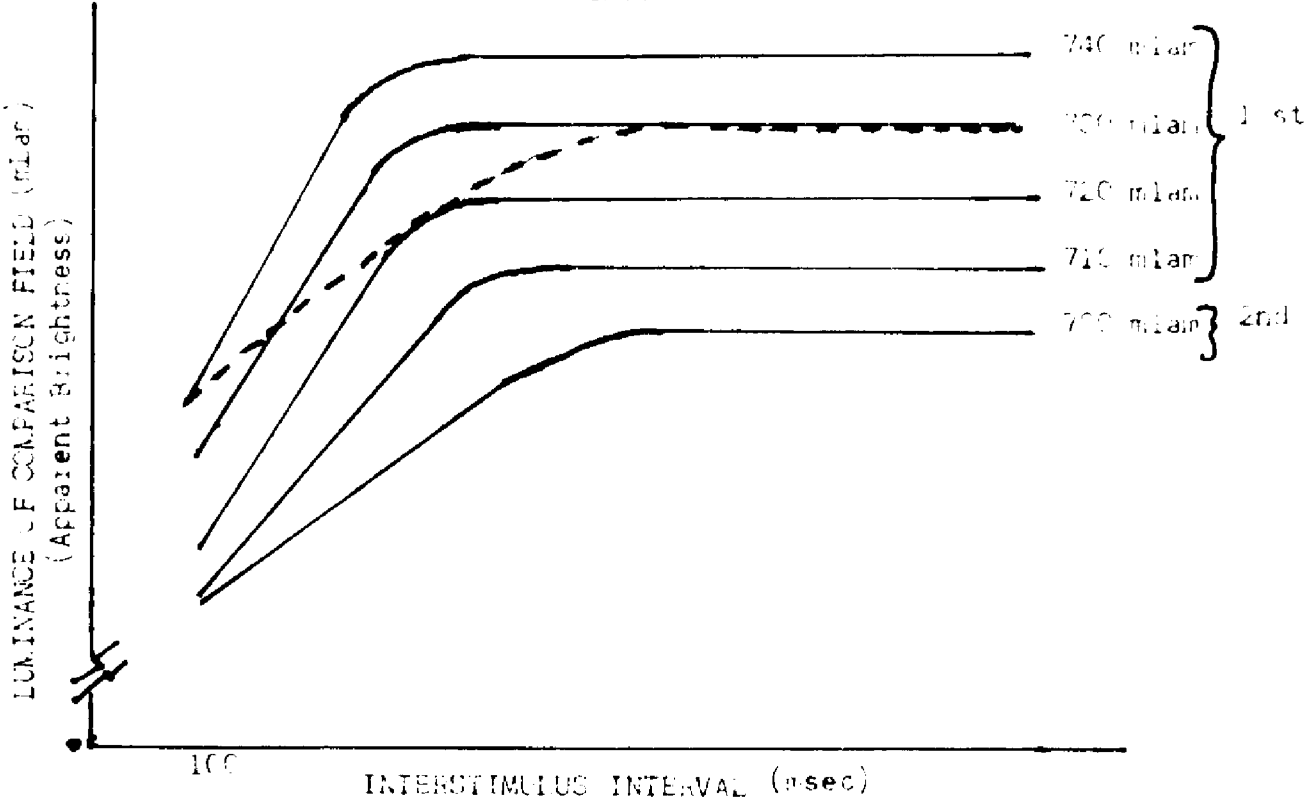


Figure 13 shows a hypothetical set of such functions. For the family of first flash apparent brightness curves the parameter on the curves is the luminance of the first flash while the in the presence of the second fixed luminance flash of 700ml. This family of curves is indicated by the solid lines. For the family of second flash apparent brightness curves the parameter on the curves is the luminance of the second flash while in the presence of a fixed luminance first flash. This family is indicated by the broken line curves. The ordinate is the luminance of the comparison field in millilamberts which is defined here as the apparent brightness of the test field under consideration. In order to simplify the presentation the present analysis will use a hypothetical family of apparent brightness curves for the first flash and only one apparent brightness curve for the second flash. The remaining members of the family of second flash apparent brightness curves will be introduced at a later point in the discussion.

Figure 14 presents the hypothetical arrangement under consideration.

Figure 14

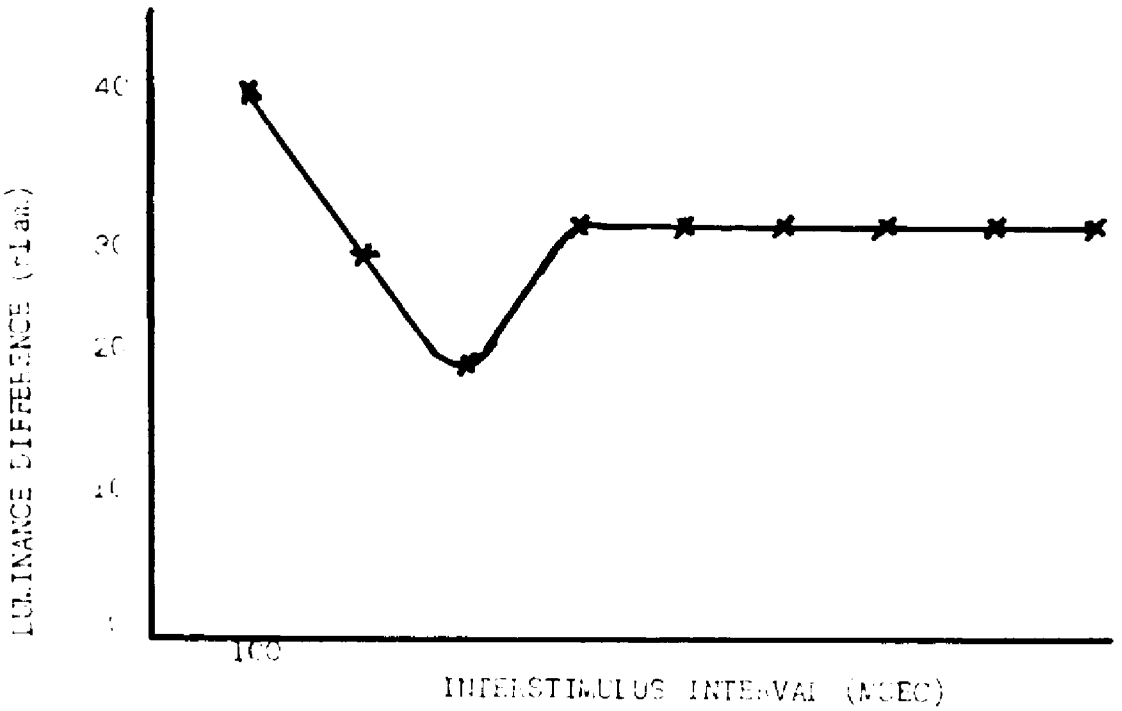


The spacing between each of the first flash apparent brightness curves at any given ISI appears to have implications for theoretical positions concerned with the relationship between apparent brightness and luminance. If it is assumed that a power law describes the relationship between apparent brightness and luminance, such a function could be fit to determine the spacing between each of the apparent brightness curves. In order to accomplish this, however, relevant information would be required concerning the relationship between the exponent of the power function and the ISI. The apparent brightness curves which are presented in Figure 14 would require that the exponent vary as a function of the ISI. Indeed, at large ISI where the curves are asymptotic, a constant exponent would be required, while at the shorter ISI a power function could not be applied unless it was known how the exponent varied with changes in ISI. At the present time this information is unknown. The spacing used between each of the apparent brightness curves is therefore, arbitrary and has been chosen to facilitate interpolation between the curves. It can equally well be assumed that the top and bottom apparent brightness curves set the limit of a range and that the intervening area represents a solid block of apparent brightness curves each being obtained for a different luminance value of the first flash.

One hypothesis which may be put forward is that a constant difference in apparent brightness (in mlam) between the two flashes is required for a difference to be detected for a particular luminance of the standard. It should be noted that this hypothesis is quite different from that advocated by Fechner, as here, the relevant variable determing apparent brightness is the ISI and not luminance since the luminances of both fields are held constant. If the further assumption that apparent brightness is directly related to neural effect is proposed, the hypothesis of a constant difference in apparent brightness is one which has previously been attributed to Crozier (Morgan, 1943). This hypothesis states that in order for a difference to be detected a constant difference in neural effect is required above or below the magnitude of the neural effect elicited by the standard intensity. It is not, however, the intent of the proposed analysis to test various hypotheses. Rather, the empirical nature of the relationship between apparent brightness and the luminance difference threshold is sought.

One possible outcome of such an experiment may be that a constant difference in apparent brightness between the two flashes is required for a difference to be detected. The luminance difference between the first and second flashes required to yield any apparent brightness difference between the fields can be obtained by cutting across the curves in Figure 14 in a particular way. That is, for any given ISI the difference in luminance between the second flash curve of apparent brightness and a constant difference in apparent brightness above this curve will intersect one of the family of first flash apparent brightness curves. Each of these apparent brightness curves has a given luminance value. The difference between the two luminances is the stimulus luminance difference required to yield a constant difference in apparent brightness between the flashes. This is illustrated in Figure 14. The height of the broken line curve represents a constant difference in apparent brightness above the apparent brightness curve for the second flash. The constant difference in apparent brightness is then indicated by the difference between the broken line curve and the solid curve of apparent brightness for the second flash. The luminance difference required to yield this constant apparent brightness difference is given, at each ISI, by the intersection of the broken line curve with each of the first flash apparent brightness curves. Specifically, the luminance difference is given by that luminance of the first flash which yields the apparent brightness value obtained at the intersection minus the luminance of the second flash (the latter always being a fixed value). The resulting values yield a curve of the luminance difference as a function of the ISI similar in shape to the one obtained in the present study (see Figures 3 and 15).

<u>Figure 15</u>



It may, however, be inappropriate to assume that a constant difference in apparent brightness is required for a difference to be detected, and the question may quite sensibly be reversed. That is, the luminance difference between the flashes required to yield a detectable apparent brightness difference is given by the difference between the luminance of the second flash and the luminance of the first flash at any given ISI. Therefore, if luminance difference judgments are made and if the apparent brightness distributions for the flashes are obtained it is possible to determine whether a constant difference or any other feature of apparent brightness is related to the luminance difference threshold. In order to make this evaluation the families of apparent brightness curves for both the first and second flashes as well as the luminance difference judgments at each ISI are required.

Figure 13 illustrates both families of apparent brightness curves. At any given ISI the luminance difference judgment defines the apparent brightness curve of the second (standard) flash above which the luminance difference between the two flashes is to be added. For example, let it be assumed that when the first flash is equal to 730ml and the second equal to 700ml a luminance difference is detected at an ISI of 105 msec. The particular apparent brightness curve of the second flash to which the luminance difference is to be added (30 ml) is the curve obtained when the first flash is fixed at 730 ml and the second at 700 ml. At an ISI equal to 105 msec 30 ml is added to this particular apparent brightness curve. If this procedure is repeated for all the detectable luminance differences obtained at each ISI it is possible to determine the relationship between the luminance difference threshold and apparent brightness empirically. By using this method it can be determined whether a constant difference in apparent brightness is required for detection or whether apparent brightness is dependent in some way upon the ISI. In order to properly evaluate the results of the present study this information is required.

2. Experiment II - Spatial Separation

The study most directly comparable to Experiment II is one by Le Grand (1933) in which he investigated the precision with which equality judgments were made in visual photometry. He investigated four different methods of obtaining photometric measurements, but we shall be concerned here with only the one having direct bearing on the present study, namely, semi-circular fields having lines of separation of variable width between them.

The visual angle of the separations between these semi-circles varied from 0' to 30'. Therefore, Le Grand's study was mainly concerned with the effects of these areas and separations in the peripheral retina using less than one log unit of monochromatic radiation. The current study was restricted to monocular foveal vision.

The function obtained by Le Grand is most directly comparable to the 70 mlam function obtained in the present set of results although the differences in stimulation circumstances are obvious. In the present study white light from a tungsten filament source was used.

In spite of differences in method of measurement, stimulation techniques, nature of the source of radiant energy, retinal location and observer individual differences, the similarity of the obtained functions is marked.

Le Grand's results show that the threshold is doubled if there is a line of separation with a width of 3' and it is quadrupled if the line of separation is 30' for this 10° field on a dark background. Above 1' and up to 30' for this 10° field sensitivity remains almost constant. Therefore, above 1'-3' the line of separation hardly influences sensitivity. For a separation of less than 1' sensitivity is found to be greatest. Le Grand also found that the smaller the field size used, the greater is the sensitivity.

While the general trend of Le Grand's function is very similar to that obtained in the current study, there were some obvious differences between the two sets of results. These differences probably arise from the differences in the two methods and the other differences already indicated above.

The rates of increase of threshold with increases in separation were found to be much greater in the present study at luminances comparable to Le Grand's. The latter shows that the threshold is doubled with a line of separation of 3'; the present study shows a change of seven times the lowest threshold value. An explanation for this may lie in the fact that sensitivity improves with decreasing field size, as shown by Le Grand. The field size used in the current study was at most, 2° while Le Grand's was 10°. In addition, as already pointed out, our fields were foveal while Le Grand's were peripheral. The difference between foveal and peripheral luminance difference sensitivity may also be reflected in the rate of threshold rise with separation. Since a greater degree of convergence of receptor elements onto a single neuron has been found in the peripheral retina, it is possible that a greater degree of spatial interaction occurred with peripheral stimuli which served to enhance luminance difference sensitivity in Le Grand's study. However, it is difficult to make any comparisons between the two sets of results because of the differences in stimulating conditions. It may be, therefore, worthwhile to investigate the effect of retinal location on luminance difference sensitivity when the test fields are spatially separated from one another in order to clarify this issue. The general finding of a minimal separation beyond which threshold for differences hardly changes is common to both sets of results.

Three other studies which appear directly relevant to the study undertaken here are those of Konig and Brodhun (1888, after Hecht, 1934), Bartlett (1942), and Cornsweet and Pinsker (1965). Konig and Brodhun presented a bipartite field, the top half being fixed, while the bottom varied in luminance. In their case the fields were separated by a small angular subtense. Their well known results are presented in Figure 13 for purpose of comparison with the other studies.

Bartlett (1942) presented a bipartite field, the halves being separated by a septum having an angular subtense of 13'. The size of each field was 0.5°. Bartlett's results are given in a form comparable to, but not identical with, the present study or with Konig and Brodhun, or Cornsweet and Pinsker. Bartlett uses the ratio of the luminance difference between the fields to the mean luminance of the fields (PSE) as the Weber ratio. Konig and Brodhun use the difference between the fields divided by the luminance of the standard rather than the mean luminance.

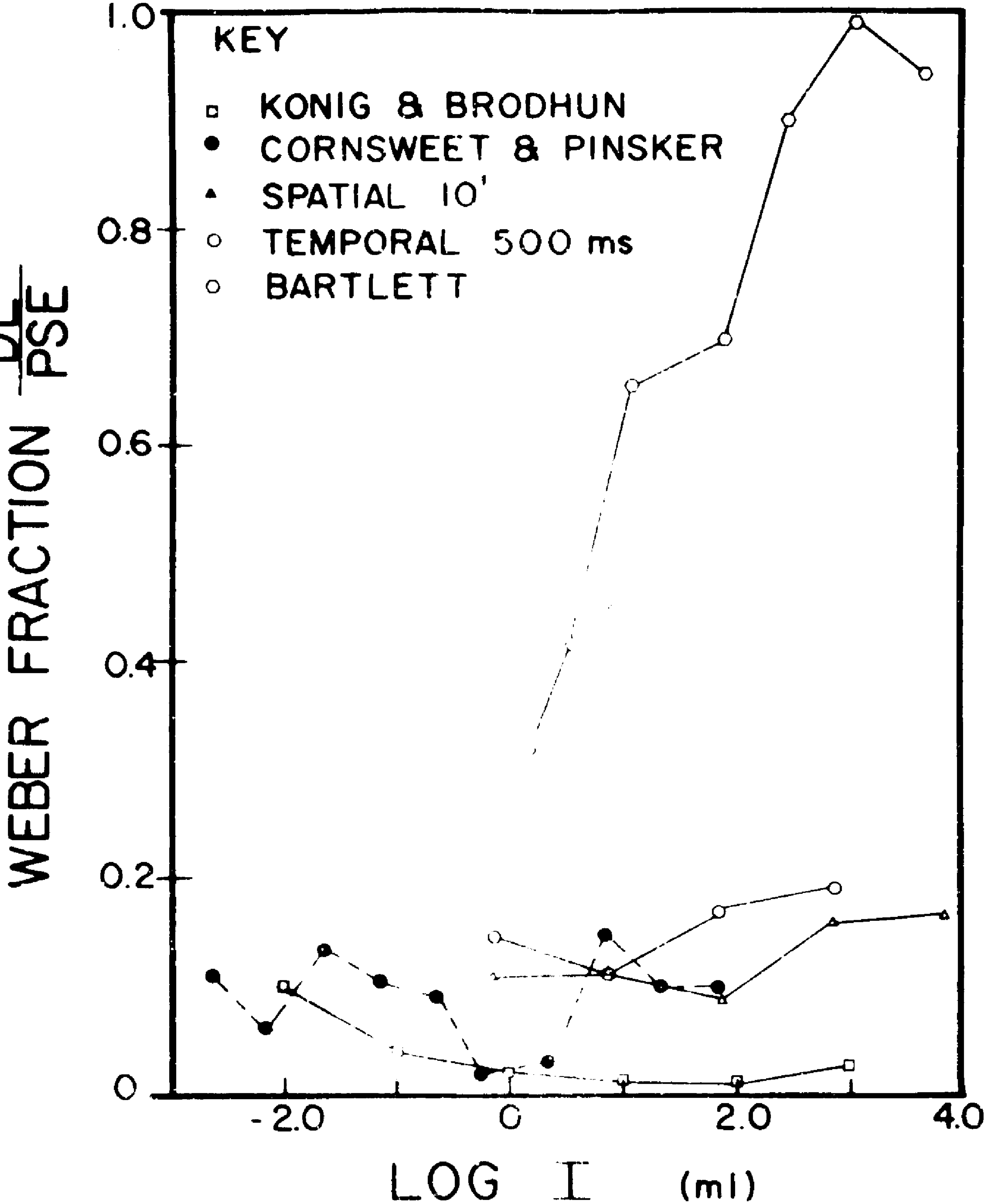
Cornsweet and Pinsker (1965) used a wide spatial separation between two fields, one being I and the other, I + I. They used three methods of stimulus presentation to obtain the Weber fraction and in this case, the Weber fraction corresponded to the more conventional I/I where I was equal to the standard. It should be pointed out that a correction procedure was used and the Ss were "shaped" to give a "luminance" judgment rather than a "brightness" judgment.

All four sets of results are plotted in Figure 13 and have been scaled for suitable shape and luminance range comparison. All values have been converted into millilamberts and in some cases were read from the published graphs.

Cornsweet and Pinsker present data that demonstrate Weber's Law over a five log unit range when two simultaneously presented fields differing in luminance are separated by 1°10' and presented to an "inactive" retina. When presented to an "active" retina upon which a field was briefly incremented in luminance, a radically different function which does not obey Weber's Law was obtained. The authors put forward a theory to account for their results but as the theory does not make any predictions concerning the effect of varying separation, it could not be evaluated by the present study.

The most outstanding feature of the representation in Figure 13 is that Bartlett's results depart from the others shown. As one of the major differences between the Bartlett study and the Cornsweet and Pinsker study was the size of the angular separation between the

<u>Figure 16.</u> Comparison of the Weber fraction as a function of luminance for five different studies. Data from Konig and Brodhun (1888) and Cornsweet and Pinsker (1965) have been extrapolated from published functions.



KEY
□ KONIG & BRODHUN
● CORNSWEET & PINSKER
▲ SPATIAL 10'
○ TEMPORAL 500 ms
○ BARTLETT
1.0
0.8
0.6
0.4
0.2
0
WEBER FRACTION $\frac{DL}{PSE}$
-2.0
0
2.0
4.0
LOG I (ml)

fields, it was though that this variable might account for the discrepancy between the two curves. Bartlett used a separation equal to 13' and Cornsweet and Pinsker's was 1°10'. In Experiment II, these two separations are both shown to be at asymptote insofar as the difference threshold is concerned. Hence, the nature of the differences in the functions cannot be attributed to this variable.

Preliminary work currently in progress suggests that the differences may be due to the criterion used by the subject. When subject SS (author) was instructed to adopt a "strict" rather than "loose" criterion, the results tended to approximate those of Bartlett.

The data for Cornsweet and Pinsker's function were read from their graphs as no tabular values are given. These data exhibit some variability and when plotted in the coordinate system of Figure 13 are basically horizontal. However, if one examines the data for Konig and Brodhun, one can equally well assume a fairly horizontal trend to fit their data. If plotted in the same coordinate system as Konig and Brodhun, the Cornsweet and Pinsker results do not appear horizontal, but, within the limits of variability, follow the Konig and Brodhun results. It should also be pointed out that the results on subject SS for the 10' separation also follow Konig and Brodhun for the luminance range used. For this range of luminances, Weber's Law can be said to hold within 1/10th of a log unit for both the temporal and spatial separations used. If Konig and Brodhun's classical results are plotted in any coordinate system with Cornsweet and Pinsker's, the results are not very distinguishable from each other as to the general shape of the functions.

The results of Experiment II appear to be explicable on the basis of what is currently known about the behavior of apparent brightness in the simultaneous contrast situation (Diamond, 1953; Fry and Alpern, 1953; Leibowitz, Mote, and Thurlow, 1953; Heinemann, 1955). The current study presented two adjacent fields simultaneously. An assessment of a brightness difference between the fields was called for. In the simultaneous contrast studies an overall brightness assessment of a test field in the presence of an inducing field is called for when both the inducing and test fields are simultaneously presented in time and spatially adjacent. The obvious similarity between the two experimental conditions would lead one to conclude that it is highly probable that the same set of mechanisms are operative in both the DL and apparent brightness measurements.

With two adjacent fields, the one that has the higher luminance will depress the apparent brightness of its neighbor (Diamond, 1953; 1960; Heinemann, 1955), thus rendering the luminance difference between the fields more perceptible. With increasing separation this effect decreases (Leibowitz, Mote, and Thurlow, 1953). Thus, for a fixed luminance difference between the two fields, the two fields will differ more in apparent brightness when close together than when farther apart.

If a constant difference in apparent brightness were needed for a difference to be detected, the luminance difference required to yield this constant apparent brightness difference would increase as the two fields were separated spatially. Hence, the closer the juxtaposition of the two fields, the smaller the expected DL.

That such an explanation may be too simple to account for the results of Experiment II is suggested by the literature dealing with effects near border or contour processes. It has been reported that the fields appear graded in brightness when the simultaneous contrast phenomena are investigated (Diamond, 1953). This suggests the presence of marginal contrast effects. When two fields of different luminances are placed adjacent to one another, a contour is formed at their place of adjacency such that on the side with the greater luminance a bright line is seen, while on the side with the dimmer luminance, a dark band is seen. These light and dark bands which appear to the perceiver are not given in the physical luminance distribution, but emerge when the apparent brightness distribution across the fields is measured (Lowry and De Palma, 1961). Effects analagous to Mach bands have been shown to occur in the eye of limulus. Ratliff (1965) has been able to account for these in terms of purely inhibitory interactions.

Heinemann (unpublished communication, 1966) has measured the apparent brightness distribution across a bipartite field, each side differing in luminance. This arrangement under which the Mach bands are measured is the same as that under which the apparent brightness measurements previously discussed (e.g., Diamond, 1953) are made. When the distribution of apparent brightness is evaluated, it is found that in that part of the field where the two regions of different luminances are closest to one another, the largest difference in apparent brightness is obtained. Heinemann has shown that, in some instances, there is no difference in apparent brightness between the centers of two adjacent fields which differ in luminance, and that the only difference in apparent brightness between the fields occurs at the contour. It is likely, then, that some aspect of the Mach bands acts as a signal for the DL, as this is the only way in which the two fields differ in brightness to the observer. Perhaps the peak-to-trough magnitude of the Mach band is critical for a luminance difference threshold, as relevant brightness difference information is contained therein. (The peak-to-trough magnitude of the Mach band is defined as the difference in apparent brightness between the bright band and the dim band found at the emergent contour in the apparent brightness distribution.)

Unfortunately, however, Mach bands have not yet been studied in enough detail. They have been investigated under situations where a linear gradient connects the two fields (Aulhorn and Harms, 1956), and under conditions where two different luminances are placed adjacent to one another without a physical septum separating the fields. The present results can only have implications for the condition where a physical septum is present between the fields and this condition has not yet been investigated insofar as the Mach band distribution is concerned.

Another line of evidence which suggests that predictions based on an overall brightness assessment of the two fields may be wrong comes from a study performed by Lamar, Hecht, Schaler, and Hendley (1947). These authors have pointed out that it is not so much the total area of the test field that mattered in the increment method of obtaining the luminance different threshold, but that the important factor was the "useful area" or events near the edges of the test field. They state that "the significant sensory events take place across a boundary...not over an area" (1947, pg. 542) and also that, "the concept of useful flux indicates that the critical sensory events in brightness discrimination take place in the narrow ribbon around the perimeter of the target...This ribbon is between 1 to 2 minutes wide." This study would tend to lend support to a contour mechanism underlying the luminance discrimination.

Hake and Averbach (1956) have shown that a luminance gradient connecting the two fields improves the difference threshold when compared to a line of separation between the fields. But, even when a dark line of separation is placed between two illuminated fields, stray light from surrounding areas falls on the line of separation and the amount of stray light falling on the septum differs at various places on the septum, dependent on the distance from the illuminated regions. This would lead one to suspect that a non-linear gradient of luminance would be formed between the fields and what effect this has on the present results cannot be evaluated as there is no information bearing on this question currently available.

Summary

Two experiments were performed using the brightness difference threshold as the dependent variable.

In Experiment I, two 1° fields, differing only in luminance, were presented for 10 msec by a Maxwellian viewing system, to the same foveal area of the retina. The subject's task was to report which one appeared brighter. All fields were superimposed on a fixed adapting luminance of .0076 mlam. The principal variables studied were the length of the dark interval separating the flashes, and the luminance at which the measurements were made. The dark interval was measured from cessation of flash one to onset of flash two, and the intervals were 95, 105, 115, 120, 130, 150, 180, 250 and 500 msec. The luminance range covered from 0.7 to 700 mlam.

In Experiment II, two adjustable rectangular fields were presented simultaneously to the subject's right eye for 10 msec. The task of the subject was to indicate which side appeared brighter. The principal variables studied were the width of the spatial separation between the two 0.5° fields, and the luminance value of the standard. The separations varied from 30" to 30' and the luminance range covered from 0.7 to 7000 mlam.

In both experiments a difference threshold was measured by the conventional Method of Limits.

The results of Experiment I indicated that the DL is a complex non-monotonic function of the inter-stimulus interval (ISI), the curve having atleast two, and possibly three changes of direction. With in-

creasing ISI the DL decreased rapidly to a minimum in the neighborhood of 130-180 msec and subsequently exhibited a rise at 250 msec ISI. Beyond 250 msec ISI the function gradually descended to a low value at an ISI of 500 msec.

In Experiment II the DL was found to be least at the smallest separation of 30", and increased until at about 3' to 7' separation between the fields the DL remained approximately constant with further separations between the fields. At 7' the DL was found to be between five to ten times higher than at 30", depending upon the luminance level considered. The same trend was found for all luminances.

In Experiment I, for all ISI values used, the Weber fraction, DL/PSE, was the same value to within 1/10 of a log unit for each of the luminance values of the standard. Here, Weber's Law held over the luminance range investigated. This finding is in agreement with the results found by many investigators.

In Experiment II, for the four smallest separations used the function relating the Weber fraction to luminance was not a horizontal line but exhibited a decrease and subsequent increase at high luminances. With larger separations there was a progressive flattening of the function.

Comparison of the largest temporal with the largest spatial separation over a four to five log unit luminance range of the standard revealed an essentially horizontal function.

It was suggested that the complex, non-monotonic function obtained for the DL as a function of ISI cannot be accounted for on the basis of either light adaptation or backward masking alone, but that the interaction of these two psychophysical effects might possibly yield such results. Further study of this matter is indicated.

In the second study it was suggested that the rise in DL as a function of spatial separation might be accounted for on the basis of changes in the apparent brightness of the fields with increasing separation between them. However, if one considers that Mach bands occur at the place where the two half fields meet, a process such as that predicted by changes in the apparent brightness of the fields with separation would be too simple an explanation.

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Autobiographical Statement

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