National Library of Canada
Bibliothèque nationale du Canada

CANADIAN THESES ON MICROFICHE

THÈSES CANADIENNES SUR MICROFICHE

NAME OF AUTHOR/*NOM DE L'AUTEUR* LUDWIG SEITHER

TITLE OF THESIS/*TITRE DE LA THÈSE* TEMPORAL RESPONSE CHARACTERISTICS OF THE VISUAL SYSTEM: TWO-PULSE DIFFERENCE THRESHOLDS AND TWO-PULSE BRIGHTNESS

UNIVERSITY/*UNIVERSITÉ* UNIVERSITY OF ALBERTA

DEGREE FOR WHICH THESIS WAS PRESENTED/ *GRADE POUR LEQUEL CETTE THÈSE FUT PRÉSENTÉE* MASTER OF SCIENCE

YEAR THIS DEGREE CONFERRED/*ANNÉE D'OBTENTION DE CE GRADE* 1975

NAME OF SUPERVISOR/*NOM DU DIRECTEUR DE THÈSE* DR. THOMAS M. NELSON

Permission is hereby granted to the NATIONAL LIBRARY OF CANADA to microfilm this thesis and to lend or sell copies of the film.

The author reserves other publication rights, and neither the thesis nor extensive extracts from it may be printed or otherwise reproduced without the author's written permission.

L'autorisation est, par la présente, accordée à la BIBLIOTHÈQUE NATIONALE DU CANADA de microfilmer cette thèse et de prêter ou de vendre des exemplaires du film.

L'auteur se réserve les autres droits de publication; ni la thèse ni de longs extraits de celle-ci ne doivent être imprimés ou autrement reproduits sans l'autorisation écrite de l'auteur.

DATED/*DATÉ* Nov. 3 1975 SIGNED/*SIGNÉ* L. Seither

PERMANENT ADDRESS/*RÉSIDENCE FIXE* 8520 - Jasper Ave.
Edmonton.

THE UNIVERSITY OF ALBERTA

TEMPORAL RESPONSE CHARACTERISTICS OF THE VISUAL SYSTEM: TWO-PULSE DIFFERENCE THRESHOLDS AND TWO-PULSE BRIGHTNESS

by

LUDWIG SEITHER ©

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE

DEPARTMENT OF PSYCHOLOGY

EDMONTON, ALBERTA

FALL, 1975

UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES

The undersigned certify that they have read, and recommended to the Faculty of Graduate Studies for acceptance, a thesis entitled "Temporal response characteristics of the visual system: Two - pulse difference thresholds and two-pulse brightness ", submitted by Ludwig Seither in partial fulfillment of the requirements for the degree of Master of Science.

Charles G. Morgan

Charles M. Bourassa

Thomas Nelson

E C Lechelt

Date: 30 Sept 1974

ABSTRACT

This study presents a number of findings on the visual discrimination of two-pulse interval differences and on the brightness of brief stimuli at different levels of illuminance.

It was shown that the temporal locus of optimal interval difference discrimination at pulse intervals between 3 and 140 msc shifts towards shorter intervals when the illuminance of the stimulus increases with increasing stimulus size and that such shifts are absent when illuminance is kept at constant energy above threshold with increasing stimulus size. The discrimination functions relating pulse interval difference thresholds to pulse interval were found to be non-nomotone for all stimulus sizes and illuminances investigated. Thresholds showed secondary fluctations at medium pulse intervals and evidence was presented which suggests that these secondary fluctuations in thresholds reflect associated changes in the apparent brightness of the stimulus.

The brightness of a two-pulse stimulus was found to be strongly dependent on its pulse interval. Brightness was shown to decrease with increasing pulse interval, the rate of decrease being effected by stimulus illuminance. Large differences in the brightness of a single pulse and a double

pulse of brief interval were observed at medium illuminances. Increasing stimulus illuminance from medium to high levels attenuated two-pulse brightness at medium pulse intervals relative to single pulse brightness.

The implications of brightness attenuation at medium pulse intervals and of shifts in optimal interval difference discrimination at high illuminances for a model of temporal discrimination were discussed and modifications of the model suggested. Brightness attenuation at medium pulse intervals was interpreted in terms of an inhibitory process operating maximally at latencies of 60 msc.

Additional evidence was presented which suggested that the inhibitory process may be associated with gain control mechanisms. It was shown that the dark time-constant of the visual system, as estimated by the two-pulse fusion threshold, is systematically and lawfully related to stimulus luminance. The implication of assuming feedback delays in the gain control mechanism were discussed and it was shown that when the brightness responses to very brief stimuli are measured brightness is non-linearly related to stimulus luminance. Further evidence was presented which showed brightness to approximate a linear function of luminance if the stimulus has a duration which corresponds to the visual system's time scale. Large differences in the brightness of single-pulse and double-pulse stimuli of brief intervals were, consequently, interpreted in terms of a relative lack of effective gain control when the brightness response to very brief stimuli is measured.

Implications for temporal discrimination of assuming a gain control mechanism were discussed and it was suggested that secondary fluctuations in interval difference thresholds are a consequence of the interaction of feedback elements with different delay constants and that shifts in optimal interval discrimination are a manifestation of changes in the time constant of the visual system.

ACKNOWLEDGEMENTS

This thesis would not have been possible without the cooperation and assistance of a great number of people. First of all, I would like to thank Dr. Thomas Nelson and Dr. Thomy Nilsson for providing the opportunity to do this research and for the patience in waiting for its results.

Special thanks is due to Dr. Nilsson for introducing me to the topic and technique of vision research and for the many hours of instructions on the optical and electronic aspects of instrumentation. Whatever I know in this domain is due to his guidance and patience. I would also like to thank him for the hours of discussion on the temporal dispersion model and for the freedom he granted me to explore its various implications.

Charles Richmond built and installed the electronic interface for the on-line operation of the glow modulator and his technical expertise made a high degree of stimulus control possible. I would also like to express my appreciation for his willingness to discuss various aspects of gain control mechanisms and time-series analysis.

Thanks are, finally, due to the observers in this experiment who performed an essentially difficult and demanding task. I would like to especially thank Terry Gee, Heather Burke and Frank Testin who, in addition to their observer duties volunteered to assume the role of experimenter.

TABLE OF CONTENTS

PAGE

LIST OF TABLES

LIST OF FIGURES

FIGURE PAGE

LIST OF APPENDICES

INTRODUCTION

The research to be reported in this paper has as its focus the investigation of the dynamics of the visual system. It is well known that a brief visual stimulus, such as a pulse of light, produces a sensory effect which outlasts the duration of the stimulus. This is indicated, for example, by the finding (Efron, 1970 a,b) that visual stimuli of less than 120 - 130 msc duration produce perceptions which have a duration equal to that produced by a stimulus of 120 - 130 msc duration. This is to say, in other words, that perceptions have a minimum duration. The minimum duration of a visual perception, or its persistence, may be assumed to reflect the differential latencies and conduction velocities of fibres in the optic tract (Bartley & Wilkinson, 1953). Other researchers, operating on a different level of analysis (for example Roufs, 1973; Sperling & Sondhi, 1968), assume visual persistence to mainly reflect the transfer characteristics of the retinal mechanism. In any case, the fact that the effect of a stimulus far outlasts its duration suggests that any interaction between responses in the visual system may be fruitfully investigated by observing the sensory effects which are produced by elementary stimuli, such as brief pulses of light, which follow each other at short intervals.

Background

The temporal dispersion of the sensory effect produced by a brief visual stimulus presumably accounts for the fact that the resolution of brief, successive visual stimuli into temporally discrete sensory effects has a lower limit or threshold. One operational measure of visual temporal resolution is provided by the absolute threshold, that is that interval between two pulses of light at which an observer can reliably distinguish between the effects produced by a single pulse and those produced by a double pulse. Absolute thresholds were investigated as early as 1915 by Dunlap who found the threshold for foveal targets to be less than 100 msc and to be little affected by the luninance of the target. An absence of a luminance effect has similarly been reported by Kietzman (1967), Kietzman & Sutton (1968), and Nilsson (1969). Other researchers, however, have consistently reported a decrease in absolute thresholds with increases in luminance (Lewis & Mertens, 1971; Mertens & Lewis, 1972). Absolute thresholds were found to decrease in negatively accelerated fashion with increases in luminance (Lewis, 1967), the rate of decrease being smaller for the larger (20'-30') foveal targets (Lewis, 1968).

Mahneke (1958) investigated two-flash resolution by asking the observer to report the presence or absence of temporal discontinuity (flicker) in a two-pulse stimulus under conditions in which both inter-pulse interval and pulse duration was varied. He found a systematic decrease in threshold with increasing pulse durations and consequently concluded that the critical parameter determining temporal resolution was the total energy of the two-pulse package. Further investigations of this particular hypothesis (Kietzman, 1967) revealed that increasing energy by increasing luminance results in only small decreases in resolution thresholds, while increasing energy by increasing pulse duration decreases thresholds substantially.

The latter finding, consequently, suggested that the critical parameter of temporal resolution was the duration of the total stimulus package. Consistent with this particular hypothesis is the finding by Kietzman & Sutton (1968) that the rate of increase in the accuracy of discriminating between single pulse and double pulse stimuli of equal energy as inter-pulse interval is increased is comparable to the improvement in the accuracy of discriminating between equal energy single pulse stimuli as the duration of the test stimulus is increased. In both tasks the duration difference for reliable discrimination was reported to be around 20 msc. Furthermore, elimination of the duration differences by [illegible]ting the duration of a single pulse comparison stimulus equal to the total duration of the two-pulse package results in a substantial reduction in the accuracy of discrimination. On the other hand, discrimination in the latter instance was reported to remain sufficiently high to suggest that discrimination did not exclusively depend on the perception of duration.

The finding that duration is an effective cue in discriminating between equal energy single pulse and double pulse stimuli points to a difficulty when measuring temporal resolution under forced choice procedures. In such a task the observer is permitted the use of any or all cues aiding discrimination. It should be remembered that a double-pulse with an inter-pulse interval of less than ca. 50 msc is generally perceived as a single flash. Cue reports by observers (Kiętzman & Sutton, 1968) indicate that discrimination within this range depends on a multiplicity of perceptual cues such as apparent brightness, rate of onset, duration and flicker, and that different cues are maximally effective within different pulse interval ranges. In a forced choice procedure, therefore, absolute thresholds will not necessarily provide a measure of the limits of temporal resolution since discrimination may not be dependent on the perception of temporal discontinuity. It will be argued, at some later point in this paper, that temporal resolution should be narrowly defined in terms of the presence or absence of a specific perceptual cue, such as flicker, using a yes/no procedure and that under these conditions resolution thresholds can be shown to be systematically related to stimulus luminance.

As a consequence of the finding that the effectiveness of a given perceptual cue varies with changes in interpulse interval, other investigators of visual dynamics employed two-pulse interval discrimination tasks. In this type of experiment the dependent variable of interest is the magnitude of the just noticable pulse interval increment (or decrement) for a given (standard) pulse interval. Lewis & Mertens (1971) report that for comparison pulse intervals ranging from 2 to 21 msc the interval increment necessary for reliable discrimination increases with increasing (standard) pulse interval. Nilsson (1969) reports, on the other hand, that interval increment and interval decrement thresholds decrease as pulse interval is increased from 3 to 30 msc, and that thresholds show an increase as pulse intervals are increased from 30 to 90 msc. To the extent that the accuracy of discriminating between two-pulse stimuli of different interval durations depends on the utilization of that perceptual cue which is maximally effective in detecting a difference on a given cue dimension, the inconsistency in the experimental findings may be due to differences in the efficiency of cue utilization between groups of observers. The study to be reported below consists of a re-investigation of interval difference thresholds using modified stimulus presentation procedures designed to maximize cue utilization by the observer. Furthermore, in order to broaden the data base the effect of manipulating stimulus conditions beyond those reported in the literature was investigated.

Present Study

The theoretical base of the present study is the temporal dispersion model of interval difference discrimination which was proposed by Nilsson (1971) to account for his earlier findings which showed interval difference thresholds to be a non-monotone function of pulse interval. In its most elementary form, this model assumes that the cortical response to a brief pulse of light is temporally dispersed due to differences in the conduction velocities of fibres (channels) in the optic tract. For purpose of exposition the shape or the temporal dispersion may be assumed to resemble a normal distribution. If a second pulse follows the first pulse with a sufficiently brief delay, 'slow' channels still responding to the first pulse may be concurrently active with 'fast' channels already responding to the second pulse. It is then assumed that to the extent to which the response distributions to the two pulses 'overlap' a single flash of enhanced brightness will be perceived, and that to the extent the two distributions do not 'overlap' two flashes will be perceived. The model, furthermore, proposes that the perception of a pulse interval difference depends on the occurrence of a fixed change in the number of overlapping channels as pulse interval is increased or decreased. In as much as brightness is an effective discriminatory cue, the last assumption suggests that interval difference threshholds reflect threshold changes in apparent brightness. It can be easily verified that, given a normal distribution of temporal dispersion, there should exist a pulse interval at which a minimum increase or decrease in pulse interval will produce a change in the amount of 'overlap' sufficiently large to result in a threshold change of apparent brightness. Given that brightness is an effective cue, minimum interval difference thresholds should be obtained in the region of those pulse intervals where apparent brightness changes most rapidly with changes in pulse interval. Nilsson (1969) reports a minimum interval difference threshold at pulse intervals around 30 msc.

It may be surmised from the foregoing that the duration of that pulse interval which results in a minimum interval difference threshold depends on the manner in which responses to a stimulus are temporally dispersed. Figure (1) graphically illustrates the effect of assuming response distributions skewed towards short as opposed to long response latencies. As can be seen, this aspect of the response distribution has no effect on the duration of the pulse interval at which the minimum interval difference threshold is expected to occur. Figure (2) shows a similar didactic representation of hypothetical response distributions. It can be seen that the magnitude of temporal dispersion of responses (i.e. its standard deviation) is directly related to the duration of the pulse interval at which optimal interval discrimination is expected to occur.

The theoretical question to be posed, then, is under which stimulus conditions one would expect the discrimination function minima to occur at longer as opposed to shorter pulse intervals. If it is assumed that the temporal dispersion of cortical response results predominantly from differences in the conduction velocities between fibres, that is to say from differences in the speed at which neural signals are transmitted within different channels, it can be shown that the location of the discrimination function minimum should be sensitive to the intensity and the spatial size of the stimulus.

It is reasonably well established that there is a direct relationship between fibre diameter and conduction velocity for the nervous system in general (Katz, 1966), and for the visual system in particular (Bishop & Clare, 1955). In addition, it is known that the distribution of ganglion cell size across the retina is non-random, that is to say the proportion of large cells for a given unit area increases towards the periphery (Stone, 1965), and that the area centralis projects the smallest diameter fibres (Stone & Hollander, 1971) and smallest conduction velocities (Stone & Freeman, 1971; Stone & Hoffman, 1971). Similar correlations have been demonstrated with respect to receptive field size: the receptive field centers of ganglion cells are significantly smaller in the area centralis than in the periphery (Stone & Fabian, 1966; Rodieck & Stone, 1965), and large and small receptive fields of optic nerve fibres (Fukada, 1971) or lateral geniculate neurons (Hoffman, 1973; Stone & Hoffman, 1971) are associated with large and small conduction velocities respectively. The response thresholds of optic nerve fibres to electrical stimulation have been shown to be inversely related to conduction velocity (Bishop & Clare, 1955). To the extent that there is spatial and/or temporal summation of energy within receptive fields (Rodieck & Stone, 1965; Enroth-Cugell & Robson, 1966), we may assume that the response thresholds of fibres to natural stimulation are related to receptive field size in a similar manner, that is to say smaller diameter fibres will have higher thresholds.

To the extent, then, that small and large diameter ganglion cells project small and large diameter fibres and to the extent that response threshold is inversely related to fibre diameter, an increase in the retinal size of the stimulus, with intensity being kept constant, should result in a change in the proportion of active fast to slow channels. More precisely, due to the lower thresholds of large fibres and due to the distribution of ganglion cell size across retinal space the ratio of active fast to slow channels should increase for a given increment in the retinal size of the stimulus. Consequently, the temporal dispersion of cortical response as measured, for example, by its standard deviation should increase. A similar increase in temporal dispersion should occur when the intensity of the stimulus is increased, retinal size being kept constant. Intensity effects on temporal dispersion may, however, be postulated only for low levels of illumination. Figure (2) graphically illustrates the effects of an increase in temporal dispersion of cortical response on pulse interval discrimination. It can be seen that the discrimination function minimum should shift towards longer inter-pulse intervals as temporal dispersion increases.

In order to investigate these implications of the temporal dispersion model the present study investigated the effect of increasing stimulus size on the interval difference threshold functions under two conditions: (1) stimulus size was increased with luminance kept at a constant level, and (2) stimulus size was increased with illuminance kept at constant energy above threshold. It was predicted that increases in illuminance when stimulus size is increased under constant luminance would result in relatively large shifts of the discrimination function minima towards longer pulse intervals, while increases in stimulus size under constant illuminance above threshold would result in relatively small shifts in the minima. The two conditions will be from here on referred to as the "constant luminance" and "constant illuminance" conditions respectively.[1]

Outline

The study to be reported here had as its main focus the investigation of the effects of changing stimulus size on pulse interval difference thresholds. In order to permit a more detailed interpretation of the findings on the effects of stimulus size, a number of subsidiary experiments were subsequently performed which were mainly concerned with studying the effects on the apparent brightness of a double-pulse stimulus when pulse interval is increased. In order to facilitate referencing of the various findings within this paper, the experiments will be identified by Roman numerals. Experiment I will refer to the investigation of the hypothesis outlined above. The methodology and results for this experiment will be reported in detail in the appropriate sections of this paper. In order to reduce the size of the latter, methodology and results for Experiments II - VI will be introduced in logical order during the discussion of the results of Experiment I.

METHOD

The purpose of this study was to measure the two-pulse difference thresholds for stimuli subtending different visual angles under conditions where either the luminance or the energy above threshold of the stimulus was held constant. Discrimination functions relating interval increment thresholds to pulse interval with stimulus size as parameter were obtained for 5 observers who were assigned to either the constant illuminance or the constant luminance condition or, in the case of one observer, to both conditions.

Observers

Observers were graduate students of the University of Alberta who had volunteered for the study. Each observer was required to complete 60 observation sessions and was given a monetary reward. Experimental sessions lasted on the average one hour. Observers J. P. and D. N. were assigned to the constant luminance condition, while observers T.G. and H. B. were assigned to the constant illuminance condition. Observers L. S. (author) participated in both conditions.

Apparatus

Light pulses were generated by a glow modulator tube[2] driven at approximately 40 ma.[3] The supply current was trimmed daily to provide a constant total illuminance of 1.04 x 10^{-5}

lumen/cm^2 as measured at the 4 mm exit pupil.[4] The light pulses were of 2 msc duration with a rise time of less than 40 usc. The duration of these pulses, their inter-pulse onset interval, and the delay interval between double pulse stimuli were controlled by a system of solid state timers[5] and were monitored on a digital counter. The obtained accuracy of the critical inter-pulse onset intervals was found to be within 1% for the briefest (2 msc) onset-intervals and within .1% for the longest (280 msc) intervals. The glow modulator light output was monitored for possible drifts on an oscilloscope while an experimental session was in progress.

Light pulses were presented to the observer via a single channel Maxwellian view system. This system consisted of a collimating lens[6] and a viewing lens.[7] Illumination was controlled by a neutral density wedge[8] and neutral density filters.[9] Five field stops produced circular stimuli which subtended visual angles of 10', 25', 1.0°, 2.5° and 7.5°. The observer viewed the stimuli with the aid of a fixation system[10] consisting of two dim-red concentric circular lines which interrupted on the horizontal and vertical plane. The distance of these circles from the centre of the stimulus subtended a visual angle of 4° and 8.5°. The illumination of the fixation system was maintained at less than 1.0×10^{-9} lumen/cm^2.

Observations were made from a room adjacent to but separated from the experimental chamber by a sound-proofed wall.

Position of the eye with respect to the 4 mm artificial pupil was maintained by a bite-board system. The observer triggered a single 3-stimulus[11] sequence electronically and signalled his responses via a buzzer system. A two-channel intercom system permitted two-way communication between observer and experimenter. The experimenter channel was inactivated during the presentation of a 3-stimulus sequence via an experimenter-operated foot switch. Throughout an experimental session low level auditory stimulation helped to maintain observer vigiliance. A single experimental session lasted between 40 and 60 minutes. The experimental layout is shown in diagrammatic form in Appendix (A).

Stimuli

Foveal thresholds were measured for each of the 5 stimulus areas using the method of adjustment. The illuminance of the 25' stimulus was set at 2.25 Log above absolute foveal threshold for all observers. The densities required to reduce the total illuminance for stimulus size 25' are shown in Table (1). For observers assigned to the constant luminance condition density settings were kept constant across the remaining stimulus sizes. For observers assigned to the constant illuminance condition the illuminance of each of the remaining stimulus sizes was set at 2.25 Log above absolute foveal threshold. Densities required to reduce total illuminance for each of these stimulus areas are also shown in Table (1). Calculated luminances derived from the measured illuminance and the added average density for each of the stimulus areas in the two conditions are shown in Table (2).

Procedure

In this study the term 'stimulus' shall refer to two brief light pulses separated by a variable inter-pulse onset interval (IPOI). The IPOI of a stimulus will from here on be referred to as its 'interval'. The term 'flash' shall refer to the perceptual effect of the stimulus.

Stimuli were presented monocularly in a Maxwellian view using an artificial pupil. Each observer used his (her) preferred eye. A single trial consisted of an observer-triggered sequence of 3 stimuli separated by inter-stimulus intervals of 1 sec. Observers proceeded on their own leisure to the next trial upon receiving a ready signal by the experimenter. Inter-trial intervals were on the average less than 3 sec.

Within each 3-stimulus sequence two of the stimuli (standard stimuli) had intervals of equal durations, while the interval of the remaining stimulus (test stimulus) had a duration which was longer by a predetermined amount. The temporal position of this stimulus was varied randomly between trials and the task of the observer consisted of judging which of the three flashes appeared to be different from the remaining two. His choice of judgements about the temporal position of the test stimulus was forced in as much as he was requested to guess in case of doubt. Observers were instructed to view all 3 stimuli before making a response and were told to make full use of any and all perceptual cues when making a difference judgement. An attempt was made to match the performance levels of observers by instructing them about the various cues available at different pulse intervals and stimulus areas. These instructions were given during the 2 training sessions for each of the 5 stimulus areas. Due to the initial unfamiliarity of the experimenter with the effects of changes in stimulus conditions on the availability of perceptual cues, the instructions for observer D. N. were less comprehensive than those for the remaining observers.

A single experimental session consisted of 12 blocks each containing 18 trials. Within each block the interval duration of the two standard stimuli remained constant while the interval duration and temporal position of the test stimulus was varied randomly. Each block contained test stimuli of 6 different interval durations replicated three times for a total of 216 experimental trials within a session. Blocks of trials, each designating a different standard stimulus, were presented in random order with rest periods between blocks.

Prior to the start of a block of trials observers were acquainted with the stimulus conditions associated with the particular block by presenting to them on 3 consecutive trials the two standard stimuli and the test stimulus with largest increment in interval over that of the standard stimulus. Responses on these familiarization trials were not treated as part of the experimental data. If the test stimulus was not successfully discriminated on the 3 familiarization trials additional trials were presented. This procedure of familiarizing the observer with the stimulus conditions was found to be advisable since task requirements between randomized blocks of different standard intervals varied with respect to which of a multiplicity of perceptual cues would be relevant to the difference judgements.

In order to encourage and maintain observer participation and motivation during the required 60 experimental sessions, observers were informed at the end of each trial whether their response had been correct. On trials on which the observer failed to discriminate the test stimulus he was informed about the temporal position of the latter. In addition, observers were informed at the end of each session about the number of incorrect trials on that session.

Since the first two observers who had volunteered for this experiment had to abort the study at an early stage, the opportunity presented itself to gain some insight into the effects of the experimental conditions on interval discrimination. Inspection of the available data indicated that discrimination performance differed widely for different pulse intervals and visual angles. This suggested that it would be impractible to present an identical range of test interval increments for all stimulus sizes and standard intervals. Since reliable estimates of difference thresholds using interpolation procedures require a distribution of percent correct responses ranging from chance performance to nearly 100%, selection of a range of interval increments based on the highest expected difference thresholds would seriously reduce the data base for the psychometric functions of those conditions in which difference thresholds were expected to be low, as responses which are always at chance or are always correct carry very little information about the threshold. It was, therefore, decided that for each combination of standard interval and stimulus size the selection of a final range of interval increments should be guided by the discrimination of each observer in that condition during the early sessions in the experiment. The following procedure in determinig the final range of interval increments was, consequently, adopted for each observer.

For the first (i.e. training) session on a given stimulus size a liberal range of interval increments was chosen. This 'starting range' was identical for all observers and conditions. At the end of the session data were inspected with respect to whether the test stimulus with the largest interval increment within a block resulted in perfect discriminations. It should be remembered that each test stimulus was replicated 3 X within a block. If more than one of the largest and adjacent interval increments satisfied the criterion of perfect discrimination a new, adjusted range was generated for the next session presenting the same stimulus size. The range was adjusted in a manner which assured that the largest interval increment within each block would barely be sufficient for perfect discrimination. This procedure was repeated in subsequent sessions. In as much as observers tended to improve their discrimination performance beyond the two training sessions it was hoped that the procedure would provide some assurance that the developing competence of observers in discriminating interval differences would be accompanied by a corresponding development in task difficulty. Range adjustments were generally not further necessary at the completion of the 5th (including training) session for a given condition of stimulus size. The finally arrived at interval increment ranges were not necessarily identical for all observers and are presented in Appendix (B). Implications of the procedure and its success will be further discussed in the discussion section of this paper.

Materials

Range adjustments requiring frequent changes in test stimulus duration were facilitated by computer generated tabulation sheets. Randomization of standard intervals between blocks and of test intervals within blocks of trials was obtained using the random number facility provided by FOCAL-RT.[12] Randomization of the temporal position of the test stimulus was done in a manner which assured that within each experimental session of 216 trials the test stimulus occurred an equal number of times in each of the 3 temporal positions. Tabulation sheets were then used to determine the appropriate timer settings and to record the responses. The computer programs which were developed to aid this experiment and to conduct the subsequent on-line experiments are presented in Appendix (E) and (F).

RESULTS

The major dependent variable in this experiment was the interval difference threshold for each of 12 intervals and 5 stimulus areas when stimulus energy is maintained at either a constant level above threshold or at a constant luminance across different stimulus areas. Observers were divided into two groups resulting in a split-plot repeated measures design in which stimulus size and pulse interval were varied within two groups of observers for which the illuminance of the stimulus was either held constant or was allowed to vary with changes in stimulus size.

The experimental design is presented diagramatically in Figure (3). Each of the 360 cells designates a pulse interval for which a discrimination function was obtained representing the relationship between the percentage of correct discriminations and the magnitude of the increment in the duration of the test interval over that of the standard interval. Each of the discrimination functions represents the detectability of 6 interval increments (see Figure (4)) based on 30 judgments at each increment. It should be remembered that in order to obtain discriminations ranging from chance to almost 100% correct the attempt was made to select for each of the 5 X 12 conditions of standard interval and stimulus size within an observer a range of interval increments appropriate to that condition. A set of typical discrimination functions is shown in Figure (4). It can be seen that discrimination improves with increasing interval differences. In a number of cases the functions are non-monotonic for this and the other observers. To provide a more valid estimate of the difference threshold at 66% correct discrimination, iterative interpolation procedures were employed. Linear interpolation was used to estimate percent correct discriminations at points intermediate to the test intervals used within a given condition. Interpolation was then re-applied to obtain the threshold increment value.[13] It should be noted at this point that in a three-alternative forced-choice procedure 66% correct discriminations correspond to 50% when corrected for chance. Difference threshold expressed as interval increments are shown in Table (3). A qualitative description of the obtained results with respect to interval difference thresholds and abolute thresholds follows.

Absolute Thresholds

The two-pulse absolute threshold defines the interval between two successive light pulses which the observer can reliably discriminate from two continguous light pulses. The briefest intervals used in this experiment had an interval of 3 msc making the two light pulses virtually contiguous. Figure (5) graphically shows absolute thresholds as a function of stimulus size when either luminance or illuminance is held constant. Inspection shows the functions to be similar within groups of observers. In the constant luminance condition absolute thresholds tend to increase with increases in stimulus area. Thresholds in the constant illuminance condition tend to be curvilinearly related to stimulus area.

The effects of increasing the luminance of a stimulus of a given area are graphically represented in Figure (6). Data points represent the group average absolute thresholds at the indicated luminance levels. The absolute threshold values were substantially higher for observer D. N. than the constant luminance group average and are not contained in this plot. It can be seen that absolute thresholds decrease when luminance is increased beyond T + 2.25 Log. For stimulus size 10' thresholds are seen to increase as luminance is increased from T + 1.85 Log to T + 2.25 Log.

Difference Thresholds

A difference threshold is here defined as that increment in the duration of the interval between two successive light pulses which the observer can reliably discriminate from a given interval. The relationship between difference thresholds and pulse interval with stimulus size as a parameter is graphically represented in Figures (7) to (12). It can be seen that thresholds are a curvilinear function for all stimulus areas. Thresholds tend to be high at short and long pulse intervals and low at the medium pulse intervals. The discrimination functions are remarkably similar for 4 observers. Observer D. N., however, generated discrimination functions which are somewhat dissimilar in as much as they exhibit substantially higher threshold values at short pulse intervals. The functions are generally bimodal with minima at 20-40 msc and 60-100 msc. This is clearly shown for observer L. S. (Figures (7), (10)); J. P. (Figure (8); H. B. (Figure (11), and to a lesser extent for observer T. G. (Figure (12)).

Inspection of the individual curves reveals that the discrimination functions of observers in the constant luminance group (L. S., J. P., D. N.) have minima which shifts towards shorter pulse intervals as stimulus size is increased from 10' to 7.5°. For observer L. S., for example, the point of optimal discrimination of interval difference shifts from 100 msc to 60 msc with increasing stimulus size. Inspection of the discrimination functions of observers in the constant illuminance group reveals an absence of a systematic shift in the minimum as stimulus size is increased.

Comparison of the discrimination functions on the basis of the magnitude of the secondary rise and fall of thresholds at pulse intervals between 30 and 80 msc indicates that the extent of this secondary rise and fall diminishes as stimulus area is increased and luminance is kept constant. This is clearly indicated for observers L. S. and J. P. Similar systematic changes associated with increases in stimulus area are lacking in the discrimination functions of observers in the constant illuminance group. The functions for L. S. (Figure (10)) and H. B. (Figure (11)) indicate that the secondary rise and fall is well maintained for even the largest stimulus area when illuminance is kept constant. The effects of keeping energy-above-threshold as opposed to luminance constant are most distinguishable when the discrimination functions of observer L. S. who participated in both conditions are compared.

In the constant illuminance group the discrimination functions of observer T. G., even though in their shape similar to those of the other observers, do not reveal any systematic effe[illegible]ges in stimulus size. The discrimination func[illegible] the smallest stimulus area exhibits a minimum which o[illegible]t a smaller pulse interval than that for the other two [illegible]vers in this group. Since the determination of vi[illegible]ility thresholds for stimulus area 10' had resulted in a t[illegible]eshold for observer T. G. which was lower by ca. .75 Log tha[illegible]hose of the other observers, it is possible that the shift in the minimum may have been due to a higher effective luminance resulting from erroneous threshold measures. In order to investigate the effects of increasing the luminance for stimulus size 10' beyond the levels used in the experiment, a discrimination function was obtained for this stimulus area at a luminance of threshold plus 3.0 Log. Figure (13) graphically displays the effect of increasing luminance beyond T + 2.25 Log for one observer. For purpose of comparison, the discrimination functions for two levels of lower luminance obtained from the same observer are also shown. It can be seen that increasing luminance beyond T + 2.25 did not shift the minimum at 80 msc towards a shorter pulse interval for this observer. On the other hand, increasing luminance to beyond T + 2.25 Log substantially lowered the threshold values for the two shortest pulse intervals and significantly enhanced the magnitude of the secondary rise and fall at pulse intervals between 30 and 50 msc,

DISCUSSION

Experiment I

The results of this experiment show that interval increment thresholds are a non-monotone function of pulse interval for all stimulus areas, confirming the findings by Nilsson (1969). The obtained discrimination functions are generally bimodal with minima at 20-40 msc and 60-100 msc. If luminance is kept constant the pulse interval which makes for optimal discrimination is seen to shift towards shorter pulse intervals as illuminance increases with increasing stimulus area. On the other hand, if illuminance as opposed to luminance is kept constant increases in stimulus area do not effect the location of the minimum. It should be noted that the shift of the minimum towards shorter pulse intervals as illuminance increases is in the opposite direction as predicted by the hypothesis.

Another finding was the occurrence of a secondary rise and fall in thresholds at intervals between 30 and 80 msc. This secondary rise and fall was shown to diminish as illuminance increased with increasing stimulus area, but was found to be relatively constant when area was increased under constant illuminance. Before addressing myself to the significance of these findings, I shall discuss the nature of the perceptual cues found to be effective in interval discrimination.

Perceptual Cues. As reported by other investigators, discrimination of two-pulse stimuli is aided by a multiciplicty of cues. The major cues reported by the observers were apparent brightness, duration, rate of onset, and flicker. It was noted that at the pulse intervals (60-100 msc) at which discrimination was optimal the major perceptual cue was a slight flicker of the test stimulus. Observers reported discrimination to be relatively easy at these pulse intervals in as much as the task consisted of discriminating between qualitatively different stimuli, the standard interval being one fused flash and the test stimulus showing a slight flicker. It should be noted that increment thresholds at these pulse intervals had a value of about 5 msc or less, even for observer D. N. who showed generally higher thresholds than the remaining observers. These findings would seem to indicate that the discrimination function minimum at intervals of 60-100 msc coincides with the temporal region within which a two-pulse stimulus changes from fusion to flicker as pulse interval is increased. Brightness cues were reported to be generally more effective at the larger stimulus areas and at short to medium pulse intervals. Rate of onset of the stimulus was found to be an effective cue for very brief pulse intervals especially under conditions where the stimulus appeared to be bright. One observer (L. S.) found the rate-of-onset cue to be extremely effective for a bright 10' stimulus at very brief pulse intervals. The low thresholds for the two briefest pulse intervals at a luminance of T + 3.0 Log (Figure (13)) are probably due to the exclusive use of the rate-of-onset cue. It was, furthermore, noticed that this cue appeared to be the one most sensitive to practice.

When pulse intervals are increased from very brief to medium durations that is to say, when a range of increasing increment intervals is presented, the perceptual cue which is maximally effective in discriminating interval differences changes in systematic fashion from rate-of-onset to duration and/or brightness and, at medium pulse intervals, to the detection of perceptual flicker. In as much as these cue changes are accompanied by a corresponding decrease in task difficulty any inter-observer variability in difference thresholds for a given pulse interval can be mainly accounted for in terms of the extent to which observers make use of the more difficult perceptual cues. Decreasing the range of interval increments, therefore, has the effect of encouraging observers to make use of the more difficult cues. The success of such a procedure may be judged by the fact that in this experiment the discrimination functions for 3 observers were quite similar. The generally higher thresholds for observer D. N., especially at short pulse intervals, are probably due to the fact that this observer received less comprehensive instructions about cue availability and consequently made predominant use of the less difficult perceptual cues (i.e. perceptual flicker) at these pulse intervals.

Secondary Rise and Fall of Thresholds. Thresholds increased and subsequently decreased at pulse intervals between 30 and 80 msc. For stimulus area 25', for example, the difference thresholds of observer L. S. and H. B. (Figures (10), (11)) rose from 7.1 and 7.5 msc at a pulse interval of 40 msc to 14.4 and 14.9 msc at a pulse interval of 60 msc. The magnitude of this secondary rise in thresholds suggests that the effectiveness of a given cue, such as apparent brightness, may change over a relatively narrow range of pulse intervals. Given that the apparent brightness of a double - pulse stimulus decreases with increases in pulse interval (Bartlett & White, 1965; Bleck & Craig, 1968), and given that a constant change in apparent brightness is required for the detection of an interval difference at pulse intervals at which apparent brightness is the maximally effective cue, the observed secondary rise and fall in the discrimination functions suggests that there may be perceptually significant changes in the rate at which brightness decreases within a relatively small range of medium pulse intervals. In order to test this hypothesis Experiment II was designed to more closely investigate the manner in which apparent brightness changes with increase in pulse interval.

Experiment II

Apparent Brightness as Function of Pulse Interval. Since this experiment was designed in order to facilitate interpretation of the earlier obtained discrimination functions, only a brief summary of the apparatus and procedure for this study will be given.

Judgements of the brightness of a two-pulse stimulus of size 30' at 46 pulse intervals from 3 to 138 msc were obtained for 3 levels of stimulus luminance using a monocular brightness matching procedure. Similar judgements were obtained for a two-pulse stimulus of size 1° at 46 pulse intervals from 3 to 183 msc for one level of stimulus luminance. The task of the observer was to match the brightness of a steady-state stimulus subtending 30' (1°) against that of a double-pulse stimulus of equal size by adjusting the luminance of a steady-state stimulus. Stimuli were presented via a two-channel Maxwellian view system. The channel presenting the light pulses consisted of an optical system and light source essentially identical to that described for Experiment I. Supply current in this channel was trimmed daily to provide a constant total illuminance[14] of 8.5×10^{-6} lumen/cm^2 as measured at the 4 mm exit pupil. The second channel presented a steady-state stimulus generated by a light bulb[15] which was driven at approximately 2.5 amp by a DC power supply[16]. Supply current in this channel was similarly trimmed daily to maintain a constant total illuminance[14] of 9.6×10^{-7}

lumen/cm^2. Two circular field stops produced stimuli subtending either 1° or 30' with the angle of separation of the stimuli 1° and 30' respectively in the horizontal. Illuminances in both channels were controlled by neutral density filters and neutral density wedges.

On a given trial the observer electronically triggered a double-pulse stimulus which then continued to cycle at inter-stimulus intervals of 1.5 sec. This permitted the observer to adjust the luminance of the steady-state stimulus via remote control of the neutral density wedge until he obtained an appropriate brightness match. The stimulus cycle was then electronically terminated by the observer and the density required for the brightness match recorded by feeding a calibrated voltage signal generated by a potentiometer mounted on the axis of the density wedge into an analog-to-digital converter. Within a given session each of 46 pulse intervals was presented 3 X, the order of presentation being fully random. Presentation of stimuli, recording of brightness values in terms of calibrated voltage levels, and analysis of the data was done on-line using a PDP-12 computer.

Results

Figure (14) and Figure (15) graphically displays the relative brightness of a two-pulse stimulus as a function of pulse interval for two observers at 3 levels of luminance and stimulus size 30'. Figure (16) shows the brightness function for stimulus size 1.0° at one level of luminance. The graphs are tracings of the original computer print-out. A typical example of the latter is given in Appendix (G). Values on the horizontal axis represent pulse intervals. For stimulus size 30' and 1.0° intervals increase in steps of 3 and 4 msc respectively. Values on the vertical axis express the relative brightness of two-pulse stimuli in terms of the Log (relative) luminance of the steady matching field. For target size 30' a given data point on the function represents the average of 15 brightness matches after linear interpolation between adjacent pulse intervals. For target size 1.0° a given data point represents the un-interpolated average of 57 brightness matches. The dashed, horizontal line segments in Figure (15) represent the brightness of a single 2 msc pulse at each of the 3 luminance levels.[17]

Inspection of the graphs indicates that apparent brightness generally decreases as pulse interval is increased from short to medium durations. At the higher stimulus luminance a subsequent increase in brightness at intervals beyond 60 msc is evident. Figure (15) also indicates that for this observer an increase in stimulus luminance from T + 2.25 to T + 2.75 is less effective in increasing the brightness of a given stimulus with very brief interval duration than increasing luminance from T + 1.75 to T + 2.25 (a discussion of these two effects of stimulus luminance will follow in later sections of this paper). A more detailed description of the obtained brightness functions and of the effects of changing stimulus conditions may be conveniently obtained by considering 3 aspects of the functions: firstly, the magnitude of the brightness decrease as pulse interval is increased. Secondly, the duration of the interval which shows maximum reduction in apparent brightness and thirdly, the extent to which brightness decreases linearly with increasing pulse interval.

With respect to the last aspect, closer inspection of the brightness functions for observers L. S. and H. B. at a luminance of T + 2.25 and target size 30' indicates noticable changes in the rate at which brightness decreases over medium pulse intervals between 60-70 msc. More specifically, brightness decreases at a lower rate at intervals between 59 and 64 msc for observer L. S. and at intervals between 56 and 61 msc for observer H. B., indicating a satisfactory consistency between the data for these two observers.

It will be remembered that the interval discrimination functions for the above two observers -- obtained under identical conditions of stimulus size and luminance -- displayed a secondary rise and fall in interval difference thresholds which maximum occurred at a pulse interval of 60 msc, and that thresholds at this pulse interval increased by a factor of 2 relative to thresholds at a pulse interval of 40 msc. In order to determine whether the decrease in the rate of brightness change, observed in Experiment II to occur around

60 msc, can account for the doubling of interval difference thresholds observed in Experiment I., the minimum change in brightness necessary for the perception of an interval difference has to be estimated. This threshold change in brightness may best be derived by calculating the change in brightness which occurs at that pulse interval for which the interval increment threshold is the smallest. Since the discrimination functions for both observers show the 40 msc pulse interval to display nearly the lowest difference threshold (7 msc), it is convenient to estimate the brightness difference threshold for each observer by calculating the brightness decrease observed as pulse interval increases from 40 to 47 msc, and to derive from this figure the increase in pulse interval at 60 msc which is necessary to bring about a threshold decrease in brightness.

Interval difference thresholds for the two observers estimated in this manner predict difference thresholds of 11.2 msc at a pulse interval of 60 msc for L. S., and of 15.1 msc at a pulse interval of 56 msc for H. B. Even though for observer H. B. the predicted doubling of interval difference thresholds on the basis of the brightness data occurred at a slightly shorter pulse interval and the predicted increase for L. S. is only 60% of that actually obtained, the predicted thresholds are in close enough agreement with the experimentally determined thresholds -- especially in view of the fact that nearly a year intervened between the two experiments and that two slightly dissimilar optical systems (25' vs 30') were involved -- to support the assumption that the secondary rise and fall in thresholds of the interval discrimination functions reflect perceptually significant changes in the rate of brightness decrease. Furthermore, to the extent that apparent brightness is an effective cue in interval discrimination, it seems plausible that the latter functions represent the first derivative of the brightness function.

In order to investigate this hypothesis, interval increment thresholds were estimated for each of 46 pulse intervals on the basis of the obtained brightness functions for luminance levels T + 1.75 and T + 2.75, using the estimation procedure outlined earlier.[18] The threshold change in apparent brightness necessary for the detection of an interval difference was set at .05 Log, this value being consistent with the magnitude of the brightness change at luminance level T + 2.25 Log associated with a threshold increment ~~in~~ pulse interval at those intervals for which interval increment thresholds are minimal. In a subsequent experiment the empirical interval discrimination functions were then obtained.

Experiment III

Predicted and Obtained Discrimination Functions. This experiment was designed to explore the proposition that the form of the interval discrimination functions may be largely accounted for in terms of the manner in which apparent brightness changes as pulse interval increases. Interval increment thresholds were obtained for 23 pulse intervals ranging from 3 to 135 msc for one observer for whom brightness functions were available. This experiment used the same optical system as described for Experiment II, except that the channel presenting the steady-state stimulus was inactivated. Procedures were identical to those described for Experiment I except that stimulus presentation and data analysis was performed on-line using the PDP-12.

Figure (17) graphically displays the interval discrimination functions estimated on the basis of the brightness functions obtained in Experiment II and the interval discrimination functions which were in fact obtained for two conditions of stimulus luminance and stimulus size 30'. Tables (4) and (5) show the numerical values of the obtained and estimated thresholds. It can be seen that for both conditions the empirical discrimination functions manifest a number of secondary rise and falls in thresholds which are essentially replicated by the estimated discrimination functions. The similarity of the two types of functions appears to be satisfactory in view of the fact that the empirical functions are based on (standard) pulse intervals which were increased in larger steps and, therefore, provide less information than the estimated discrimination functions.

The effect of increasing illuminance by increasing luminance can be gleaned from a comparison of the two (empirical) discriminations functions. Increasing luminance to T + 2.75 Log decreases the magnitude of the secondary rise and falls in thresholds at pulse intervals between 40 and 60 msc. Furthermore, in the high luminance condition the function minimum clearly occurs at an interval of 75 msc while in the lower luminance condition an additional minimum is observed at an interval of 93 msc. Shifts in minima towards shorter intervals and decreases in the magnitude of secondary rise and falls observed in this experiment are consistent with identical changes observed in Experiment I when illuminance was increased by increasing stimulus area.

In concluding the discussion on the significance of the secondary rise and falls of interval difference thresholds the evidence presented so far supports the conclusion that for pulse intervals up to 80-100 msc the fluctuations in thresholds are essentially due to corresponding changes in the rate at which apparent brightness decreases with increasing pulse interval. By way of generalization, the observed secondary rise and fall of thresholds for stimulus areas which are larger or smaller than the stimulus size for which brightness data are available may similarly indicate the presence of non-linear changes in brightness across restricted and well defined ranges of pulse intervals. The absence of a systematic rise and fall in thresholds for observers D. N. (Figure (9)) and T. G. (Figure (12)) probably reflects a lower efficiency in the utilization of brightness information. The clear presence of such rise and fall for 3 observers, however, and the relative accura[illegible] which discrimination functions may be predicted from b[illegible] functions lends support to the view that secondary [illegible]tions in interval difference thresholds reflect [illegible]der[illegible] changes in the efficiency at which temporal information is processed at different pulse intervals.

It should be [illegible]d, finally, that minimum interval increment thresholds of between 4 and 7 msc which were observed in Experiment I and II and which were predicted in Experiment II on the basis of assuming a just noticable brightness difference o[illegible]05 Log are entirely compatible in magnitude with luminance differential thresholds (Nilsson, 1968). They are, furthermore, in close agreement with data reported by Bird & Mowbray [illegible]3) who showed that the change in the period of a train of rectangular light pulses for a just noticable transient change in brightness has a magnitude of 3.8 msc.

Experiment I (Continued)

Interpretation of the Discrimination Function Minima. Inspection of the discrimination functions obtained in Experiment I revealed a systematic shift of the function minima towards shorter pulse intervals as illuminance increases with increasing stimulus area (constant luminance condition) and an absence of such shifts when luminance is adjusted to maintain constant illuminance with increasing target size. Table (6) shows the numerical values of the threshold increments at the function minima for different observers and conditions. The shift of the minimum has a magnitude of between 20 and 30 msc and is most apparent in the data of observer D. N. (Figure (9)) where the minimum shifts from a pulse interval of 80-100 msc to an interval of 50 msc as target size increases from 10' to 7.5°. Inspection of the data for observer L. S. (Figure (7) and (10)) indicates that the shift may also be observed when illuminance is increased by increasing stimulus luminance. For both the smallest (10') and the largest (7.5°) stimulus area increasing luminance shifts the minimum by 20 msc. Similar evidence was obtained in Experiment III for stimulus size 25' (Figure (17)). It is, therefore, a reasonable assumption that the shifts in the minima reflect the increasing energy content of the stimulus.

The observed shifts are clearly in the opposite direction from that predicted by the original hypothesis. It will be remembered that the temporal dispersion model of interval difference discrimination outlined earlier was based on the assumption that the magnitude of the temporal dispersion of cortical response is determined by the degree of variability of transmission rates between fibres (channels), and that increases in temporal dispersion should shift the locus of optimal discrimination towards longer pulse intervals. In view of the obtained findings it must now be asked whether the temporal dispersion model can be re-formulated to account for the data.

The Temporal Dispersion Model Restated. For purpose of exposition a number of concepts shall at first be more precisely defined. The term 'channel' shall refer to a fibre projected from a given ganglion cell and shall include the various synaptic delays between ganglion cell and cortex. The term 'channel responses; shall refer to a train of neural impulses within a given channel. In order to distinguish between a channel response and the total cortical response to a brief impingement of luminous energy, the term 'ensemble response' shall refer to the cortical effect produced by volley of channel responses. The concept of temporal dispersion is, therefore, assumed to refer to the extent to which the ensemble response is dispersed over time. In order to distinguish between the response latency of a given channel and the latency of the ensemble response, the latter will be referred to as 'implicit time" and the former as 'peripheral latency'. In addition, we shall distinguish between the duration of a channel response (i.e. the duration of a train of neural impulses) and the duration of the ensemble response, which is assumed to be a function of the degree of temporal dispersion. Finally, the transmission rate of a given channel shall be defined as the velocity with which a ch annel response is transmitted to the cortex. The transmission rate character-istics of a channel are assumed to be solely due to factors such as fibre size, synaptic delays, meyelinization etc.

The question to be asked is to what an extent it is necessary and reasonable to assume that the temporal dispersion of the ensemble response is predominantly due to the transmission rate characteristics of the channels. Transmission time as determined by the latency of response in the lateral geniculate (LGN) to orthodromic or antidromic stimulation varies between 1-4 msc and 2-10 msc respectively in rats (Noda & Iwama, 1967). Total transmission time to the visual cortex for the slowest (area centralis) and fastest channels (peripheral retina) has been estimated to range from 7.5 to 10 msc and from 4 to 5 msc respectively (Stone & Hoffman, 1971). The reported range in the variation of transmission times in terms of absolute values, is relatively small when compared with the range of response latencies of ganglion cells (Cleland et al, 1970) or visual cortex neurons (Bartlett & Doty, 1974) to photic stimulation, which have been reported to vary between 30 and 80 msc. It is, consequently, doubtful whether the temporal dispersion of the ensemble response or its perceptual analog, the persistence of the sensory effect of a brief photic stimulus, can be solely accounted for by the conduction time characteristics of the channels.

The contribution which the transmission rate characteristics of the system make to the temporal dispersion of the ensemble response may also be evaluated in the light of assumptions about the magnitude of the response duration for a given channel. Data on the scotopic system of the cat retina indicate that there exists a minimum average response duration such that for stimulus durations of less than 32 msc the channel response duration remains constant at 70 msc (Levick & Zacks, 1970). If one grants the assumption that the duration of a channel response is essentially maintained across the various synaptic delays, then it would seem that transmission times reported to range from 4-10 msc contribute relatively little to the duration of the ensemble response.

The assumption that channel responses have a minimum duration has important conceptual implications for the model under discussion. According to the alternation of response theory (for example, Bartley & Nelson, 1963) the first pulse of a train of light pulses or a single, isolated pulse results in relative synchrony of channel responses. For a brief, isolated pulse the degree of synchrony is assumed to be solely determined by variations in the sensitivity of receptors. To the extent that increases in stimulus intensity bring more receptors to threshold level, channel response synchrony for a brief, isolated pulse will increase with increasing stimulus intensity. Since the duration of a channel response (but not its impulse frequency) is independent of stimulus intensity (Levick & Zacks, 1970), the magnitude of any asynchrony of responses which may result when a second brief pulse follows the first with a given delay is a function of the degree to which transmission rates between channels vary. Furthermore, this asynchrony (or overlap) has a limit which is determined by the channel response duration. In other words, if the difference in the implicit time of the fastest and slowest channels due to differences in transmission rates is, for example, 10 msc and if the average channel response has a duration of 70 msc then the duration of an ensemble response initiated by a light pulse occurring at time t_o is defined by the time interval t_{o+n} to t_{n+70+m} (where n and m are the peripheral latency and transmission time of the fastest channel). Since the fastest channel will not cease to respond until time t_{n+70+m} it is conceptually implausible to speak of an asynchrony (or overlap) <u>between</u> channels at pulse intervals smaller than 70 msc. This is a logical consequence of the assumption that channel responses have a finite duration and that asynchrony is mainly determined by transmission rates which display a relatively small range of variation.

What is required, then, to make the temporal dispersion model more workable is a mechanism which provides for an asynchrony of responses which is relatively independent of factors such as fibre size and transmission rates. It is a well confirmed finding that the mean latency of retinal ganglion cells decreases with increasing stimulus strength (Hartline, 1934, 1940; Cleland & Enroth-Cugell, 1970; Levick, 1973). For the cat ganglion cell, for example, response latency decreases form 100 to 30 msc as intensity is increased over a 5 Log range (Ogawa et al, 1966). In addition, Levick (1973) reports that the response latency of a given ganglion cell under constant stimulus conditions displays a substantial variability over time with the standard deviation of the cell's latency distribution being about 1/10-1/20 of the cell's mean latency. This relative constant relation between SD and mean response latency means, in other words, that an increase in the strength of stimulation which reduces the mean response latency of a given channel also reduces the variability of its latencies. It seems a reasonable assumption that a similar relation between the mean and SD of latencies exist also for a <u>set</u> of channels activated by a given stimulus at a given time. There are, furthermore, indications that the variability of latencies between channels is larger than the variability within a given channel (Levick, 1973). These findings suggest that it should be possible to estimate, firstly, the duration of the ensemble response to a brief stimulus and, secondly, the magnitude and the direction of shifts in the interval discrimination function minima as illumination is varied.

In order to estimate the magnitude of the temporal dispersion of the ensemble response (i.e. its duration) the following assumptions will be made:

(1) Under high illuminance conditions mean latency of a given number of channels is estimated at 30 msc.

(2) Under low illuminance conditions mean latency of a given number of channels is estimated at 80 msc.

(3) The SD of the variability of a given set of channels is assumed to be 1/5 of the set's mean latency.

(4) The response duration of a given channel has a minimum of 70 msc for stimuli of less than 32 msc duration.

(5) The distribution of response latencies for a set of channels is assumed to be normal.

(6) The variation of transmission times for a set of channels is negligible.

Assumptions (1) and (2) are based on the data by Levick (1973) and Ogawa et al, (1966). Assumption (3) implies that the absolute value of the SD ranges between 6 and 16 msc, depending on the level of illumination. These values are compatible with the estimated SD's of the latency distributions of hypothetical ganglion cell responses determining performance in judgments of temporal order (Zacks, 1973). Assumption (4) seems justified in view of the data obtained by Levick & Zacks (1970). Assumption (6) is a consequence of the earlier discussion on the variability of transmission times.

The duration of the ensemble response to a brief visual stimulus is determined by two factors: channel response duration and variability of peripheral latencies. The latter factor implies that for a given set of channels the onset of the channel responses is dispersed over time. Due to the assumed constant relation between mean latency ($\bar{X}_{lat.}$) and SD on the one hand and the effect of stimulus strength on $\bar{X}_{lat.}$ on the other, the peripheral dispersion will decrease with increasing stimulus strength. The magnitude of the dispersion of channels response onsets may be estimated according to the formula:

$$\bar{X}_{lat.} \pm 3 \frac{\bar{X}_{lat.}}{5}$$

This means that if a light pulse occurs at time t_o the onset of the channel responses is dispersed over the time interval t_{0+12} to t_{0+48} and t_{o+32} to t_{0+128} for the high and low illuminance condition respectively. Assuming negligible transmission times and a channel response duration of 70 msc, time elapsing between the onset of the ensemble response (implicit time) and its offset will, therefore, be defined by the time interval t_{0+12} to t_{0+118} for a total duration of 106 msc for the high illuminance condition, and by the time interval t_{0+32} to t_{0+198} for a total duration of 166 msc for the low illuminance condition. It should be noted that the estimated durations of the ensemble response are compatible with the minimum duration (120-240 msc) of a visual perception (Efron, 1970).

The just derived estimates of ensemble response durations allow an estimate of the magnitude and the direction of shifts in the minima of interval discrimination functions as illumiance is varied. Figure (18b) graphically displays the temporal dispersion of hypothetical ensemble responses to a double pulse stimulus with an onset interval of 83 msc under the assumption that mean peripheral latency is 80 msc (low illuminance condition) and that the SD is 1/5 of the mean latency. The pulse interval represents that interval at which a minimum increase in interval results in a given (criterion) change in the overlap of the ensemble responses. Figure (18a) shows the pulse interval which is needed for maximum interval discrimination under the assumption that mean peripheral latency is 30 msc (high illuminance condition) and the SD is again 1/5 of the mean latency. As can be seen, the pulse interval at which maximum discrimination is expected to occur shifts from 80 to 50 msc as mean latency decreases from 80 to 30 msc. The direction and the magnitude of the estimated shifts in function minima compares favorably with the shifts observed in Experiment I.

The above discussion permits the conclusion that the temporal dispersion of ensemble response may be solely accounted for by the distribution of peripheral response latencies and the duration of channel responses and that shifts in the discrimination function minima may be explained in terms of the effects of illuminance on the mean of the peripheral latency distribution and the relation between the mean of the latency distribution and measures of its variability. In the following section a number of aspects of the functions relating apparent brightness of a two-pulse stimulus to pulse interval which have not yet been discussed will be related to the re-formulated model of temporal dispersion.

Experiment II (Continued)

It will be remembered that Experiment II was designed to facilitate the interpretation of the secondary rise and fall of interval difference thresholds observed in Experiment I. Inspection of the brightness functions suggested that these secondary fluctuations in thresholds may be accounted for in terms of variations in the rate at which brightness decreases with increasing pulse interval. It was also suggested at that time that the over-all rate of brightness decrease and the magnitude of brightness decrease are two other aspects which characterize the brightness functions. The latter two aspects will now be related to the model of temporal dispersion.

In its most simple form the temporal dispersion model of two-pulse discrimination (Nilsson, 1968) assumes that to the extent to which the two ensemble responses overlap a single flash of enhanced brightness will be perceived, and that to the extent these responses do not overlap two flashes will be perceived. It is, furthermore, assumed that the enhanced brightness of the stimulus as pulse interval is decreased is due to a process of algebraic summation of activity in overlapping (asynchronous) channels. I shall, for the moment, adhere to these assumptions.

It follows from these assumptions that the pulse interval at which brightness has declined to asymptotic levels should be identical to the pulse interval at which the model predicts optimal interval difference discrimination and that, furthermore, the apparent brightness of a double pulse at that interval should be equal to the brightness of a single pulse of the same luminance. Decreases in pulse interval should increase double pulse brightness while increases in pulse interval should leave brightness essentially unchanged. Figure (19) graphically illustrates these propositions.

Table (7) compares the values of the pulse intervals at which brightness has decreased to asymptotic level, or in the case where brightness decreases non-monotonically the pulse interval which shows maximum brightness attenuation, with the values of the pulse intervals at which interval difference discrimination is optimal. The entries in Table (7) represent the data of those observers for whom both discrimination and brightness functions for given conditions of luminance and target size are available. It can be seen that for the two lower luminance levels optimal interval discrimination occurs at shorter pulse intervals than maximum brightness attentuation and that a close correspondence between the two measures can be observed only for the T + 2.25 (30') condition.

Table (7) also indicates that the effects of increasing the luminance of a target of given size are such as to shift both the temporal locus of optimal interval discrimination and of maximum brightness attenuation towards shorter pulse intervals. The consistency of the effect of luminance on the latter measure is more convincingly demonstrated in the graphs of the brightness functions (Figures (14) and (15)). For both observers increasing luminance from T + 1.75 to T + 2.75 shifts the temporal locus of maximum brightness decrease towards shorter pulse intervals. Figure (20) presents the brightness functions for another observer (T. N.) for whom luminance was increased up to T + 3.25 Log. The temporal locus of maximum brightness decrease (dashed diagonal) shifts from 90 msc to 70 msc as luminance increases from T + 2.25 to T + 3.25. Note, however, that for this observer luminance levels as high as T + 3.25 fail to shift the temporal locus of maximum brightness attenuation to the short interval (60 msc) observed for H. B. and L. S. when luminance was increased to T + 2.75. The just described trends in the effects of stimulus luminance are not inconsistent with the expectations of the modified temporal dispersion model which predicts that increasing illuminance by increasing stimulus luminance should diminish the temporal dispersion of the ensemble response and that, consequently, brightness should decrease more rapidly with increases in pulse interval.

The last aspect of the brightness functions to be discussed, that is the magnitude of the brightness decrease as pulse interval increases, reveals upon inspection a puzzling phenomena. The brightness functions for the low and medium luminance condition for stimulus size 30' (Figures (14) and (15)) and for the medium luminance condition for stimulus size 1.0° (Figure (16)) indicates a brightness difference of ca. .7 Log between the brightness of the double pulse of briefest interval and the brightness of the stimulus at intervals where brightness has declined to asymptotic levels. Since brightness at asymptotic levels corresponds closely to the brightness of a single pulse (Figure (15), it would seem that were pulse intervals further decreased beyond that of the briefest (3 msc IPOI) interval such that two pulses of intensity I are temporally superimposed to make for a single pulse of intensity 2 X I, brightness would have to decrease by approximately .4 Log to satisfy the reasonable expectation that a pulse of intensity 2 X I should be brighter by ca. .3 Log than a pulse of intensity I. A preliminary investigation of the effects of decreasing IPOI's beyond 3 msc indicated an absence of any systematic changes in brightness with changes in pulse interval within this extremely narrow range of intervals. An alternative explanation must, therefore, be sought and will be offered in a later section of this paper when the results of further experiments on the visual brightness of transients are discussed. In order to provide a theoretical and empirical background for this explanation, I shall in the next section discuss the effects of high luminance conditions on the brightness functions generated in Experiment II.

Effects of High Luminance on Two-pulse Brightness.

Figure (14) and Figure (15) graphically display the effect on the brightness of two-pulse stimuli of increasing luminance to T + 2.75 Log. It can be seen that for both observers brightness decreases non-monotonically as pulse interval increases from 3 to 138 msc. For both observers brightness decreases up to an interval of 60 msc. Further increases in pulse interval result in a subsequent increase in apparent brightness. The brightness of a single pulse of the same luminance is indicated for observer L. S. by the dashed horizontal. It can be seen that a double pulse is judged to be brighter than a single pulse by this observer at pulse intervals smaller than ca. 50 msc, while at longer intervals a double pulse is generally judged to be less bright than a single pulse. It is further noted that at the briefest pulse interval the brightness difference between a double pulse and a single pulse is relatively small (ca. .2 Log). In addition, inspection of the brightness function for this observer (L. S.) reveals relatively pronounced fluctuations in brightness at intervals beyond 60 msc, that is at intervals beyond the temporal locus of maximum brightness attenuation. Figure (21) presents a replication of the brightness function at T + 2.75 for observer L. S. The fluctuations in brightness beyond 60 msc appear like damped oscillations.

Since the effects of increasing luminance beyond T + 2.25 are rather striking, additional brightness data were obtained for another observer (T. N.) for 5 luminance conditions ranging from T + 2.25 to T + 3.25 for stimulus size 30'. Figure (20) shows the effects on the brightness functions of changing luminance over this range. The horizontal line segments in Figure (20) indicate the judged brightness of a single pulse at each of the 5 luminance conditions. As can be seen, the over-all effect of increasing luminance is such as to increase that region of pulse intervals in which a double pulse is of lower brightness than a single pulse. This effect appears at luminance levels of T + 2.75 and beyond. For the higher luminance conditions brightness tends to increase again as intervals are increased from medium to long durations, the effect being, however, not as pronounced as for observers H. B. and L. S. Figure (20) also indicates that for medium and long interval durations Log brightness is approximately linearly related to Log stimulus luminance, while for very brief interval durations a non-linear relation is in evidence.

The finding of reduced brightness responses of the visual system at pulse intervals beyond 40-50 msc when luminance is increased above a certain level is not consistent with the temporal dispersion model as reformulated earlier. The fluctuations in the rate of brightness decrease, that is the findings of Experiment II, could possibly be explained by assuming that the shape of the ensemble response is multi modal rather than Gaussian. It is not possible, however, to account for the observation that at pulse intervals at which the ensemble responses to a two-pulse stimulus can be assumed to still manifest a certain amount of 'overlap', the apparent brightness of such stimulus is smaller than that of a single pulse. Nor can the model give an account of the non-monotonic changes of brightness with increases in pulse interval which were observed under high luminance conditions. It should be remembered that it was assumed that any overlap results in a linear addition of activity in asynchronous channels and that increases in pulse interval beyond a certain duration should leave brightness essentially unchanged.

An interpretation of the above findings will be aided by relating them to a number of psychophysical and physiological findings on the responses to visual transients which show evidence of response interaction at certain critical interstimulus intervals. Baumgardt & Segal (1946) observed that the brightness of a double pulse consisting of two concentric squares of unequal size was reduced below that of a single element at pulse intervals between 40 and 70 msc. Ikeda (1965) investigated temporal summation of incremental and decremental double pulses and reports temporal summation of energy to decreases below that expected by probability summation at pulse intervals of 52 and 70 msc for the high and low adapting luminance condition respectively. Similar evidence for response interaction at intervals between 40 and 70 msc is provided by the temporal summation studies of Uetsuki & Ikeda (1970), Rashbass (1970, 1974), Roufs (1973c), and Titarelli et al (1970). Ikeda & Fujii (1966) investigated the temporal summation of more than two pulses and report evidence of response interaction at intervals of around 60 msc.

The above data are compatible with a number of studies using two-flash detection or increment detection measures of temporal summation which indicate that threshold energy rises to a maximum at pulse intervals of 60 msc and subsequently declines again (Herrick, 1974, 1973, 1972; Herrick & Theissen, 1972). Grossberg (1970) investigated the latency of detecting near-threshold double pulse stimuli and reports that reaction time increases gradually to a peak as pulse interval is increased to 70-80 msc, and subsequently decreases to a value equal to that for a single pulse as pulse intervals are further increased. Schuckman & Orbach (1965), investigating the detection thresholds of twin 'dark pulses' as function of pulse interval, reports that at intervals around 50-60 msc detection thresholds of a double pulse are approximately 20% higher than those for a single pulse. Their data indicate that at pulse intervals between 40 and 70 msc thresholds are increased relative to those for a single pulse, while at intervals smaller or larger than this range double pulse thresholds are decreased relative to those for a single pulse. Phillips & Singer (1974) presented two, temporally successive random dot patterns and reports that for brief (2 msc) durations of the first pattern detection of the appearance of a single (10') additional element in the second pattern increases to a maximum as stimulus interval increases to 60 msc, and decreases again as stimulus interval is further increased. The authors interpret the findings in terms of inhibition between ON and OFF responses (Singer & Phillips, 1974) and report that effects of changes in pulse interval on detection are absent under dichoptic stimulus presentation procedures.

The above cited evidence of response interaction at certain critical pulse intervals is compatible with similar evidence in the physiological and psychophysiological domain. Polyanskii (1967), recording from the rabbit visual cortex, infers the presence of post-excitatory inhibition from the finding that the reduced responsivity to the second pulse of a pair reaches a maximum at pulse intervals between 40-90 msc, the integrity of the response to the second pulse being restored at intervals greater than 90 msc. Donchin et al (1963) reports an interaction of photically evoked responses to double-pulses at intervals of less than 100 msc as measured by the human visual evoked response. Grüsser & Kapp (1958), recording from single cat ganglion cells, report that the response of the cell to the second pulse of a pair begins to decrease at pulse intervals of 85 msc, with complete suppression of the response to the second pulse occurring at intervals below 52 msc. The pulse interval at which the response to the second pulse is absent was shown to decrease with increases in stimulus intensity. The latter was interpreted as reflecting the decrease in the latency of postexcitatory (recurrent) inhibition with increases in stimulus intensity.

In view of these findings it is suggested that the reduced brightness of two-pulse stimuli at higher luminance levels reported in Experiment II is due to the presence of an inhibitory mechanism initiated by the first pulse and which operates maximally with a delay of approximately 60 msc. In view of the findings by Grüsser & Kapp (1958) and Phillips & Singer (1974), it is likely that this mechanism is located at relatively peripheral levels of the afferent visual system. The presence of such a response-attenuation mechanism indicates that the temporal dispersion model should be modified accordingly. More specifically, the shape of the temporal dispersion of channel responses should be conceived to be diphasic rather than monophasic, given certain (i.e. high luminance) stimulus conditions, to take account of an assumed post-excitatory inhibition phase.

Diphasic responses have been predicted, for example, by Ikeda (1965) on the basis of results of studies on the temporal summation of combinations of incremental and decremental pulses. Roufs (1973c) derived hypothetical responses to twin incremental pulses from flicker - fusion data and predicts diphasic responses for higher levels of base line luminance. In addition his model suggests a second negative phase with a latency of approximately 65 msc. Diphasic responses are similarly predicted by psychophysical models of the dynamic properties of the eye which attempt to give an account of flicker-fusion data (Kelly, 1961b) or of flicker-fusion data and data on temporal summation (Sperling & Sondhi, 1968). The latter model predicts negative response phases to be more pronounced at higher levels of background luminance. The inhibitory processes which are assumed to underly the negative phase of the diphasic response may be either of the self-inhibitory or lateral, recurrent type (for example, Ratliff et al, 1963; Grüsser & Kapp, 1958; Cornsweet, 1971). It may be noted at this point that the latency of the maximum inhibitory effect suggested by the brightness data in Experiment II (see for example Figure (21)) is compatible in its magnitude with data on the time course of lateral inhibition reported by Petry et al (1973). The latter report a maximum increase in the incremental threshold of a test stimulus, spatially superimposed on an edge stimulus, at stimulus intervals of between 30 and 50 msc.

It is, finally, proposed that the inhibitory processes which have been postulated in the experiments and models referred to above and which operate maximally at certain, critical inter-stimulus intervals have essentially the function of a gain-control mechanism which manifests itself mainly at higher luminance levels. In later sections of this paper additional experimental evidence will be adduced which suggests that a number of aspects of both the brightness - and interval discrimination functions observed in Experiments I and II can be explained in terms of the operation of such gain control mechanism. In the immediately following section a brief discussion of the operating principles of gain control mechanisms will be given and their implications for an interpretation of the oscillatory brightness changes observed in Experiment II will be noted.

Gain Control Mechanisms. The gain control characteristics of models of visual dynamics in which the main elements are Resistance-Capacitance (RC) stages have been extensively discussed in a number of theoretical papers (Fuortes & Hodgkin, 1964; Sperling, 1964; Sperling & Sondhi, 1968; Lange, 1952; Matin, 1968; Marks, 1972). A given RC stage or element may be conceived as the electrical (circuit) analog of a nerve cell's resistance and capacitance. If the input of such a single element system is an impulse the output wave form will have a steeply rising leading edge and a falling edge which decays exponentially. It suffices to say that the rate of exponential decay is a function of the product RC, the latter being referred to as the time constant τ of the element. Furthermore, if a number of such RC elements are connected in series and the time constant of each element is assumed to be fixed, it can be shown that the output wave form of the system (given the input is an impulse) will display an increasing attenuation of amplitude and of the rate at which the response begins to build up and subsequently declines as the number of RC stages is increased. In other words, the greater the number of RC stages the greater will be the 'spreading out' of the output wave form. This type of system is essentially the type of model which has been proposed for the frequency response characteristics of the visual system.[19]

In as much as the amplitude of the output wave form (i.e. its attenuation) is a function of the over-all time contant of the system and the latter can be altered by changing the resistance of all or some of the RC elements, gain control models have been proposed in which the time constants of the RC stages are controlled by the output of the system. The function of such a system is to compress a large range of inputs into a smaller range of outputs. RC stages with variable time constant are assumed to be analogous to synaptic inhibitory processes (Fatt & Katz, 1953). Similarly, RC stages with output (i.e. feeback) controlled time constants may be conceived to be analogous to recurrent inhibitory processes. Systems which have variable, output controlled time constants shall be from here on referred to as feedback (FB) filters with variable time constant. One characteristic of such systems is that, given that the feedback signal passes through the feedback loop with a certain delay, the output of the system to a pulse or a step input may initially undergo a series of oscillations (i.e. the system will operate alternately at maximum or minimum gain) until it 'settles' at a final, average output level.

Damped oscillations which are the result of time delays in negative feedback loops have been described for the Limulus eye (Ratliff et al, 1963) and for the cat retina (Grüsser & Kapp, 1958) and they are implicit in models of visual dynamics such as in the cascade-filer models for the Limulus eye (Fuortes & Hodgkin, 1964) and for the analysis of human flicker-fusion data (for example Lange, 1952).

It is, therefore, instructive to consider the high luminance brightness functions of Experiment II. The function for observer L. S. (Figure (21)) clearly shows a series of damped oscillations at pulse intervals beyond 60 msc. The period of these osciallations is approximately 15 msc. In order to determine the extent to which a high frequency component of about 60-70 Hz may also be present in the data of the other observers and conditions, a Fourier analysis of the available set of brightness functions was performed (Figures (22 to 25)) show the power density spectra for the available brightness data. Since the lower frequency components are of little interest here, the fundamental frequency and the first 3 harmonics were removed by digital filtering.[20] The graphs display Log relative power for each of the frequencies indicated on the horizontal axis. Inspection of the power spectra indicates the presence of a high frequency component of between 60-66 Hz which power is genarally larger for the high luminance than for the low luminance condition. This trend is more apparent for the spectra of observer T. N. and L. S. than for observer H. B.

The above analysis supports to some extent the assumption that high frequency oscillations with a period of at least[21] 15 msc are present in the brightness functions of all observers and that these oscillations are more pronounced at the higher luminance levels. If one grants the assumption that these oscillations are the manifestation of a system with negative feedback characteristics then the period of these oscillations would seem to suggest a delay in the negative feedback loop of at least 15 msc. It is interesting in this respect that the cascade-filter model proposed by Lange (1952) to account for human flicker-fusion data postulates time delays in the negative feedback loop of 11 to 14 msc. It should also be noted that measurements of the changes in the apparent brightness of a flash of light made by Bidwell (1899) show damped oscillations of apparent brightness with a period of approximately 15 msc.[22] Finally, Regan (1968) and Tweel & Verduyan (1965) report the presence of a 45-55 Hz component in the human visual evoked potential for higher stimulus intensities, which has an apparent latency of 60 msc.

In view of these findings, I shall as a working hypothesis adopt the proposition that the high frequency oscillations in the high luminance brightness functions are the manifestation of a system operating according to negative feedback principles. Additional support for such an interpretation would be obtained if it could be shown that the effect on the over-all time constant of the system of changes in stimulus conditions is consistent with the predictions generated by models which postulate FB filters as elements in gain control mechanisms. Experiment IV was, therefore, designed to estimate the over-all time constant of the system.

Experiment IV

The theoretical point of departure for this experiment is a model of visual dynamics proposed by Sperling & Sondhi (1968). This model attempts to account both for data on visual luminance discrimination and flicker detection. The model consists essentially of 3 components: (1) A two-element FB filter with variable, output-controlled RC stages whose function is the reduction of the dynamic range of response and the reduction of the over-all time constant of the system as the input level increases. (2) A one-element feedforward (FF) filter with variable, input-controlled RC stage which accounts for the Weber law behavior of the system. (3) A series of low-pass (LP) filters with fixed RC stages which accounts for the frequency response characteristics of the system.

In order to compare his model with the luminance discrimination data of Herrick (1956) and Graham & Kemp (1938), Sperling & Sondhi make use of two significant quantities: Sensitivity, S, which is defined by the reciprocal of the constant threshold energy, Lt, for pulse durations, t_i, smaller than the critical duration of Bloch's law and, secondly, the critical duration, τ, which is defined by that pulse duration at which the relation ΔL = constant energy changes to ΔL = constant luminance.

The model makes two predictions with respect to these quantities: Firstly, Log $1/\tau$ increases non-linearly with decreases in Log S. This is to say, in other words, that a decrease in (energy) sensitivity is accompanied by a non-linear increase in temporal resolution. This prediction fits the luminance discrimination data rather well. Secondly, Log $1/\tau$ is predicted to increase non-linearly with increases in Log L. This prediction may be contrasted with the interpretation which Herrick and Graham & Kemp give their own data. They suggest that the data are better fitted by assuming a linear relation between Log $1/\tau$ and Log L (see also Matin, 1968). The following experiment proposes to investigate the relation between $1/\tau$ and L, using a different measure to estimate the time constant, τ.

It will be remembered that a decrease in the time constant of an RC system implies an increase in the rate at which the response occurs. Since decreases in the rate at which output develops mean that the system will have a reduced capacity to resolve rapid and successive inputs, the time constant of the system is inversely related to temporal resolution. Conversely, measures of temporal resolution may permit estimates of the system's over-all time constant. It was suggested earlier that measures of temporal acuity, such as absolute thresholds determined in a forced choice procedure, provide less meaningful measures of temporal resolution (as defined above) since in a forced choice procedure cues not directly related to temporal resolution (such as apparent brightness) are used by the discriminating observer. An alternative way of measuring temporal resolution is to require the observer to respond to the presence or absence of a specific cue closely tied to temporal resolution, such as the detection of the slight undulations in apparent brightness which can be perceived when the pulse interval of a double pulse stimulus is increased from the region in which the stimulus appears as one fused flash to that in which it begins to 'flicker'. It was, therefore, decided to estimate the time constant involved in the processing of two-pulse stimuli by measuring their fusion thresholds at different levels of luminance.

The procedure adopted for this experiment was briefly as follows: For each of 9 levels of stimulus luminance, ranging from T + 1.25 to T + 3.25 Log, the approximate region of pulse intervals within which the fusion threshold was expected to occur was determined by visual inspection of the stimuli. This preliminary estimate of fusion thresholds seemed justified in view of previous findings by Venables & Warwick-Evans (1968) which showed fusion thresholds to be effected by stimulus luminance. This preliminary estimate resulted in 9 regions of pulse intervals (not necessarily different) corresponding to the 9 luminance levels within each of which the shortest pulse interval defined the point at which a two-pulse stimulus would be perceived as <u>clearly</u> fused and the longest pulse interval defined the point at which the stimulus would be perceived as <u>clearly</u> 'flickering'. The temporal extent of each region of pulse intervals was fixed at 30 msc for the 3 lowest luminance levels and at 20 msc for the remaining luminance levels.

Following these preliminary investigations a single experimental session was run for each of the 9 luminance conditions in which the observer made judgements with respect to the perceived presence or absence of flicker of a two-pulse stimulus. On a given trial a 3-stimulus sequence was presented in which the first two stimuli had a (standard) pulse interval corresponding to the lower point of the fusion-flicker region and the third (test) stimulus had a pulse interval which duration was longer by 2-20 msc (3-30 msc for the lower luminances). The task of the observer was to indicate whether or not the test stimulus manifested 'flicker'. A block of trials consisted of a single judgement for each of 10 different, randomly presented pulse interval increments - a block being replicated 20 x within a given experimental session.

In most respects the experiment was identical to the procedures and apparatus used for Experiment III. The interval durations of the standard and test stimuli are shown in Appendix H.

Table (8) shows the 50% fustion thresholds at each of 9 luminance levels for one observer.[23] The values define that interpolated pulse interval at which the observer's responses indicated the presence of flicker in the test stimulus occurred 50% of the time. It can be seen that fusion thresholds decrease from about 87 to 59 msc as luminance increases from T + 1.25 to T + 3.25 Log. This decrease in fusion thresholds may be interpreted as reflecting the increasing temporal resolution of the system as the input level increases or, in other words, the decrease in the system's time constant. It will be remembered that the Sperling & Sondhi model predicts non-linear increases in Log $1/\tau$ with increases in Log L. Figure (26) graphically displays the relation between Log $1/\tau$ and Log L as determined by the results of this experiment. As predicted by the Sperling & Sondhi model (their Figure (4) center plate) the time constant approaches asymptotic values at both extremes of the luminance range. The similarity between the predicted and obtained functions is remarkable in view of the fact that the estimate of τ in this experiment is based on a different measure. Compatibility of predicted and obtained results would, furthermore, seem to indicate that the dark time-constant of the system (as estimated here by the fusion threshold under dark adaptation) has a similar relation to input levels as the light time-constant (as estimated in Sperling & Sondhi's model by the critical duration of Bloch's law under light adaptation).

The above results tend to support the conclusion that the fusion threshold of two-pulse stimuli provides a valid estimate of the visual system's time constant. It will be remembered that FB-filter models of gain control which postulate variable, output-controlled RC stages assume that part of the output is fed back to re-set the transfer function of the system (Filter). In the Sperling & Sondhi model the two-stage FB-component is designed to change one aspect of the system's transfer function, i.e. the time constant, when the input level increases. It is, therefore, instructive to again consider the brightness functions obtained in Experiment II and to compare them with the Log $1/\tau$ vs Log L function. Figure (26) indicates that the greater proportion of the total decrease in τ with increases in luminance occurs between T + 2.0 and T + 2.50 Log and that τ decreases to asymptotic levels at approximately T + 2.75 Log. Inspection of the brightness functions shows a corresponding increase in the brightness attenuation of double pulses at medium intervals (relative to single pulse brightness) when luminance is increased to above T + 2.25 Log for observer T. N. (Figure (20)). Similarly, the functions for observer L. S. (Figure (15)) shows two-pulse brightness to be smaller than single pulse brightness at T + 2.75 and the absence of such attenuation at the two lower luminance levels. The relationship between brightness attenuation and ι tends to support the earlier assumption that brightness attenuation observed at higher luminance levels reflects the operation of a gain control mechanism which appears to reach maximal effectiveness at latencies of approximately 60 msc. This conceptualization is also consistent with the occurrence of (damped) oscillations in brightness, observed at pulse intervals beyond 60 msc (Figure (21)), in that they may be a manifestation of a negative feedback mechanism with delay periods in its feedback loop.

As was noted earlier, the major function of the FB-filter in the Sperling & Sondhi model is the reduction in the dynamic range of response and the reduction in the time constant with increasing input levels. For steady-state inputs and for extremely brief inputs the output of the FB-filter increases as a power of the input with exponents of 1/n+1 and 1/n respectively, where n is the number of stages. A two-stage FB-filter, consequently, predicts cube-root and square-root input-output relations for steady state- and transient inputs respectively. It should be noted, however, that the model makes the (simplifying) assumption that the feedback signal acts with zero delay. To the extent, then, that the gain in the system is output controlled and to the extent that the feedback signal acts with a delay, the gain will not be an instantaneous function of the input. This implies that were the output of the system to very brief inputs be measured one could observe the system under conditions in which control of gain has not yet reached that level of effectiveness which results in power law input-output relations when the input is of longer duration.

What are the consequences of these considerations with respect to the perceptual domain or, more specifically, with respect to visual brightness measured by intra-sensory matching procedures? The results of experiments employing mangitude estimation procedures show that for stimulus durations (1 sec) approaching quasi-steady state conditions subjective brightness increases as a power of luminance with an exponent equal to .33 (Mansfield, 1973; Anglin & Mansfield, 1968; Stevens & Hall, 1966). In view of these findings I make the assumption that the subjective brightness of the steady state matching field employed in Experiment II increases as the cube root of luminance. This assumption implies that if in an intra-sensory matching procedure Log matching field luminance increases linearly with the Log of the luminance of a brief pulse of light and this relation has unity slope, then it can be inferred that the subjective brightness of the transient is related to intensity in a similar manner as that of the steady state stimulus. It follows, furthermore, that if the slope of the relation is greater than unity it can be inferred that the subjective brightness of the transient stimulus increases as a power of luminance with an exponent which is greater than that for the steady state stimulus.

It will be remembered that the latter state of affairs is predicted by the feedback model under the simplifying assumption that the feedback signal acts with zero delay. Under more realistic assumptions of a finite feedback delay the brightness response of the system to very brief inputs may not be related to stimulus intensity by a simple power function.[24] This state of affairs would be reflected by the presence of a non-linear relation between Log luminance matching field and Log luminance transient. In order to investigate this proposition, Experiment V was designed to measure the brightness of a single (2 msc) pulse stimulus at different levels of stimulus luminance.

Experiment V

The procedure and apparatus for this experiment were identical to that outlined for Experiment II. Measures of the brightness of a single 2 msc pulse were obtained for each of the 9 luminance levels used in Experiment IV to measure two-pulse fusion thresholds. Since the luminance levels in the previous 4 experiments were specified with respect to the illuminance above absolute foveal threshold of a 30' two-pulse stimulus of 3 msc onset-to-onset interval, luminance for a single 2 msc pulse shall be similarly specified.

Figure (27) graphically displays the relation between Log stimulus illuminance of a single pulse and the illuminance of a steady (matching) field required to match the apparent brightness of a single pulse for one observer. The illuminance of the steady field is expressed in terms of Log units above its absolute foveal threshold for this observer. It can be seen that for the 3 lowest stimulus illuminances Log brightness increases nearly linearly with Log illuminance. For the remaining illuminances single-pulse brightness appears to be non-linearly related to stimulus illuminance. Figure (28) shows the calculated gain[25] at the various illuminances. As can be seen, gain increases non-linearly with stimulus illuminance with maximum gain indicated for the higher illuminance levels.

An interpretation of the gain function in Figure (28) may be aided by considering the following propositions: if zero gain had been obtained for all illuminance levels this would merely express the fact - by the definition of gain in this representation - that equal increases in the luminance of the transient are matched by equal increases in the luminance of the steady field. If the assumption is granted that the subjective brightness of a (quasi) steady state input increases as a power of the intensity of the input with a fractional exponent of .33, then zero gain implies that the subjective brightness of the transient is related to luminance in identical fashion. Similarly, if the gain in Figure (28) were to increase linearly with increases in illuminance it can be inferred that the subjective brightness of the transient increases as a power of illuminance with an exponent which is larger than that under (quasi) steady state conditions. On the other hand, to the extent that gain increases non-linearly with illuminance it can be inferred that the brightness-intensity relation for brief inputs cannot be described by a simple power function. Figure (28) suggests the existence of the latter state of affairs. Some independent evidence for this hypothesis will be provided in the discussion of the results of Experiment V.

The gain vs Log illuminance (single pulse) function may be compared with Log $1/\tau$ vs Log illuminance (double pulse) function (Figure 26 same page). It can be seen that illuminance levels resulting in a maximum decrease of the time constant τ (i.e. maximum increase in $1/\tau$) correspond to the illuminance levels resulting in maximum gain. This correspondence is consistent with the operation of a system which time constant is controlled by its output (i.e. gain). For such a system one would expect a large gain to result in a correspondingly large decrease in the time constant. The compatibility of the functions with respect to the predictions of the gain-control model provides additional support for the assumption that fusion threshold measures provide valid estimates of the time constant.

In discussing the results of Experiment II, that is the functions relating apparent brightness to double-pulse interval, it was noted at that time that a double-pulse of very brief interval was judged to be considerably brighter (.7 Log) than a single pulse under stimulus illuminances corresponding to T + 1.75 and T + 2.25 Log for a double-pulse of 3 msc onset-onset interval. It was, furthermore, noted at that time that such a large brightness difference was inconsistent with the expectation that the brightness of a double pulse of 3 msc onset-onset interval and pulse amplitude I, which can be considered to be virtually a single pulse of amplitude 2 x I, should be brighter by approximately .3 Log than a single pulse of amplitude I. Inspection of the gain vs Log illuminance (single pulse) function suggests that this expectation may not be justified. The gain function indicates that a near doubling of illuminance from T + 1.95 to T + 2.25 Log has the result of increasing the gain of the system by approximately 9 Db. In terms of brightness this means that the system shows a <u>change</u> in brightness gain of approximately .45 Log. It follows directly that were the illuminance of a single pulse at T + 1.95 Log doubled by replacing this stimulus by a 3 msc double-pulse of an illuminance corresponding to T + 2.25 Log, the apparent brightness of the latter should increase by .3 + change in gain = .75 Log, a value which is satisfactorily close to the obtained brightness difference (Figure (15)). The gain function indicates, furthermore, that a doubling of illuminance at those levels of input where the gain changes little with changes in input should result in brightness differences between a single pulse and a 3 msc double pulse which are much closer to .3 Log. Inspection of the T + 2.75 Log brightness function for observer L. S. (Figure 21) shows this to be the case.

The results of this experiment support the conclusion that if the response of the system to very brief inputs, be they single pulses of light or double-pulses of brief interval, is measured the output of the system (i.e. its brightness response) will manifest a lack of 'effective' gain control. In terms of the model, the outcome of an 'effective' gain control is an input-output relation which can be described by a simple power function. The presence of such input-output relation can be inferred, as mentioned above, from a linear relation between input level and gain. It was mentioned earlier that the lack of effective gain control can be assumed to be due to the fact that for a system in which the gain is output-controlled and which incorporates feedback delays the gain cannot be an instantaneous function of the input. The latter consideration suggests, on the other hand, that were the output of the system measured at some later time the characteristics of effective control of gain by the system may become manifest. In other words, if a second pulse of light were to follow the first with a delay sufficiently long to permit the output-control of the system's time constant to become effective the combined effects of the two pulses should display the extent of effective gain control. Experiment VI was, therefore, designed to measure the brightness response, at different levels of stimulus illuminance, to two pulses of light separated by a delay period which corresponded to the system's time scale for each of the different illuminance levels.

Experiment VI

Brightness matches were obtained under 9 conditions of stimulus illuminance ranging from T + 1.25 to T + 3.25 Log. For a given illuminance condition the stimulus was a double-pulse with a pulse interval equal to the time constant for that illuminance level as estimated by the fusion threshold measures obtained in Experiment IV. Procedure and apparatus was otherwise identical to that described for the previous experiments.

Figure (29) graphically shows the apparent brightness of a two-pulse stimulus as a function of Log stimulus illuminance when the pulse interval is equal to the time constant. Brightness values (vertical axis) are expressed in terms of the relative illuminance of the steady field required to match the brightness of the two-pulse stimulus. Comparison with Figure (27) on the same page indicates that the brightness of a double-pulse, when the ISOI = τ, is a generally more linear function of stimulus illuminance than the brightness of a brief, single pulse. Deviations from linearity for the two-pulse function are, however, still indicated for the medium and high illuminances. Figure (30) graphically displays the calculated gain in two-pulse brightness as a function of Log stimulus illuminance. Comparison with Figure (31) on the same page indicates that the over-all brightness gain for the two-pulse stimulus has been substantially reduced relative to that for the single-pulse stimulus. The gain function for the former stimulus still indicates a maximum gain at the higher illuminances, the magnitude of maximum gain being, however, substantially reduced. Comparison of the two-pulse gain function with the Log $1/\tau$ vs Log illuminance function (Figure (26)) shows that maximum brightness gain occurs at illuminances which result in maximum reduction of the time constant, this relationship being consistent with the one observed in Experiment V.

It will be remembered that by the definition of 'gain' in the representation in Figure (30) and Figure (31) a constant gain of zero across all illuminance levels expresses a linear relation of unity slope between the luminance of the transient stimulus and the luminance of the steady matching field and that it may be inferred from such a relation that the brightness response to transient input increases at the same rate as the corresponding response to steady-state input. In other words, if one grants the assumption that the subjective brightness of the steady-state stimulus increases as a power of intensity with an exponent equal to .33 then it follows that to the extent a constant zero-gain is evident the input-output relation for a transient stimulus approximates the input-output relation for the steady state stimulus.

From the presence of the relatively small (average) gain in Figure (30) it can, therefore, be inferred that when the brightness response to two pulses is measured under conditions where the second pulse follows the first with a delay sufficiently long to reflect the time scale of the system the brightness-intensity relation will approximate a simple power function. Furthermore, the exponent of this power function will approximate that for steady-state input, reflecting an effective control of gain or, in other words, an effective reduction in the dynamic range of response. It is suggested that the characteristics of effective gain control become manifest in the two-pulse situation because the introduction of a (delayed) second pulse causes the brightness response to be measured at a later time, as it were, relative to the onset of the first pulse. The substantial, non-linear increase in gain Figure (31) indicates, on the other hand, that when the brightness response is measured at an early time, as it were, relative to the onset of the pulse initiating the feedback control of the time constant (single- or brief double pulse situation) the brightness-intensity relations cannot be described by a simple power function.

The foregoing conceptualization would be considerably strengthened if it could be demonstrated that the brightness-intensity relation for brief inputs cannot be described by a simple power function while the corresponding relation for longer duration inputs can. Appendix D shows the empirical relation between brightness and intensity for a number of pulse durations. The data were obtained by re-analyzing the findings published by Raab (1962) on magnitude estimates of visual brightness as a function of stimulus duration and luminance. Values of the magnitude estimates for each combination of luminance and duration were obtained from the published graph by measurement. Magnitude estimates were then converted to Log values and plotted against equivalent energy. The solid lines in Appendix D connect the data points for each of 7 stimulus durations (.5,1,2,5,10,20,50 msc). The dashed line connects the data points for a 100 msc stimulus. It can be seen that even though the brightness-intensity relation for all stimulus duration shows a concave-downward deviation from linearity, this trend is much less pronounced for the long stimulus duration than for the set of short durations. The data suggest that for the shorter durations brightness is not related to energy in a simple manner: if one disregards, for a moment, the two high magnitude estimates at .74 and .84 Log relative energy, it would seem that the data for the short durations are best fitted by two straight line-segments of different slopes intersecting at about 2.04-2.54 Log relative energy. It should be noted at this point that analysis of the brightness-duration-luminance relations as determined by intra-sensory matching procedures and direct magnitude estimation methods has suggested to some investigators (Aiba & Stevens, 1964; Stevens & Hall, 1966; Stevens, 1966) that a concave downward relation should be expected only for some (intermediate) stimulus durations within that region of durations where the input-output relations change from a (flash) exponent of .5 to a (steady-state) exponent of .33. It may also be noted that were the magnitude estimates for flashes of equivalent energy averaged across all durations within the Bloch-law region any deviation from Log-Log linearity would have to be less pronounced (for example Mansfield, 1973; his Figure (3)).

The results of the last three experiments and of the re-analysis of the Raab (1962) data suggest the following generalization: to the extent that the stimuli - be they single pulses of light or double-pulses - are of brief duration flash brightness, whether measured in terms of Log matching field luminance or in terms of Log direct (magnitude) estimates, increases non-linearly with Log stimulus intensity; to the extent that the stimuli are of longer duration relative to the time scale of the system Log brightness will tend towards a linear function of Log intensity.

SUMMARY AND CONCLUSION

In a series of experiments the temporal discrimination and resolution characteristics of the eye and its brightness responses to brief stimuli were investigated.

Experiment I showed that the optimal discrimination of pulse interval differences shifts towards shorter pulse intervals when illuminance increases with increasing stimulus size, and an absence of such shift when illuminance above threshold was kept constant with increases in stimulus size. The direction of the shift of the temporal locus of optimal interval difference discrimination was found to be inconsistent with the predictions derived from one interpretation of the temporal dispersion model. The discrimination functions relating interval difference thresholds to pulse interval, furthermore, showed a secondary rise and fall in thresholds at medium pulse intervals which was interpreted as reflecting fluctuations in the rate at which apparent brightness decreases with increases in pulse interval.

Experiment II investigated the brightness of two-pulse stimuli as a function of pulse interval with stimulus illuminance as parameter. The results of this experiment indicated the occurrence of changes in the rate of brightness decrease within restricted and well-defined pulse interval regions which corresponded to the pulse intervals for which a secondary rise and fall of difference thresholds was observed. This finding suggested that for short and medium pulse intervals the interval discrimination function for a given leve of stimulus size and illuminance may be predicted by differentiating the corresponding brightness function. Experiment III, therefore, replicated the discrimination functions for one observer, using smaller increments in (standard) pulse interval, and it was shown that the discrimination functions estimated from the first derivative of the brightness function approximates the experimentally obtained discrimination function.

The experimental findings obtained up to this point suggested a modification of the temporal dispersion model in two respects: (1) Shifts in the discrimination function minima towards shorter intervals with increases in illuminance may be accounted for by assuming changes in the distribution of peripheral response latencies when stimulus conditions are changed rather than by assuming associated changes in the distribution of conduction velocities. (2) Since the brightness functions for the higher stimulus illuminances showed an attentuation of two-pulse brightness relative to single-pulse brightness for a region of medium pulse intervals it was suggested that the ensemble response of the visual system to pulse stimuli of higher illuminance should be considered as diphasic rather than monophasic. The negative phase of the diphasic response was assumed to reflect inhibitory processes associated with gain control which are maximally effective at latencies of approximately 60 msc.

In order to provide some empirical support for the above assumption, Experiment IV investigated one aspect of the impulse transfer function. It was shown that the dark time-constant τ, as estimated by the two-pulse fusion threshold, changes in systematic fashion with changes in stimulus illuminance and that the shape of this function corresponds closely to that predicted by one model postulating a negative feedback gain control mechanism.

Experiment V was designed to investigate the implication of assuming a delay in the negative feedback loop of the gain control mechanism. It was shown that the apparent brightness of a very brief pulse of light changes in non-linear fashion with increases in stimulus illuminance. Comparison of the brightness gain with the time constant τ for comparable levels of illuminance indicated a close correspondence between maximum brightness gain and maximum decrease in the time constant - demonstrating the consistency of the experimental findings with the gain control model. The non-linearity of single pulse brightness was consequently interpreted as reflecting the relative absence of effective gain control when the response of the system to very brief inputs is measured. On the basis of these results it was possible to explain the unexpectedly large brightness differences between a single pulse and a double pulse of very brief interval which had been observed in Experiment II for some illuminance conditions.

Experiment VI added further support to the above interpretation by showing that if the second light pulse of a pair follows with a delay corresponding to the time scale of the system the brightness response will manifest effective gain control. It was shown that under these conditions two-pulse brightness approaches a linear function of Log stimulus illuminance and it was argued that the presence of such linear relationship obtained by intra-sensory matching procedures indicates a simple power law relation between subjective brightness and transient illuminance. A re-analysis of some published data on magnitude estimates of the subjective brightness of brief stimuli provided additional support for the findings and conslusions generated by Experiments IV - VI by showing that for stimuli of equivalent energy within the Bloch law region the brightness - energy relationship approaches a simple power function for stimuli of longer duration but not for stimuli of brief duration.

I shall briefly return to the findings of Experiment I. It was shown there that the temporal locus of optimal interval difference discrimination shifts towards shorter pulse intervals with increases in stimulus illuminance. In the discussion of the temporal dispersion model it was suggested that the shift can be accounted for in terms of assuming associated changes in the temporal disperion of the ensemble response. In view of the obtained data on the visual brightness of transients, this change in the dispersion of the ensemble response may be assumed to reflect the operation of two mechanisms. Firstly, increases in illuminance will decrease the time constant for a given channel, that is to say it will increase the speed of the channel response. Decreases in the time constant are, consequently, reflected by a reduction in the mean latency of ganglion cell response. Secondly, due to the assumed constant relation between the mean latency and the standard deviation of the peripheral latency distribution, the temporal disperion of the ensemble response will be reduced to the extent that the mean (channel) time-constant is reduced. The overall effect of a reduction in channel τ is, therefore, a reduction in the time constant of the ensemble response. It follows immediately that the shift in the discrimination function minima towards shorter pulse intervals reflects an associated reduction of the mean channel time-constant. The discrimination function for stimulus size 7.5° when the illuminance is at approximately T + 4.5 Log (Figure (7)) suggests a mean channel time-constant of approximately 60 msc for this stimulus condition.

It was noted in Experiment I that the extent of the secondary rise and fall in thresholds at medium pulse intervals diminished when illuminance increased with increasing stimulus size. A similar effect was observed in Experiment III when illuminance was increased by increasing luminance, keeping stimulus size constant. To the extent that these variations in thresholds reflect underlying variations in apparent brightness it is possible that the latter are an (early) analog of the high frequency oscillations of brightness observed at pulse intervals beyond 60 msc for the higher stimulus illuminances. The presence of a high-frequency component of at least 60-70 Hz in the power spectra of the brightness functions suggests that this may be the case. It is, therefore, possible that oscillations in brightness at pulse intervals shorter than 60 msc are another manifestation of the operation of a gain control mechanism, based on negative feedback principles, which imposes complex oscillations in response on the system due to the interaction of a network consisting of elements with different feedback delay constants.

It is, finally, suggested that future research attempting to investigate phenomena associated with responses to pulse intervals of short or medium duration may not be substantially advanced by techniques such as interval discrimination. The success of the brightness matching procedure in explaining some of the phenomena reported in this research suggests an alternative research avenue for this temporal range of stimuli offering, perhaps, greater success.

FOOTNOTES

[1] At constant energy above threshold the average measured illuminance across observers was not precisely constant for different visual angles. The average illuminance for the 7.5° target was larger by a factor of ca. 5 than that for the 10' target. See Table (2).

[2] Sylvania R1131C.

[3] Hewlett-Packard Model 6209-B.

[4] E. E. & G. Model 580/585. Measured illuminance obtained with a 30' field stop in place.

[5] T. H. Nilsson, Behav. Res. Meth. Inst. 1, 256 (1969).

[6] Bausch & Lomb 7X Hastings Triplet.

[7] Carl Zeiss 90 mm f.l. P-Planar projection lens.

[8] Kodack Iconel.

[9] Tiffen.

[10] Edmund Scientific Model 70,774 gunsight with Kodack Wratten 89 - B filter.

[11] The term 'stimulus' shall refer to a double-pulse package of light.

[12] Siegel W., Behav. Res. Meth. Inst., 4,105, (1972) The periodicity of the FRAN( ) function is in the neighbourhood of 67 million.

[13] Interpolation and threshold calculation was programmed in PDP-8 FORTRAN.

[14] E. E. & G. Model 580/585. Measured illuminance obtained with a 30' field stop in place.

[15] General Electric No. 1142.

[16] Harrison DC Model 6434 B.

[17] In this and all other graphs luminance is specified in terms of luminance above threshold of two 2-msc pulses with a 3-msc onset-to-onset interval.

[18] The estimation procedure was programmed in FOCAL-RT and is contained in the subprogram GRAPH shown in Appendix F.

[19] This section follows closely the paper by Sperling & Hill, 1964: Linear Theory and the Pscyhophysics of Flicker.

[20] Frequency analysis was performed with a LINC-8 program using the Fast Fourier Transform Algorithm. The obtained amplitude spectra (after digital filtering) were integrated to obtain the power density spectra. Values on the vertical axis are abitrary and represent Watt/Hz.

[21] Since pulse intervals were incremented in steps of 3 msc, the observed frequency of the oscillations may be a multiple of a higher 'true' frequency. The results of a subsequent experiment suggest the presence of high-frequency oscillations with a period of 5 msc for observer L.S. For possible physiological correlates of these high-frequency oscillations see: Wachtmeister L. "On the oscillatory potentials of the human electroretimegram in light and dark adaptation." Acta Ophthalmel. (Kobhg.), 1972, Suppl., 116.

[22] From Ratliff et al., J. Opt. Sco. Am., 53, 110, (1963).

[23] The entry for T + 3.50 shown in Table 8 was obtained from a replication of Experiment IV performed at a later date.

[24] This author does not have the necessary mathematical competence to determine the implication of violations of this assumption within the Sperling & Sondhi model. The proposition that for a finite delay system very brief inputs will not result in simple power law relations is, therefore, an assumption on the part of this author.

[25] The gain of an input-output system is defined by the relation E_o/E_i where E_o and E_i are the output- and input

quantities respectively. In this paper the quantities E_o and E_i are defined by the luminance (above absolute visual threshold) of the matching and transient target respectively. The added density at threshold of the steady-state matching field was 5.08 Log for observer L. S. This value (and the gain calculation) does not include the equivalent neutral density (.63 Log) of a number of color-correction filters which were necessary in the matching channel throughout the experiments.

BIBLIOGRAPHY

Aiba, T. S. and Stevens, S. S., Relation of brightness to duration and luminance under light- and dark-adaptation. Vis. Res., 1964, 4, 391-401.

Anglin, J. M. and Mansfield, J. W., On the brightness of short and long flashes. Perception & Psychophys. 1968, 4, 161-162.

Bartley, S. H. and Nelson, T. M. Some relations between sensory end results and the neural activity in the optic pathway. J. of Psychol., 1963, 55, 121-143.

Bartley, S. H. and Wilkinson, F. W. Certain factors in producing complexity of responses to a single pulse of light. J. of Psychol., 1953, [illegible], 299-306.

Bartlett, J. R. and Doty, R. W. Response of units in the striate cortex of squirrel monkeys monkey to visual and electrical stimuli. J. Neurophysiol., 1974, 37, 621-641.

Baumgardt, E. and Segal, J. La fonction inhibitrice dans le processus visuel. C. R. Soc. Biol., 1946, 140, 231-233.

Bidwell, S. Curiosities of light and sound. Swan Sonnenschein and Company, London, 1899.

Bird, J. F. and Mowbray, G. H. Analysis of transient visual sensations above the flicker fusion frequency. Vision Res., 1973, 13, 673-687.

Bishop, G. H. and Clare M. H. Organization and distribution of fibres in the optic tract of the cat. J. Comp. Neurol., 1955, 103, 269-304.

Cleland, B. G. and Enroth-Cugell C. Quantitative aspects of gain and latency in the cat retina. J. Physiol. (London). 1970, 206, 73-91.

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

Davies, P. W. The action potential. In: Medical Physiology, Vol. II. V. B. Mountcastle (Ed.), C. C. Mosby Company, St. Louis, 1968.

Donchin, E., Wicke, J. D. and Lindsley, D. B. Cortical evoked potentials and perception of paired flashes. Science, 1963, 141, 1285-1286.

Dunlap, K. The shortest perceptibel time interval between two flashes of light. Psychol. Review, 1915, 22, 226-250.

Efron, R. The relationship between the duration of a stimulus and the duration of a perception. Neuropsychologia, 1970 (a), 6, 37-66.

Efron, R. The minimum duration of a perception. Neuropsychologia, 1970 (b), 8, 57-63.

Efron, R. An invariant characteristic of perceptual systems in the time domain. In: Attention and Performance. S. Kornblum (Ed.), Academic Press, New York, 1973 (c).

Enroth-Cugell C. and Robson, J. G. The contrast sensitivity of retinal ganglion cells of cat. J. Physiol., 1966, 187, 517-552.

Fatt, P. and Katz, B. The effect of inhibitory nerve impulses on a crustacean muscle fibre. J. Physiol. (London), 1953, 121, 374-389.

Fuortes, M. G. F. and Hodgkin, A. L. Changes in the time scale and sensitivity ~~in~~ the ommatidia of Lumulus. J. Physiol. (London), 1964, 172, 239-263.

Fudaka, Y. Receptive field organization of cat optic nerve fibres with special reference to conduction velocity. Vision Res., 1971, 11, 209-226.

Graham, C. H. and Kemp, E. H. Brightness discrimination as a function of the duration of the increment of intensity. J. Gen. Physiol., 1938, 21, 635-650.

Grossberg, M. Frequencies and latencies in detecting two-flash stimuli. Percept. & Psychophys., 1970, 7, 377-380.

Grüsser, O. J. and Kapp, H. Reaktionen retinaler neurone nach Lichtblitzen. II. Doppelblitze mit wechselnden Blitzabstand. Pflüger'sArch. 1958, 266, 111-129.

Hartline, H. K. The effects of spatial summation in the retina on the excitation of the fibres of the optic nerve. Am. J. Physiol. 1940, 130, 700-711.

Hartline, H. K. Intenstiy and duration in the excitation of single photoreceptor units. J. Cellul. & Comp. Physiol. 1934, 5, 229-247.

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

Herrick, R. M. Foveal increment thresholds for multiple flashes. J. Opt. Soc. Am. 1973, 63, 870-878.

Herrick, R. M. Increment thresholds for two identical flashes. J. Opt. Sco. Am. 1972, 62, 104-110.

Herrick, R. M. and Theissen, C. J. Increment thresholds for two non-identical flashes. J. Opt. Soc. Am. 1972, 62, 588-593.

Herrick, R. M. Foveal luminance discrimination as a function of the duration of the decrement or increment in luminance. J. Comp. Physiol. Psychol. 1956, 49, 437-443.

Hoffman, K. P. Conduction velocity in pathways from retina to Superior Colliculus in cat: A correlation with receptive fields. J. Neurophysiol., 1973, 36, 409-424.

Ikeda, M. and Fujii, T. Diphasic nature of the visual response as inferred from the summation index of n flashes. J. Opt. Soc. Am. 1966, 56, 1129-1132.

Ikeda, M. Temporal summation of positive and negative flashes in the visual system. J. Opt. Soc. Am. 1965, 55, 1527-1534.

Katz, B. Nerve, Muscle, and Synapse. McGraw-Hill, 1966.

Kelly, D. H. Visual responses to time-dependent stimuli. II. Single channel model of the photopic visual system. J. Opt. Soc. Am. 1961, 51, 747-754.

Kietzman, M. L. and Sutton, S. The interpretation of two-pulse measures of temporal resolution in vision. Vision Res. 1968, 8, 287-302.

Kietzman, M. L. Two-pulse measures of temporal resolution as a function of stimulus energy. J. Opt. Soc. Am. 1967, 57, 809-13.

de Lange, H. Experiments on flicker and some calculations on an electrical analogue of the foveal system. Physica, 1952, 935-950.

Levick, W. R. Variation in the response latency of cat retinal ganglion cells. Vision Res. 1973, 13, 837-853.

Levick, W. R. and Zacks, J. L. Responses of cat retinal ganglion cells to brief flashes of light. J. Physiol. (London). 1970, 206, 677-700.

Lewis, M. F. Two-flash thresholds as a function of flash luminance and area. Percept. & Psychophys. 1968, 4, 241-244.

Lewis, M. F. Two-flash thresholds as a function of luminance in the dark-adapted eye. J. Opt. Soc. Am. 1967, 57, 814-815.

Lewis, M. F. and Mertens, H. W. Two-flash thresholds as a function of comparison stimulus duration. Aerospace Medicine, 1971, 42, 393-395.

Mahneke, A. Fusion thresholds of the human eye as measured with successive light flashes. Acta Ophthal., 1958, 36, 12-18.

Mansfield, R. J. W. Brightness function: effect of area and duration. J. Opt. Soc. Am., 1973, 63, 913-920.

Matin, L. Critical duration, the differential luminance threshold critical flicker frequency and visual adaptation: A theoretical treatment. J. Opt. Soc. Am., 1968, 58, 404-415.

Marks, L. E. Visual Brightness: some applications ~~of~~ a model. Vision Res., 1972, 12, 1409-1423.

Mertens, H. W. and Lewis, M. F. Temporal discrimination of two-pulse stimuli as a function of psychophysical method and luminance. J. Opt, Soc. Am., 1972, 62, 823-826.

Nilsson, T. H. Temporal dispersion in the visual pathway, some evidence and implications. In: Symposium on alternation of response. T. M. Nelson, S. H. Bartley, C. M. Bourassa and R. J. Ball (Eds.). J. Gen. Psychol., 1971, 84, 3-177.

Nilsson, T. H. Two-pulse difference thresholds and their implications about sensory processes which limit temporal acuity. M.Sc. Thesis, University of Alberta, 1968.

Nilsson, T. H. Two-pulse interval thresholds. J. Opt. Soc. Am., 1969, 59, 753-756.

Noda, H., Iwama K. Unitary analysis of retinogeniculate response time in rats. Vis. Res., 1967, 7, 205-213.

Ogawa T., Bishop, P. O. and Levick, W. R. Temporal characteristics of response to photic stimulation by single ganglion cells in the unopened eye of the cat. J. Neurophysiol., 1966, 29, 1-30.

Petry, S., Hood, D. C. and Goodkin, F. Time course of lateral inhibition in the human visual system. J. Opt. Soc. Am. 1973, 63, 385-386.

Phillips; W. A. and Singer W. Function and interaction of ON and OFF transients in vision. I. Psychophysics. Exp. Brain Res., 1974, 19, 493-506.

Polyanskii, V. B. Cycles of excitability in neurons of visual cortex in waking rabbits in response to double flashes. Neurosciences Translations, 1967, 4, 383-389.

Rashbass, C. The visibility of transient changes of luminance. J. Physiol. (London). 1970, 310, 165-186.

Rashbass, C. Transformations of waveform under which incremental visual thresholds are invariant. Vision Res., 1974, 14, 97-99.

Ratliff, F., Hartline, H. K. and Miller, W. H. Spatial and temporal aspects of retinal inhibitory interaction. J. Opt. Soc. Am., 1963, 53, 110-120.

Regan, D. A high frequency mechanism which underlies visual evoked potentials. Electroenceph. Clin. Neurophysiol., 1968, 25, 231-237.

Rodieck, R. W. and Stone J. Analysis of receptive fields of cat retinal ganglion cells. J. Neurophyiol., 1965, 28, 833-849.

Roufs J. A. J. Dynamic properties of vision I. Experimental relationships between flicker and flash thresholds. Vision Res., 1972, 12, 261-278.

Roufs, J. A. J. Dynamic properties of vision: II. Theoretical relationships between flicker and flash thresholds. Vision Res., 1972, 12, 279-291.

Roufs, J. A. J. Dynamic properties of vision: III. Twin flashes, single flashes and flicker fusion. Vision Res., 1973, 13, 309-323.

Schuckman, H. and Orbach, J. Detection thresholds as a function of interval separation between successive targets. Science, 1965, 150, 1623-1625.

Sperling, G. and Hill, M. Linear theory and the psychophysics of flicker. Doc. Ophthalmol., 1964, 18, 3-15.

Sperling, G. and Sondhi, M. M. Model for visual luminance discrimination and flicker detection. J. Opt. Soc. Am., 1968, 58, 1133-1145.

Stone, J. A. quantitative analysis of the distribution of ganglion cells in the cat's retina. J. Comp. Neurol., 1965, 124, 337-352.

Stone, J. and Freeman, R. B. Conduction velocity groups in the cat's optic nerve classified according to their retinal origin. Exp. Brain Res., 1971, 13, 489-497.

Stone, J. and Hoffman, K. P. Conduction velocity as a parameter in the organization of the afferent relay in the cat's lateral geniculate nucleus. Brain Re., 1971, 32, 454-459.

Stone J. and Hollander H. Optic nerve axon diameters measured in the cat's retina: some functional considerations. Experimental Brain Res., 1971, 13, 498-503.

Stone J. and Fabian M. Specialized recpetive fields in the cat's retina. Science, 1966, 152, 1277-1279.

Singer W. and Phillips, W. A. Function and interaction of ON and OFF transients in vision. II. Neurophysiology. Exp. Brain Res., 1974, 19, 507-521.

Stevens, J. C. and Hall, J. W. Brightness and loudness as a function of stimulus duration. Perception & Psychophys., 1966, 1, 319-327.

Stevens, S. S. Duration, luminance and the brightness exponent. Perception & Psychophys., 1966, 1, 96-100.

Tittarelli, R. M. and Marriott, F. H. Temporal summation in foveal vision. Vision Res., 1970, , 1477-1481.

Uets[illegible]i, T. and Ikeda, M. Study of temporal visual response by summation index. J. Opt. Soc. Am., 1970, 60, 377-381.

van der Tweel, L. H. and Verduyn Lunel, H. F. E. Human visual responses to sinusoidally, modulated light. Electroenceph. Clin. Neurophysiol., 1965, 18, 587-598.

Venables, P. H. and Warwick-Evans, L. A. The effect of stimulus amplitude on the threshold of fusion of paired flashes. Quarterly J. Exp. Psychol., 1968, 20, 30-37.

Zacks, J. L. Estimation of the variability of the latency of response to brief flashes. Vision Res., 1973, 13, 829-835.

Raab, D. H. Magnitude estimation of the brightness of brief foveal Stimuli. Science, 1962, 135, 42-44.

TABLES

TABLE I

ABSOLUTE FOVEAL THRESHOLDS FOR A TWO-PULSE STIMULUS OF 3 MSC INTERVAL

Observer	Visual Angle	Added Density at Threshold (Log)	Added Density for Constant Luminance (Log)	Illuminance Above Threshold (Log)
L. S.	10'	4.76	2.91	T + 1.85
	25'	5.16	2.91	T + 2.25
	1.0°	5.32	2.91	T + 2.41
	2.5°	6.15	2.91	T + 3.34
	7.5°	7.46	2.91	T + 4.55
D. N.	10'	4.41	2.55	T + 1.86
	25'	4.80	2.55	T + 2.25
	1.0°	5.60	2.55	T + 3.05
	2.5°	6.31	2.55	T + 3.76
	7.5°	7.41	2.55	T + 4.86
J. P.	10'	4.46	2.70	T + 1.76
	25'	4.95	2.70	T + 2.25
	1.0°	4.95	2.70	T + 2.25
	2.5°	5.74	2.70	T + 3.04
	7.5°	7.16	2.70	T + 4.46

TABLE 1 (Continued)

Observer	Visual Angle	Added Density at Threshold (Log)	Added Density for Constant Energy Above Threshold (Log)	Illuminance Above Threshold (Log)
L. S.	10'	4.76	2.51	T + 2.25
	25'	5.16	2.91	T + 2.25
	1.0°	5.32	3.29*	T + 2.25
	2.5°	6.15	4.12*	T + 2.25
	7.5°	7.46	5.11*	T + 2.25
T. G.	10'	3.78	1.63*	T + 2.25
	25'	5.07	3.04*	T + 2.25
	1.0°	5.58	3.33	T + 2.25
	2.5°	6.64	4.49*	T + 2.25
	7.5°	7.46	5.11*	T + 2.25
H. B.	10'	4.57	2.32	T + 2.25
	25'	5.09	3.04*	T + 2.25
	1.0°	5.38	3.13	T + 2.25
	2.5°	6.17	3.92	T + 2.25
	7.5°	7.26	4.91*	T + 2.25

*Adjusted for Filter Non-Equivalence

TABLE 2

MEASURED AVERAGE ILLUMINANCE AND CALCULATED LUMINANCE FOR EACH OF FIVE VISUAL ANGLES

Visual Angle*	Average Added Density for Constant Luminance (Log)	Average Measured Illuminance (Lumen/cm^2)	Calculated Luminance (candela/m^2)
10'	2.72	7.0 X $10^{-9.72}$	2.00 x 10^0
24' 30"	2.72	4.85 X $10^{-8.72}$	2.33 x 10^0
58' 30"	2.72	2.6 X $10^{-7.72}$	2.13 x 10^0
2.5°	2.72	2.02 X $10^{-6.72}$	2.59 x 10^0
7° 26'	2.72	1.63 X $10^{-5.72}$	2.34 x 10^0

Visual Angle	Average Added Density for Constant Energy above Threshold (Log)	Average Measured Illuminance (Lumen/cm^2)	Calculated Luminance (candela/m^2)
10'	2.15	7.0 X $10^{-9.15}$	3.13 x 10^0
24' 30"	2.72	6.85 X $10^{-8.72}$	2.33 x 10^0
[illegible] 30"	3.25	2.6 X $10^{-8.25}$	6.29 x 10^{-1}
2.5°	4.18	2.03 X $10^{-8.18}$	8.95 x 10^{-2}
7° 26'	5.04	1.63 X $10^{-8.04}$	1.12 x 10^{-2}

*Nominal Values.

TABLE 3

INTERVAL DIFFERENCE THRESHOLDS

Visual Angle:	10'	25'	1.0°	2.5°	7.5°
Observer: L. S.	Constant Luminance				
Interval: (msc)	Threshold Increment (msc)				
3	31.3	19.4	12.4	15.4	12.5
10	17.1	9.6	9.4	9.5	6.9
20	17.3	9.1	6.7	8.3	7.0
30	17.5	7.4	4.8	4.5	6.8
40	26.4	7.1	6.0	4.7	6.2
50	28.0	10.3	8.8	5.4	7.5
60	22.7	14.4	6.4	3.9	4.6
70	14.7	7.2	4.4	4.0	5.2
80	14.7	6.4	4.4	4.8	10.3
100	10.4	7.1	14.3	13.2	14.3
120	22.5	14.7	13.5	13.2	13.9
140	19.2	18.3	9.2	17.7	20.0
Observer: J. P.	Constant Luminance				
	Threshold Increment (msc)				
3	28.1	21.5	19.2	16.5	13.8
10	24.5	11.5	12.5	6.9	7.1
20	25.0	11.0	7.9	7.2	7.8
30	16.0	9.5	7.5	6.7	6.8
40	28.0	11.8	9.9	9.6	7.0
50	20.8	18.1	13.5	6.8	8.7
60	16.9	14.4	10.8	5.0	2.5
70	11.2	9.9	7.5	3.9	5.6
80	8.2	8.2	5.2	4.3	11.0
100	12.5	9.2	12.5	21.0	16.1
120	18.9	11.4	18.5	15.0	16.2
140	18.5	16.7	20.0	18.2	12.5

TABLE 3 (Continued)

Visual Angle:	10'	25'	1.0°	2.5°	7.5°
Observer: D. N. Interval: (msc)	Constant Luminance Threshold Increment (msc)				
3	95.7	103.2	51.5	65.5	70.3
10	57.5	77.1	63.9	61.0	66.1
20	71.6	72.5	48.0	46.1	48.9
30	65.5	56.2	61.5	48.0	34.2
40	55.4	44.9	37.0	35.7	26.3
50	50.7	36.6	27.1	25.7	11.6
60	41.5	24.2	20.2	8.9	7.5
70	34.8	16.2	6.9	7.2	7.9
80	19.2	9.5	9.4	9.4	22.2
100	19.3	25.0	23.3	23.7	17.7
120	40.4	33.6	31.8	22.5	28.0
140	38.2	57.5	35.0	27.5	32.5
Observer: L. S. Interval: (msc)	Constant Illuminance Threshold Increment (msc)				
3	35.2	19.4	16.2	15.7	21.9
10	31.2	9.6	9.9	12.2	11.3
20	27.9	9.1	9.0	11.0	16.7
30	35.7	7.4	6.1	10.3	10.0
40	36.2	7.1	5.8	9.9	28.7
50	25.4	10.3	5.5	7.5	27.9
60	22.5	14.4	10.5	12.0	19.2
70	13.2	7.2	6.3	9.3	12.4
80	5.5	6.4	4.8	6.2	7.1
100	20.0	7.1	5.2	10.3	19.1
120	22.5	14.7	11.4	10.5	21.4
140	20.0	18.3	14.2	19.5	37.1

TABLE 3 (Continued)

Visual Angle:	10'	25'	1.0°	2.5°	7.5°
Observer: T. G.	Constant Illuminance				
Interval: (msc)	Threshold Increment (msc)				
3	46.5	30.8	25.7	25.3	43.8
10	48.9	16.7	27.1	39.7	27.1
20	30.0	21.8	21.7	34.7	19.2
30	21.7	15.7	12.5	25.6	17.5
40	18.4	20.6	12.5	23.3	16.7
50	13.7	18.7	15.2	22.3	13.4
60	15.8	20.0	11.0	18.9	15.0
70	17.3	12.2	10.6	22.5	8.0
80	17.5	5.7	8.0	22.5	8.5
100	39.7	12.5	10.8	19.2	12.1
120	24.0	23.3	18.1	26.7	18.3
140	22.5	22.5	23.3	36.1	17.9
Observer: H. B.	Constant Illuminance				
Interval: (msc)	Threshold Increment (msc)				
3	38.5	24.0	18.5	24.0	24.0
10	30.2	15.7	13.7	18.1	14.7
20	31.2	10.8	10.0	17.5	18.8
30	30.0	11.0	8.6	16.2	16.8
40	22.0	7.5	8.1	15.0	17.9
50	24.0	13.7	10.3	12.5	18.6
60	21.4	14.9	13.3	11.0	11.4
70	15.3	9.8	6.2	7.2	8.6
80	15.8	9.1	5.4	4.3	8.8
100	21.2	10.2	9.1	12.9	18.9
120	17.8	17.3	8.6	12.5	20.8
140	25.9	19.2	16.2	23.7	15.0

TABLE 3 (Continued)

Visual Angle:	10'
Observer: L. S. Interval: (msc)	T + 3.05 Log Threshold Increment (msc)
3	19.5
10	18.3
20	22.0
30	37.5
40	30.0
50	33.6
60	22.5
70	14.0
80	8.0
100	11.9
120	12.5
140	20.0

TABLE 4

INTERVAL DIFFERENCE THRESHOLDS (EXPT. III)

Visual Angle:	30'	30'
Observer: L. S.	T + 2.75	T + 1.75
Interval: (msc)	Threshold Increment (msc)	
3	18.0	19.0
9	37.0	15.0
15	26.0	18.5
21	24.0	14.0
27	22.5	12.5
33	19.0	11.5
39	12.0	13.0
45	15.0	15.5
51	7.5	14.0
57	10.0	8.0
63	6.0	12.0
69	4.0	12.0
75	3.0	7.0
81	13.5	10.0
87	15.0	9.0
93	17.0	7.5
99	14.0	9.0
105	13.5	9.5
111	12.0	11.0
117	15.0	13.5
123	22.0	19.5
129	10.0	21.0
135	26.0	27.0

TABLE 5

INTERVAL DIFFERENCE THRESHOLDS PREDICTED ON THE BASIS OF ASSUMING A .05 LOG CHANGE IN APPARENT BRIGHTNESS REQUIRED FOR THE DETECTION OF AN INTERVAL DIFFERENCE

Visual Angle:	30'	30'
Observer: L. S.	T + 2.75	T + 1.75
Interval: (msc)	Threshold Increment (msc)	
5	13.0	14.1
8	29.1	10.9
11	26.7	11.0
14	23.0	13.6
17	29.4	6.7
20	26.8	11.5
23	23.5	11.9
26	21.2	9.6
29	15.2	7.6
32	13.2	6.5
35	13.5	5.9
38	13.8	8.3
41	11.6	10.1
44	8.4	9.6
46	9.3	7.8
49	8.0	7.4
52	6.9	7.5
55	5.4	9.5
58	14.4	8.7
61	10.2	6.6
64	17.6	7.5
67	5.1	15.4

TABLE 5 (Continued)

Visual Angle:	30'	30'
Observer: L. S.	T + 2.75	T + 1.75
Interval: (msc)	Threshold Increment (msc)	
70	14.5	13.9
73	Exceeds Range	16.8
76	Exceeds Range	12.5
79	Exceeds Range	6.9
83	Exceeds Range	12.4
85	Exceeds Range	13.7
88	Exceeds Range	35.7

TABLE 6

INTERVAL DIFFERENCE THRESHOLDS AT THE FUNCTION MINIMA

Visual Angle:		10'	25'	1.0°	2.5°	7.5°
Obs.	Minimum (msc)	Constant Luminance Increment Threshold (msc)				
L. S.	70-80	14.7				
	80		6.4			
	70-80			4.4		
	60				3.9	
	60					4.6
D. N.	80-100	19.2				
	80		9.5			
	70			6.9		
	70				7.2	
	60					7.5
J. P.	80	8.2				
	80		8.2			
	80			5.2		
	70				3.9	
	60					2.5
Obs.	Minimum (msc)	Constant Illuminance Increment Threshold (msc)				
L. S.	80	5.5				
	80		6.4[1]			
	80			4.8		
	80				6.2	
	80					7.1
T. G.	50	13.7				
	80		5.7			
	80			8.0		
	60				18.8	
	70					8.0

TABLE 6 (Continued)

Visual Angle:		10'	25'	1.0°	2.5°	7.5°
Obs.	Minimum (msc)	Constant Illuminance Increment Threshold (msc)				
H. B.	70	15.3				
	80		9.1			
	80			5.4		
	80				4.3	
	70					8.6
Obs.	Minimum (msc)	T + 3.05				
L. S.	80	8.0				

TABLE 7

COMPARISON OF THE PULSE INTERVAL SHOWING OPTIMAL INTERVAL DISCRIMINATION WITH THE PULSE INTERVAL SHOWING MAXIMUM BRIGHTNESS ATTENTUATION

Visual Angle	Obs.	Illuminance	Max. Brightness Attenuation (msc)	Max. Interval Discrim. (msc)
1.0°	L. S.	T + 2.25	95	80
30'	L. S.	T + 1.75	105	79-93
	L. S.	T + 2.25	85	80
	H. B.	T + 2.25	85	80
	L. S.	T + 2.75	59	75

TABLE 8

THE THRESHOLD OF FUSION OF A TWO-PULSE STIMULUS AT DIFFERENT ILLUMINANCES

Visual Angle	Observer	Illuminance (Log)	Threshold Interval (msc)	Log (τ^{-1})
30'	L. S.	T + 1.25	86.5	.063
		T + 1.50	86.0	.066
		T + 1.75	82.0	.086
		T + 2.00	78.0	.108
		T + 2.25	68.0	.168
		T + 2.50	63.5	.196
		T + 2.75	61.0	.215
		T + 3.00	60.5	.218
		T + 3.25	59.0	.229
		T + 3.50	60.0	.223

FIGURES

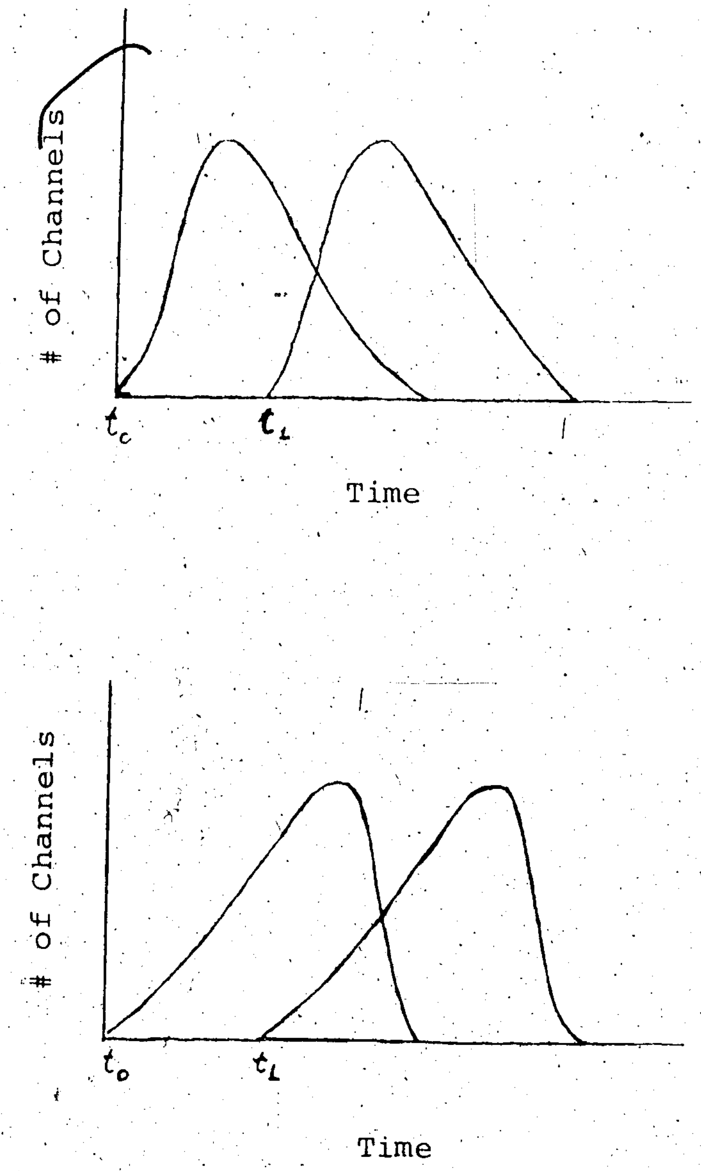


Figure 1: The effect on the duration of the pulse interval of optimal interval discrimination of assuming response distributions skewed towards short as opposed to long latencies

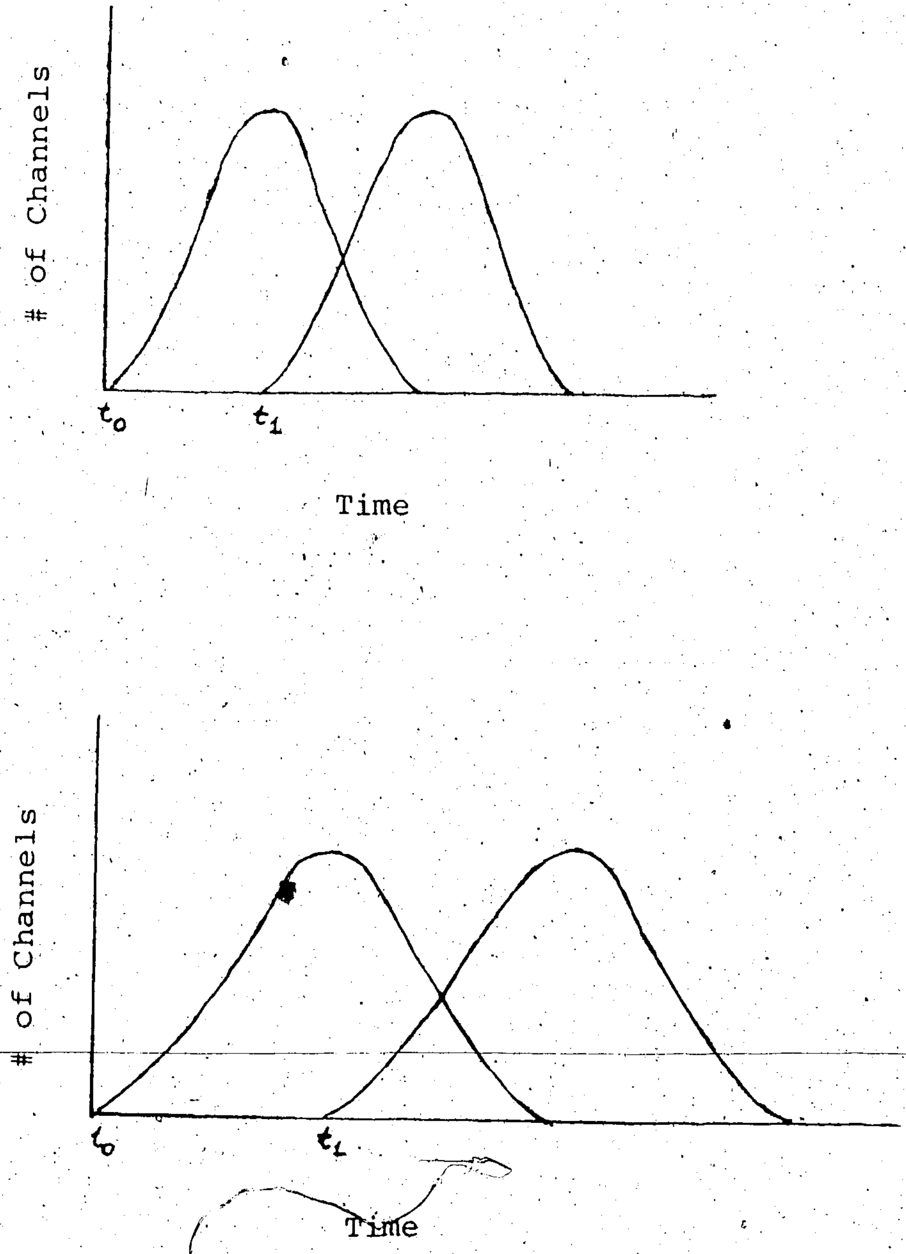


Figure 2: The effect on the duration of the pulse interval of optimal interval discrimination of assuming response distributions with large as opposed to small standard deviation

VISUAL ANGLE		10'	25'	1°	2.5°	7.5°
PULSE INTERVAL (MSC)		1-140	1-140	1-140	1-140	1-140
CONSTANT LUMINANCE	L.S.	12 PULSE INTERVALS				
	D.N.					
	T.G.					
CONSTANT ILLUMINANCE	L.S.					
	H.B.					
	J.P.					

Figure 3: Experimental Design for Experiment I

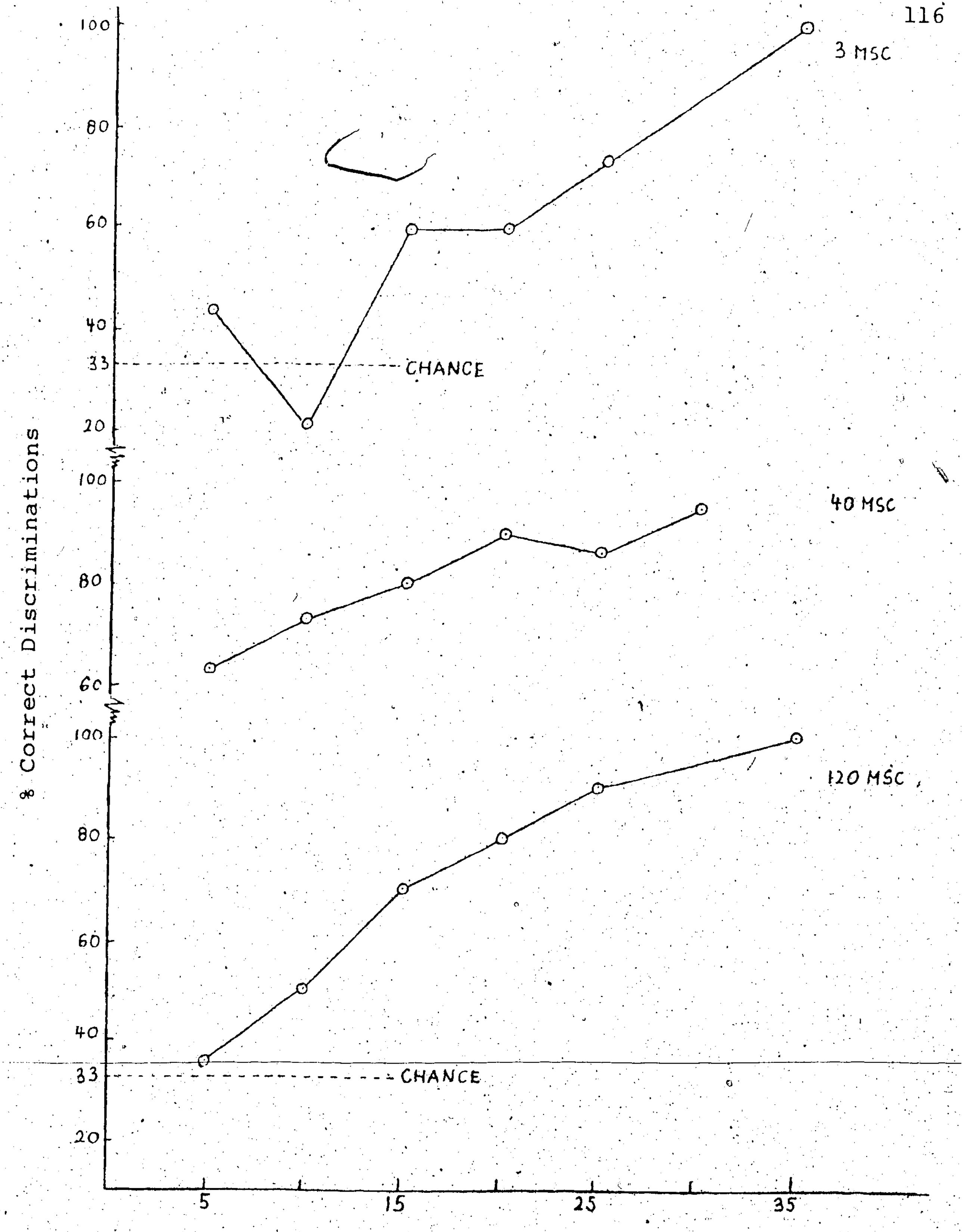


Figure 4: Typical interval increment discrimination functions for 3 (standard) pulse intervals

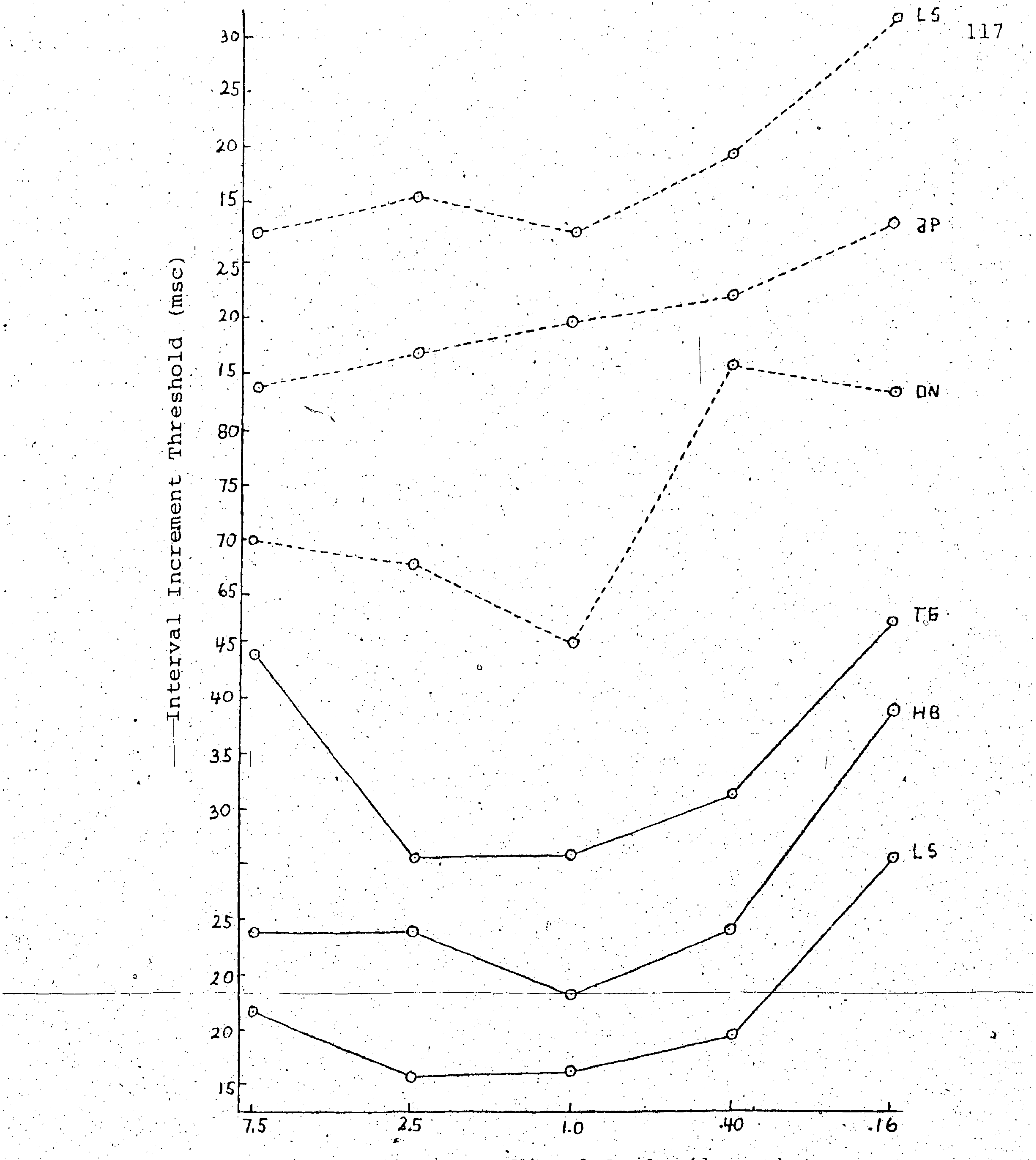


Figure 5: The effect of stimulus size on interval increment discrimination when the (standard) pulse interval is 3 msc and either luminance (o---o) or illuminance (o——o) is held constant

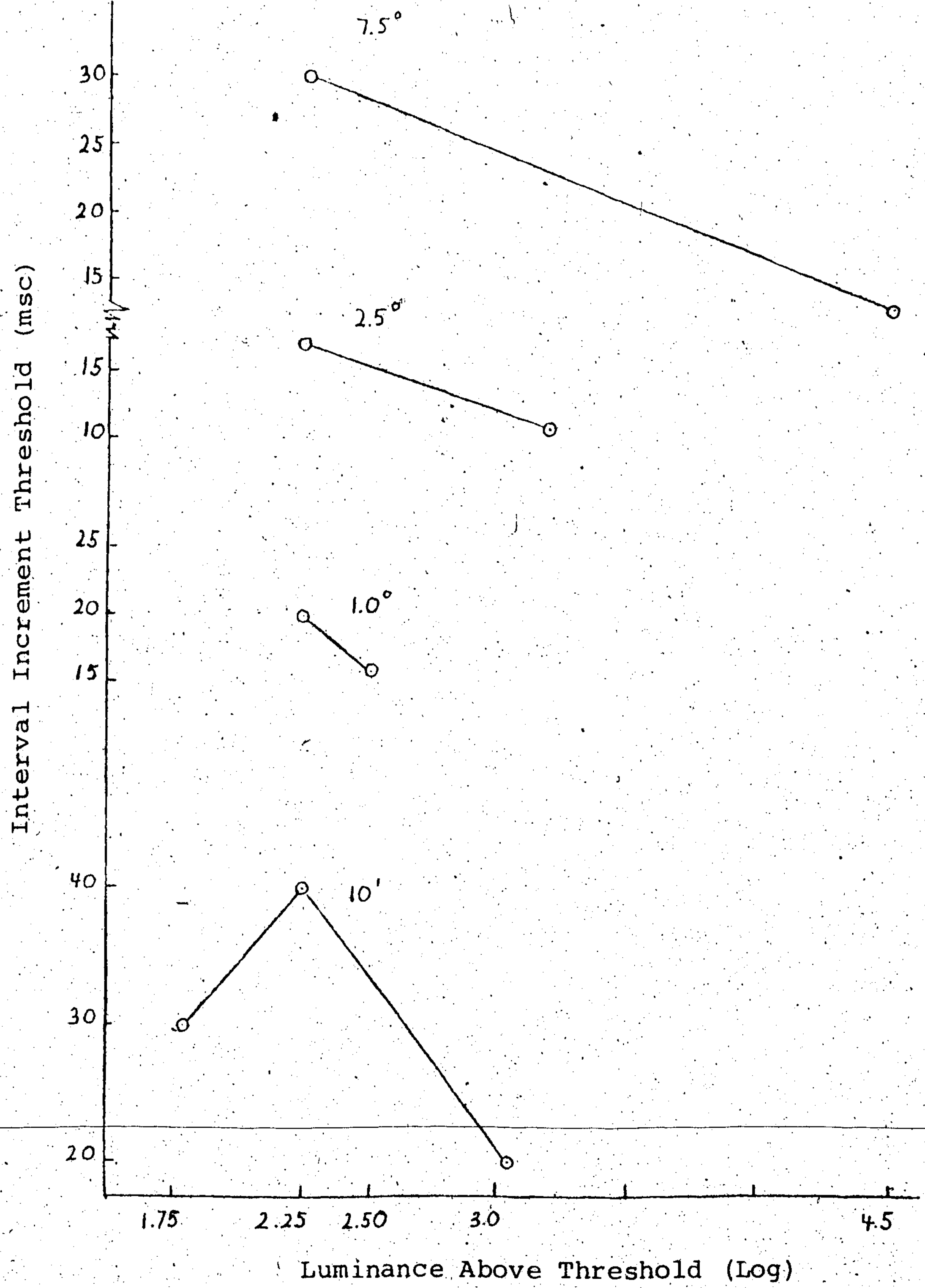


Figure 6: The effect of luminance on interval increment thresholds when the (standard) pulse interval is 3 msc. and visual angle is the parameter. Thresholds for a given combination of stimulus size and luminance represent the average across observers

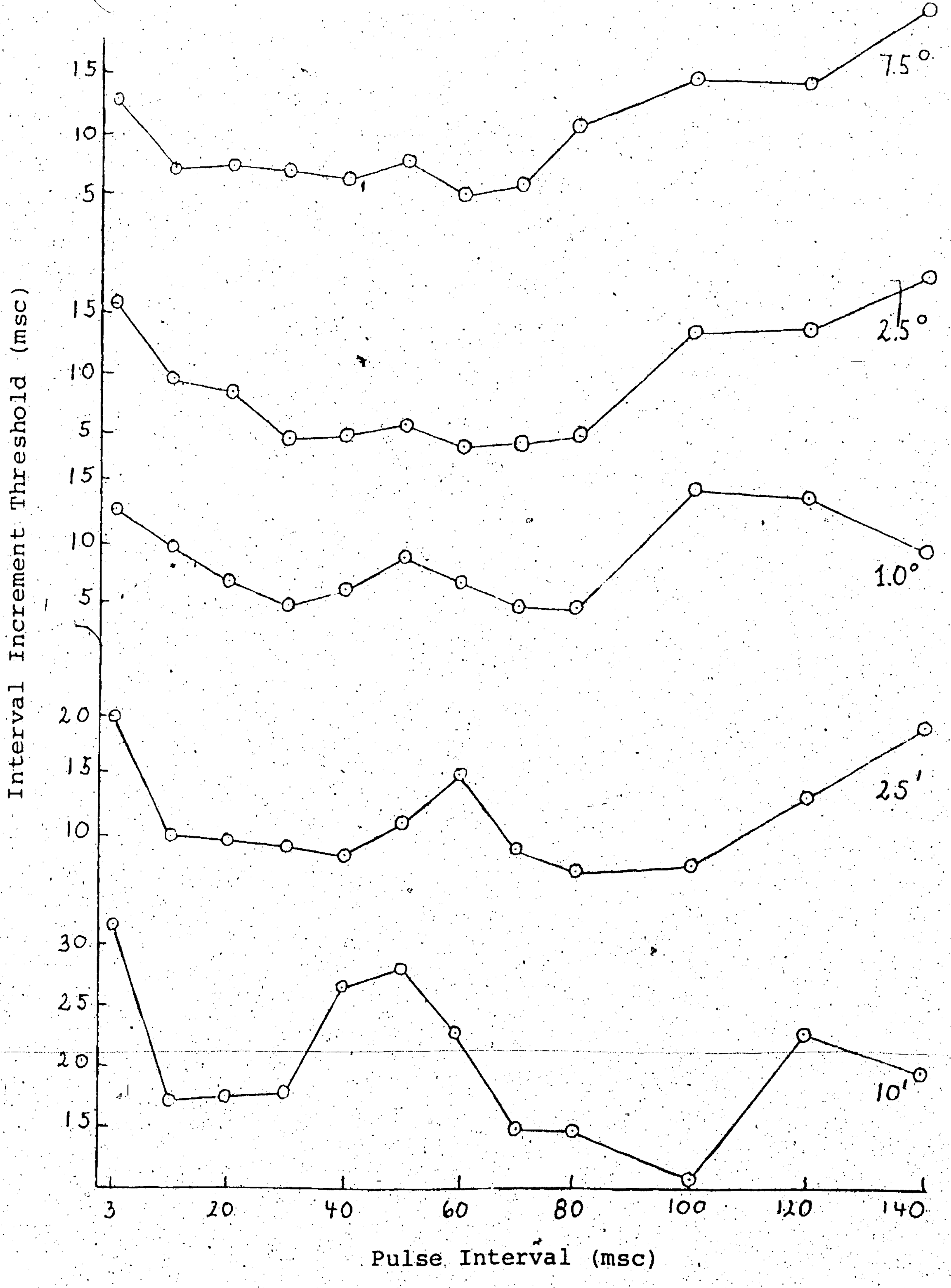


Figure 7: Interval increment Thresholds as a function of (standard) pulse interval and stimulus size when luminance is held constant. Observer L. S.

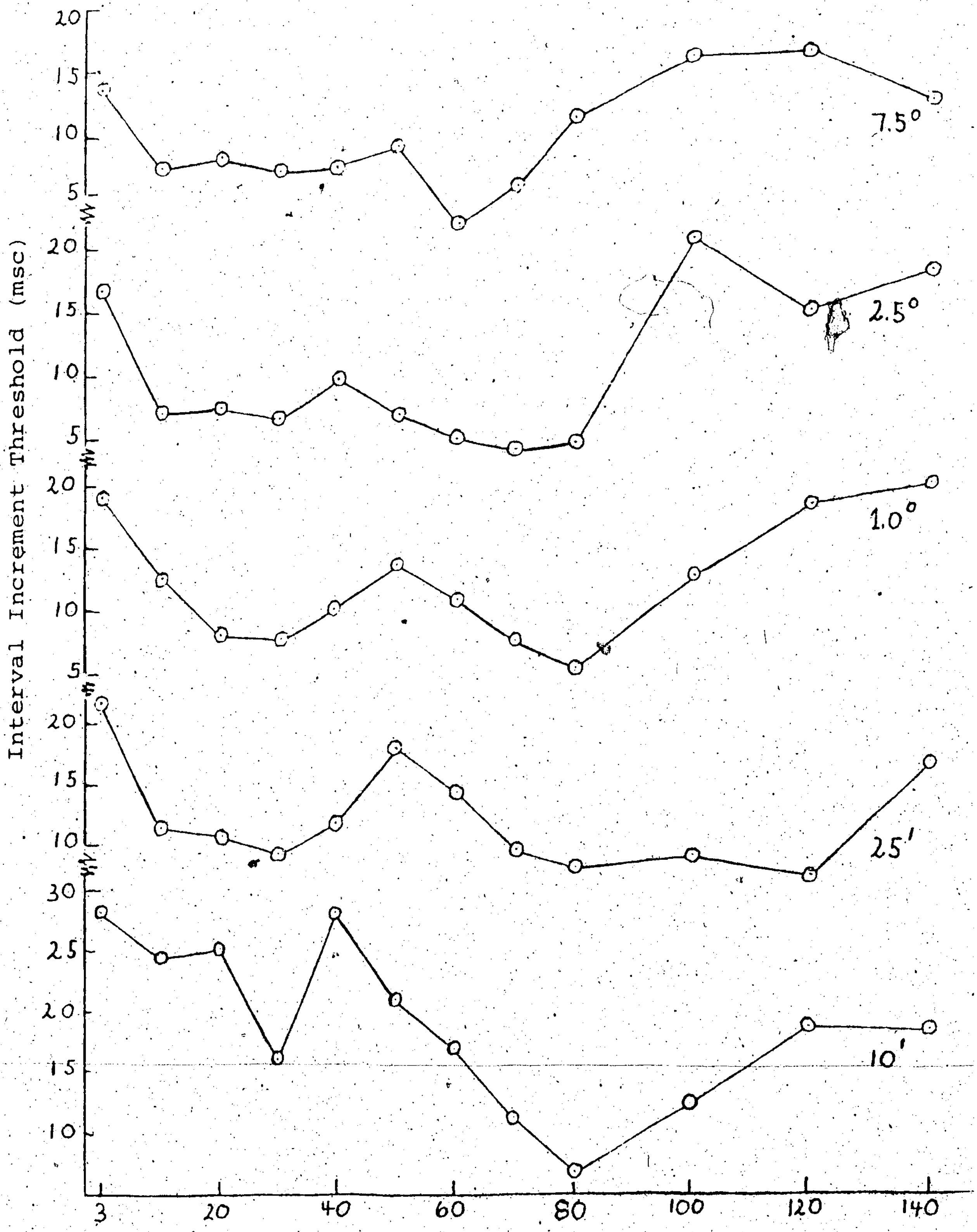
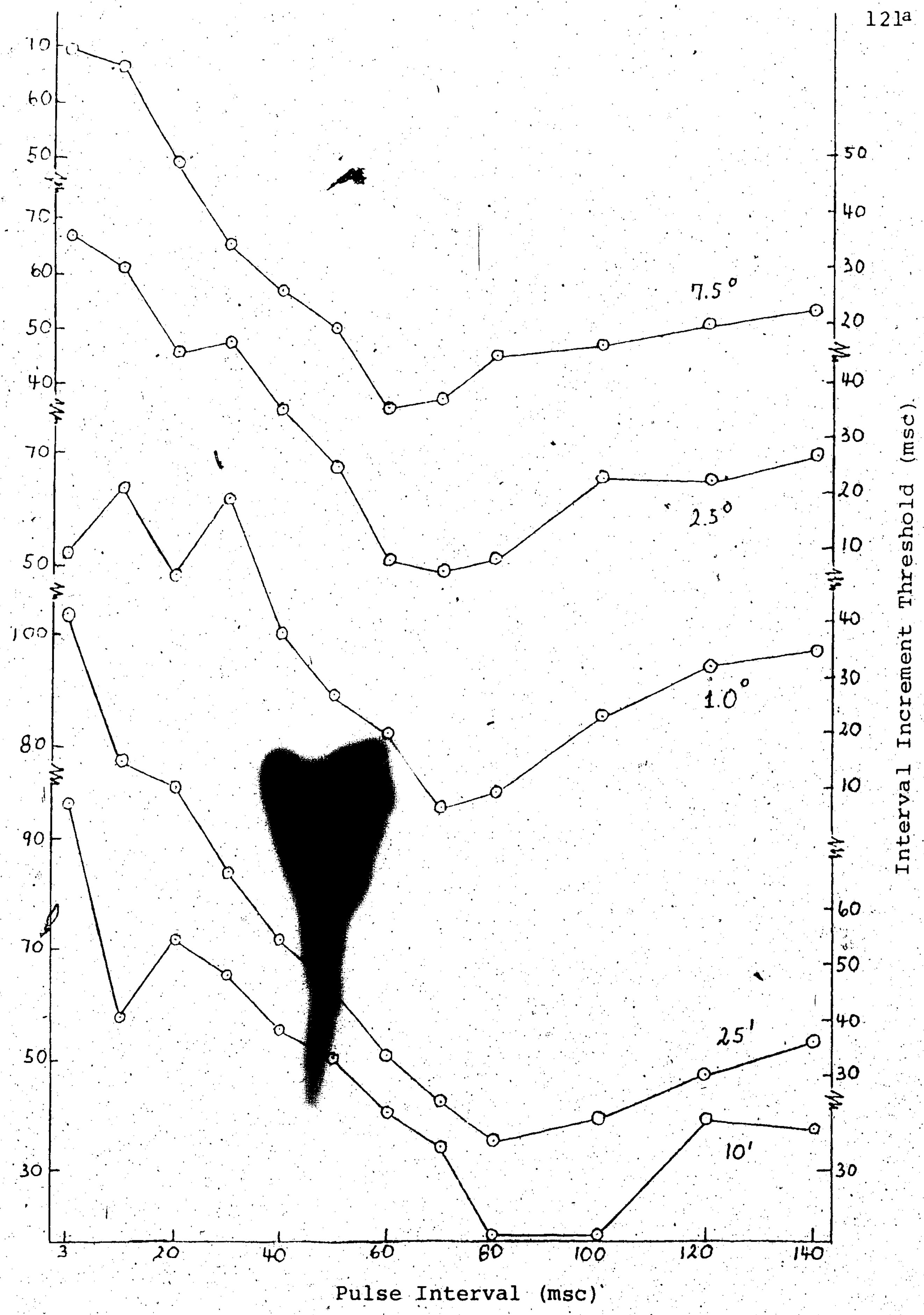


Figure 8: Interval increment thresholds as a function of (standard) pulse interval and stimulus size when luminance is held constant. Observer J. P.

Figure 9: Interval increment thresholds as a function of (standard) pulse interval and stimulus size when luminance is held constant. Observer D. N.


70
60
50
70
60
50
40
70
50
100
80
90
70
50
30
50
40
30
20
40
30
20
10
40
30
20
10
60
50
40
30
30
7.5°
2.5°
1.0°
25'
10'
3
20
40
60
80
100
120
140
Pulse Interval (msc)
Interval Increment Threshold (msc)

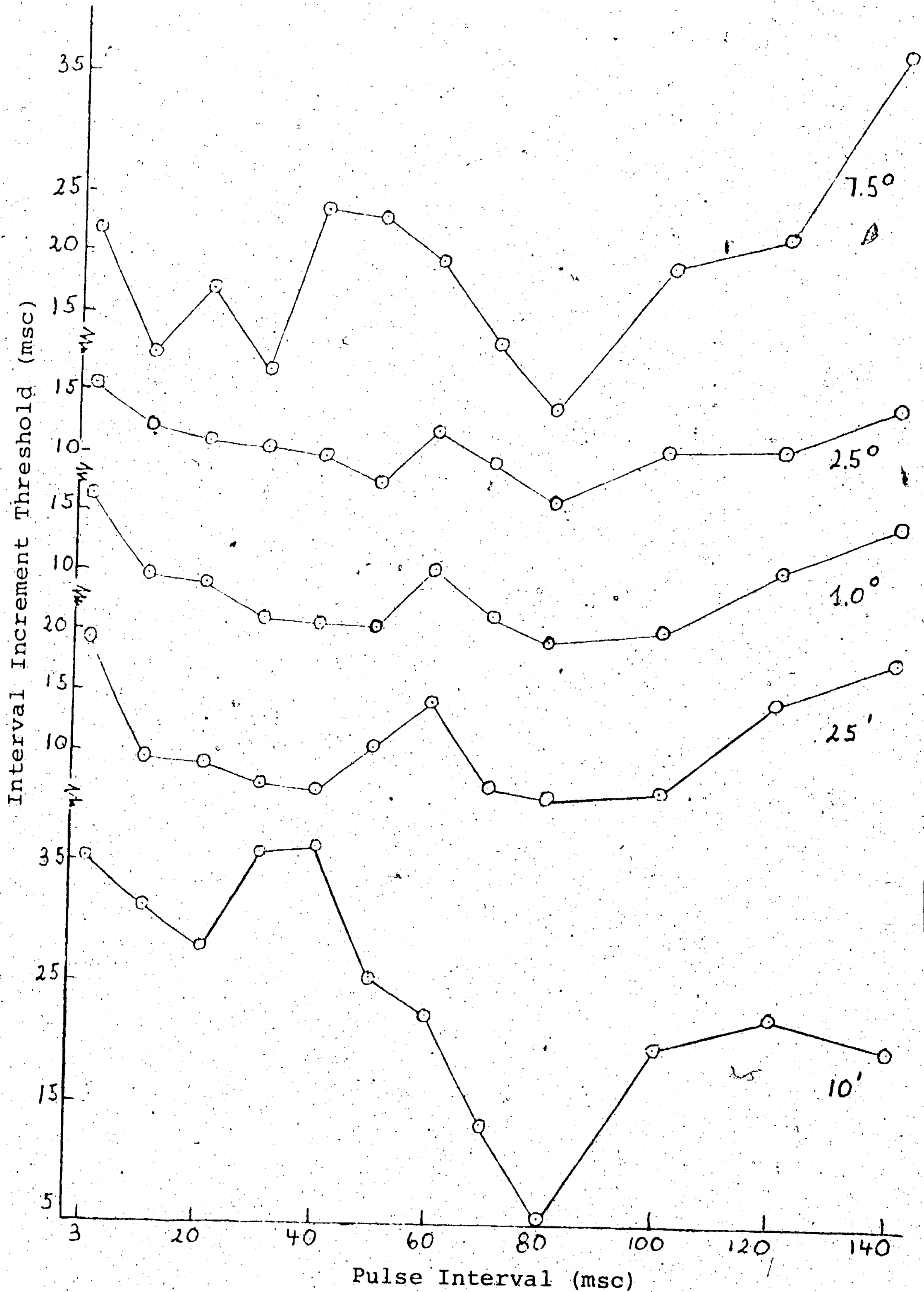


Figure 10: Interval increment thresholds as a function of (standard) pulse interval and stimulus size when illuminance is held at a constant energy above threshold. Observer L. S.

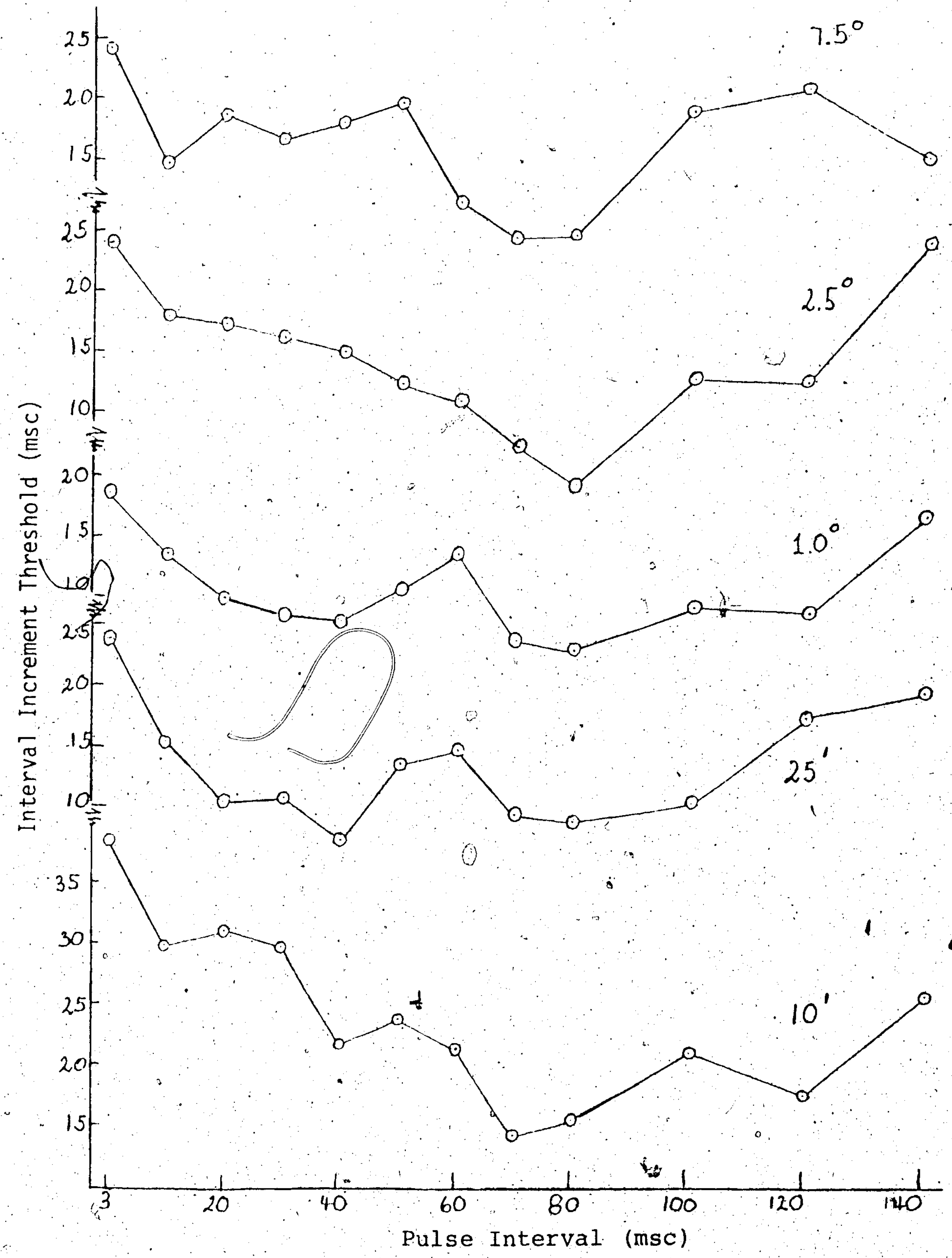


Figure 11: Interval increment thresholds as a function of (standard) pulse interval and stimulus size when illuminance is held at constant energy above threshold. Observer H. B.

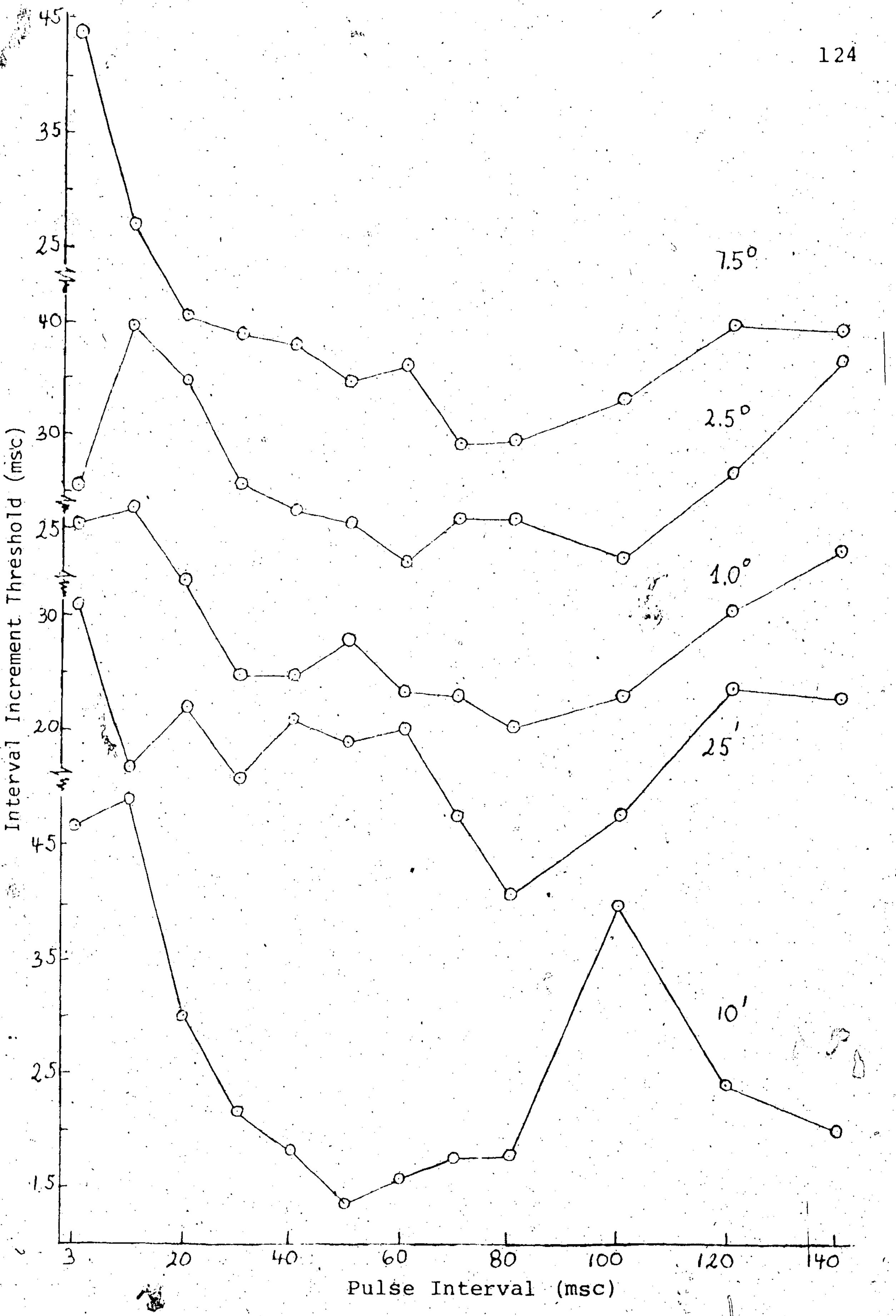


Figure 12: Interval increment thresholds as a function of (standard) pulse interval and stimulus size when illuminance is at constant energy above threshold. Observer T. G.

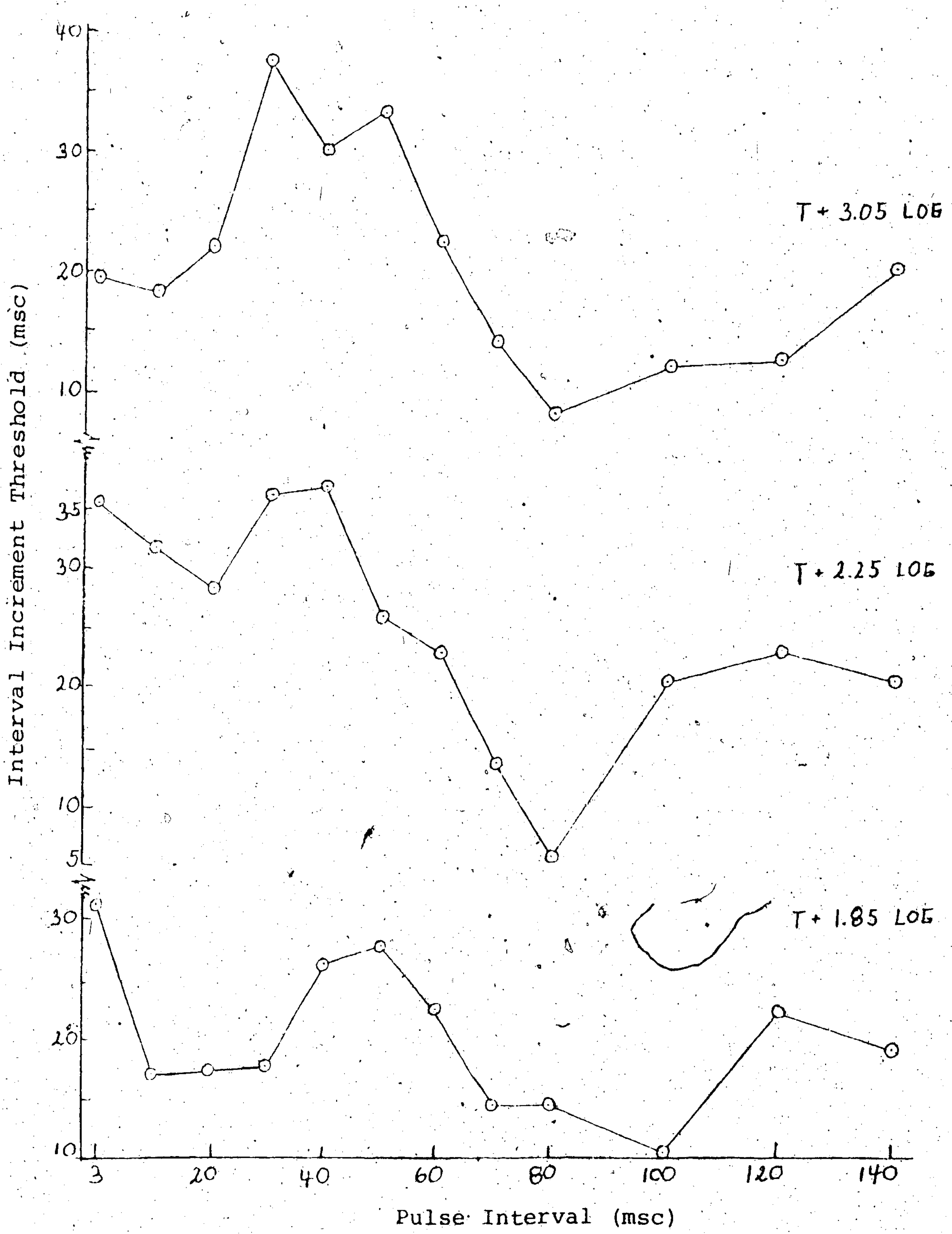


Figure 13: Interval increment thresholds as a function of pulse interval and luminance for stimulus size 10'. Observer L. S.

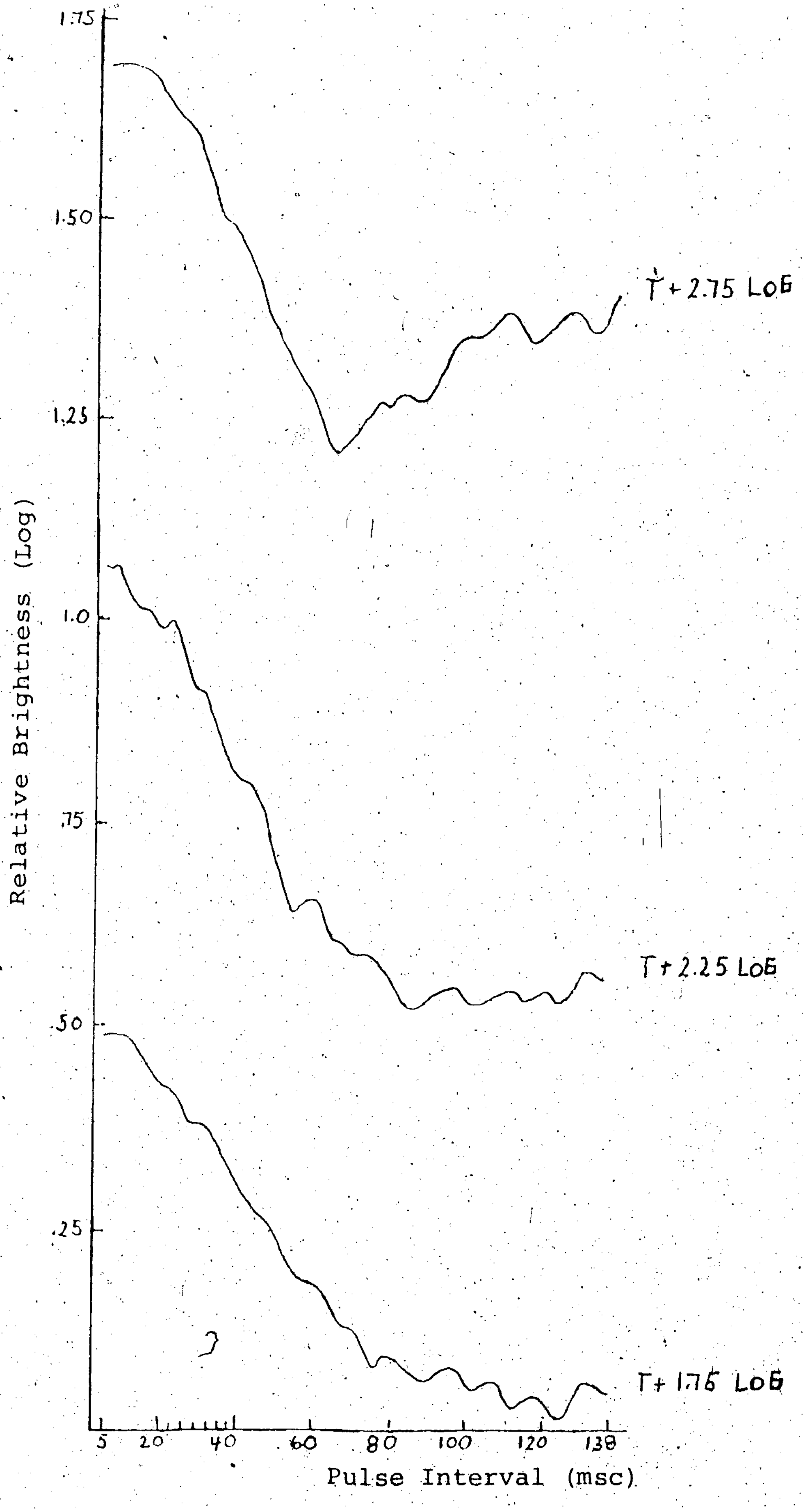


Figure 14: The brightness of a two-pulse stimulus as function of pulse interval and luminance. Observer H. B.

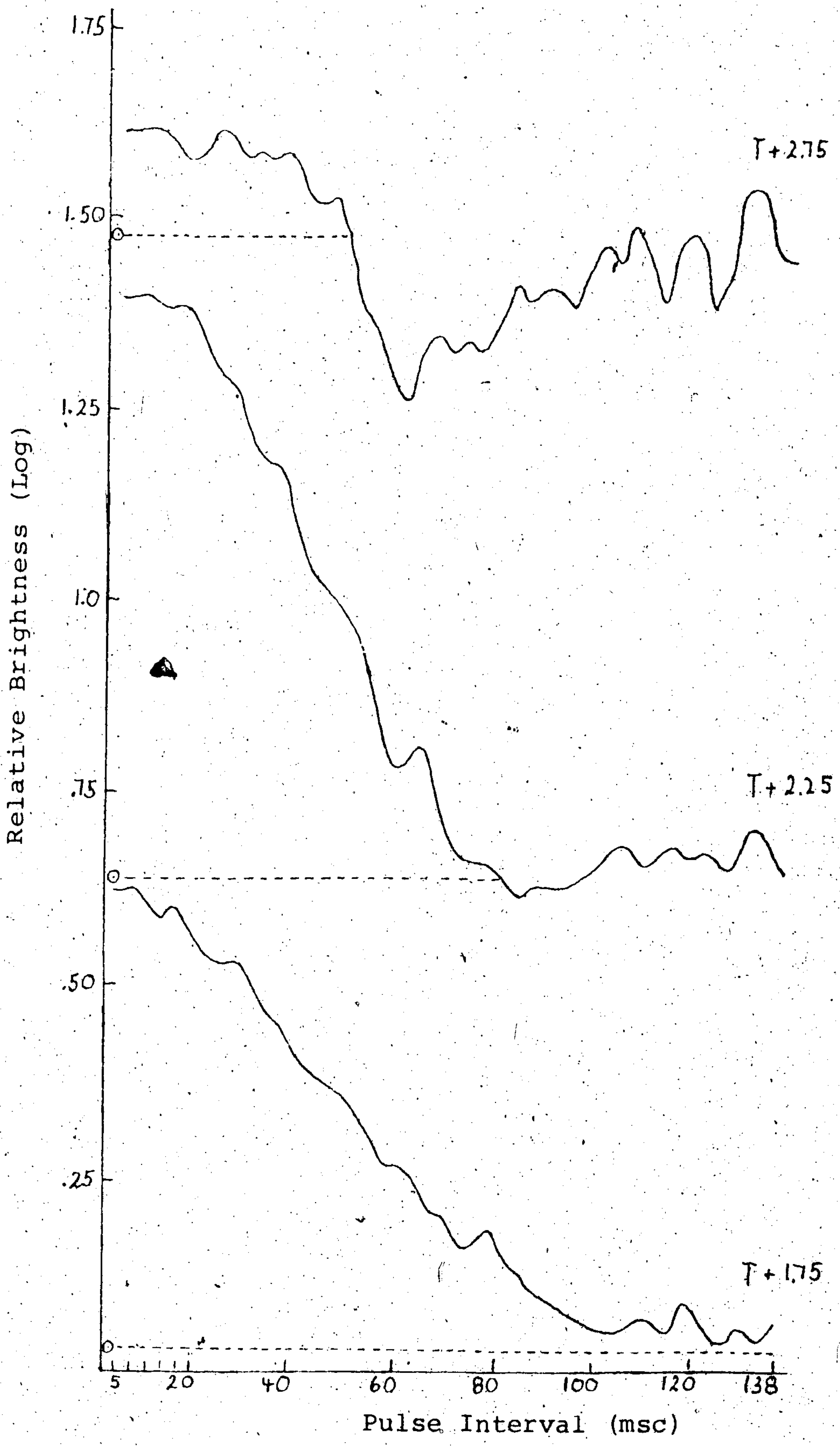


Figure 15: The brightness of a two-pulse stimulus (30') as function of pulse interval and luminance. Horizontal line segments indicate brightness of a single pulse. Observer L. S.

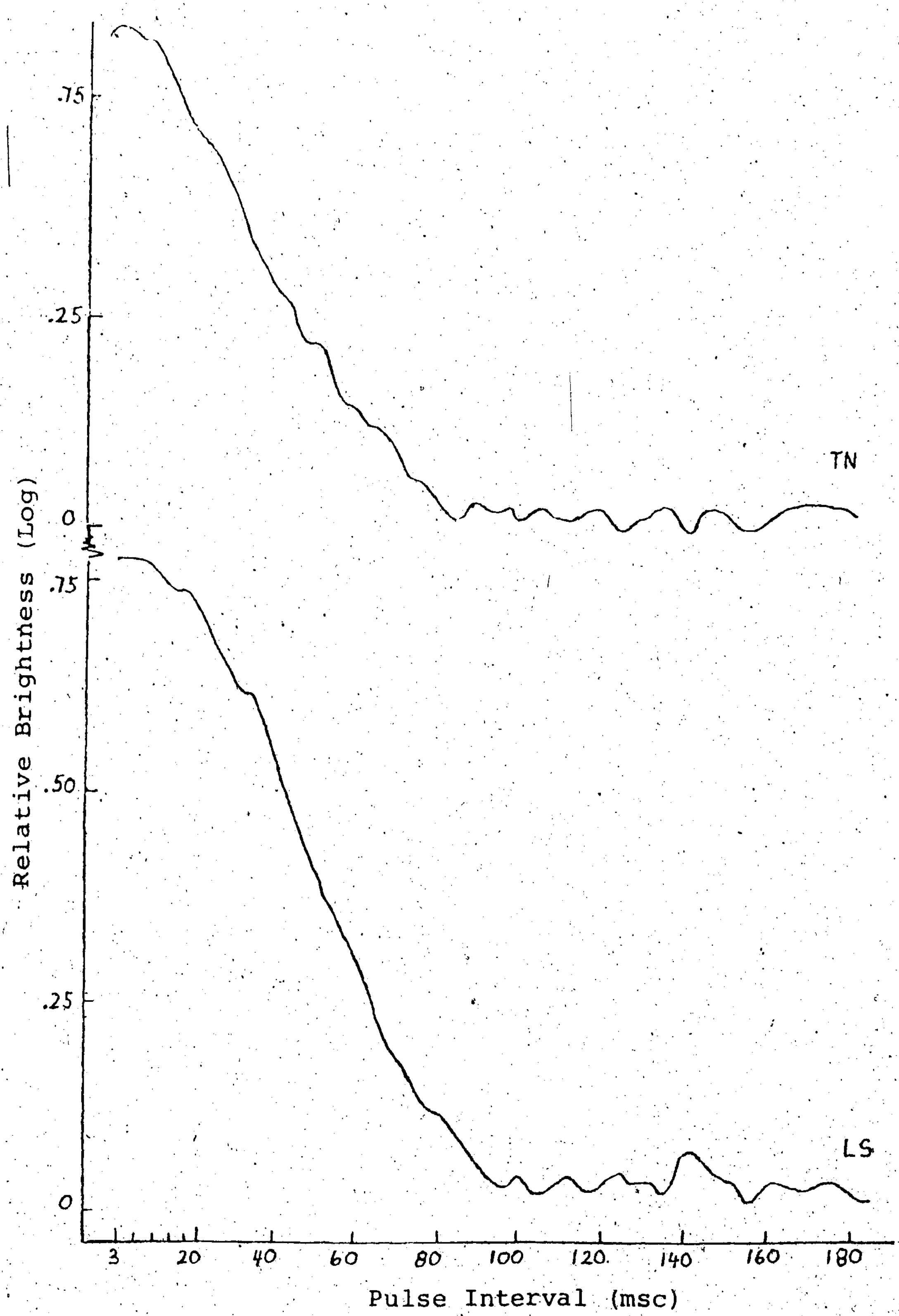


Figure 16: The brightness of a two-pulse stimulus (1°) as function of pulse interval. Observer L. S. and T. N.

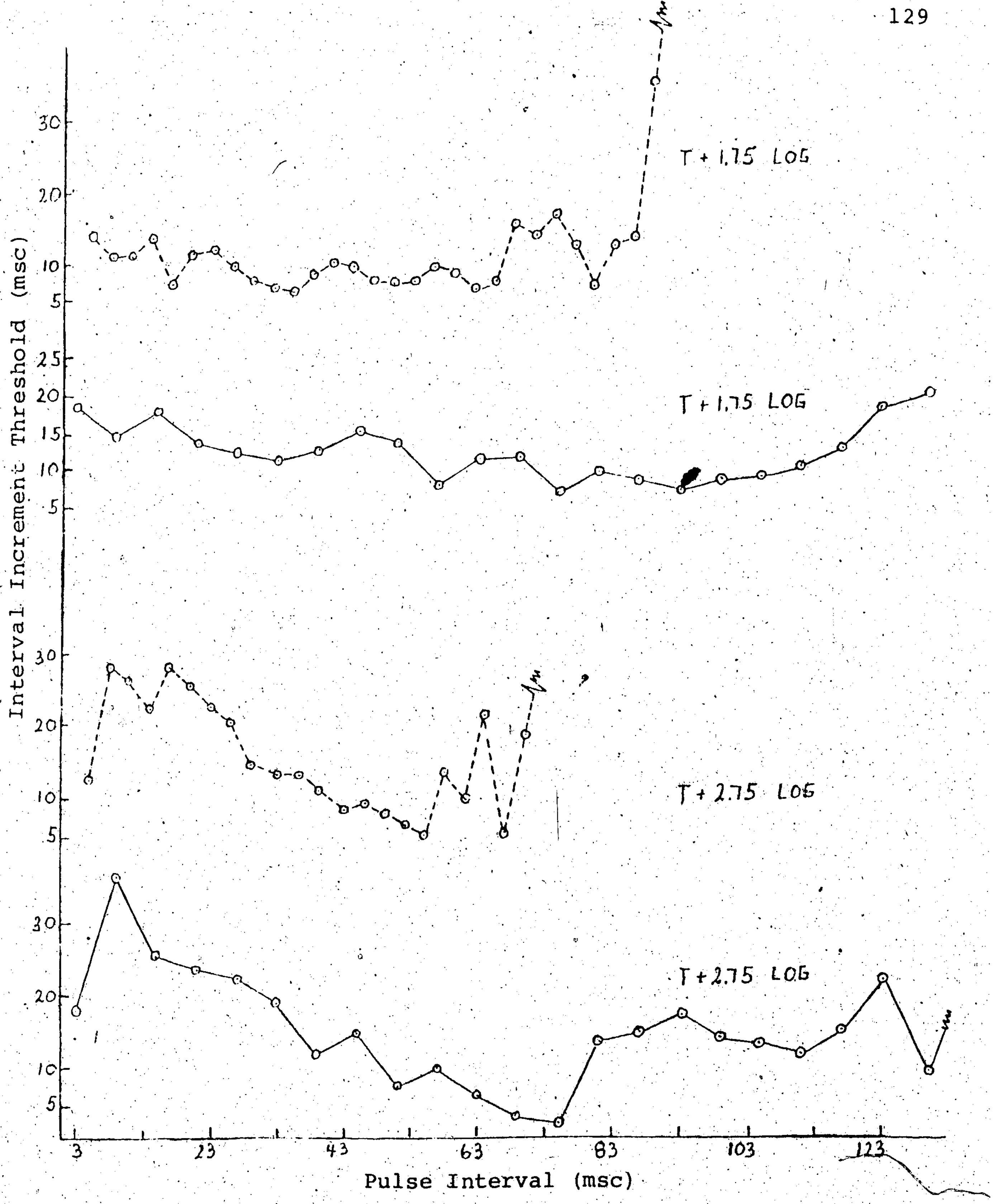


Figure 17: Interval increment thresholds predicted from a two-pulse brightness function (o---o) and exprimentally obtained interval increment thresholds (o——o) for two levels of luminance. Observer L. S.

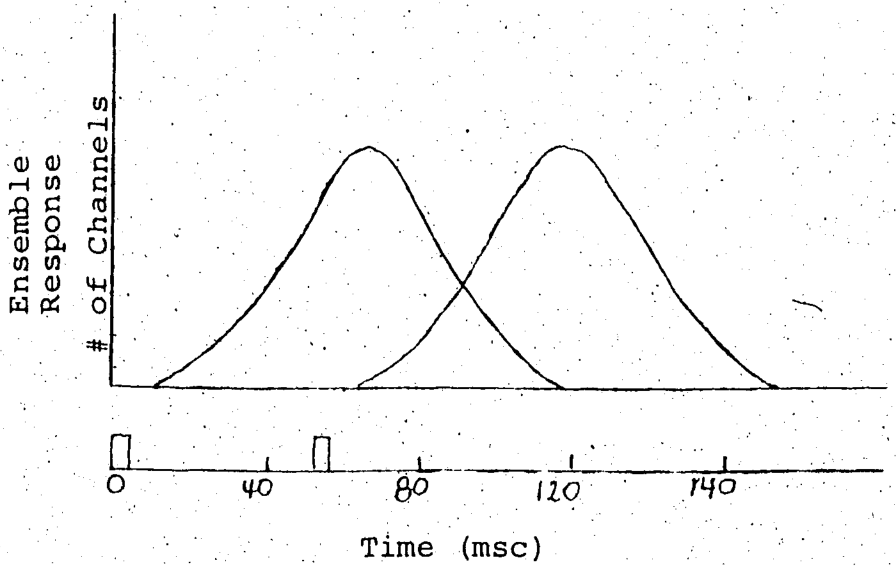


Figure 18 a. The pulse interval duration necessary for optimal interval increment discrimination when the mean of the peripheral response latencies is 30 msc.

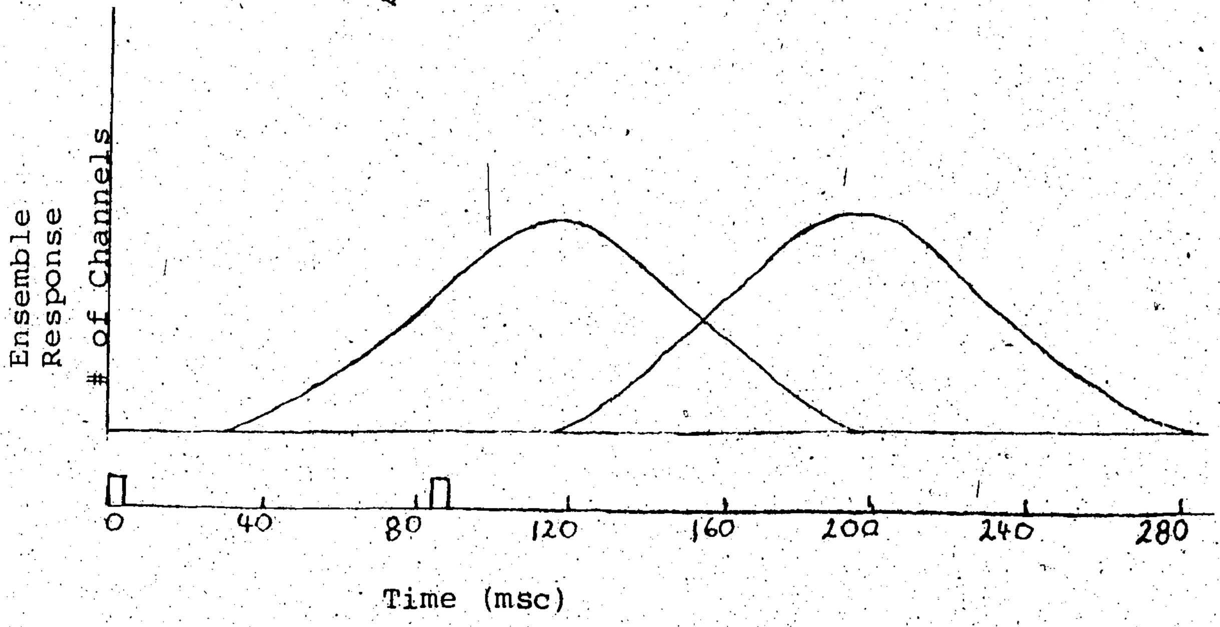


Figure 18 b. The pulse interval duration necessary for optimal interval increment discrimination when the mean of the peripheral response latencies is 83 msc.

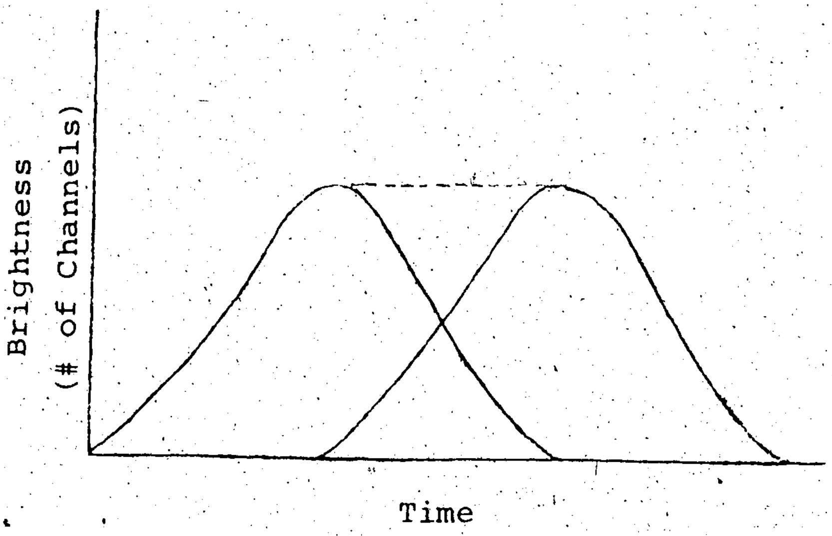


Figure 19 a. Brightness of the fused flash when the pulse interval is equal to the interval required for optimal interval discrimination

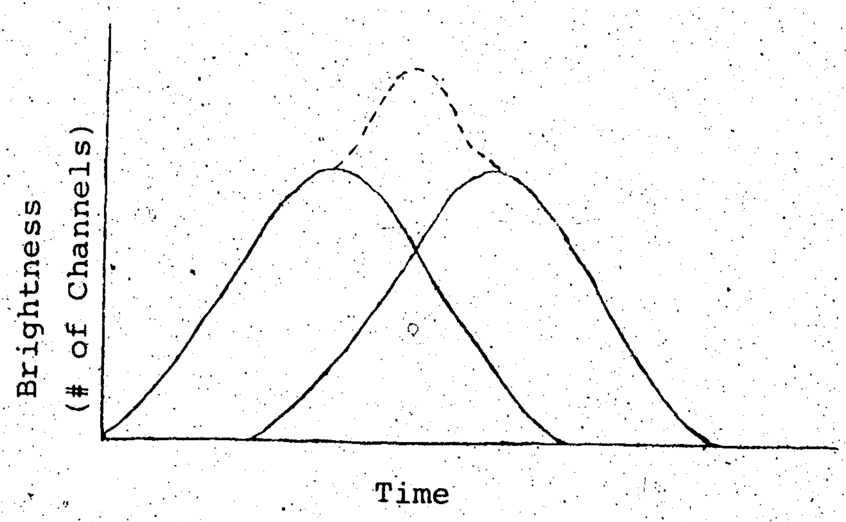
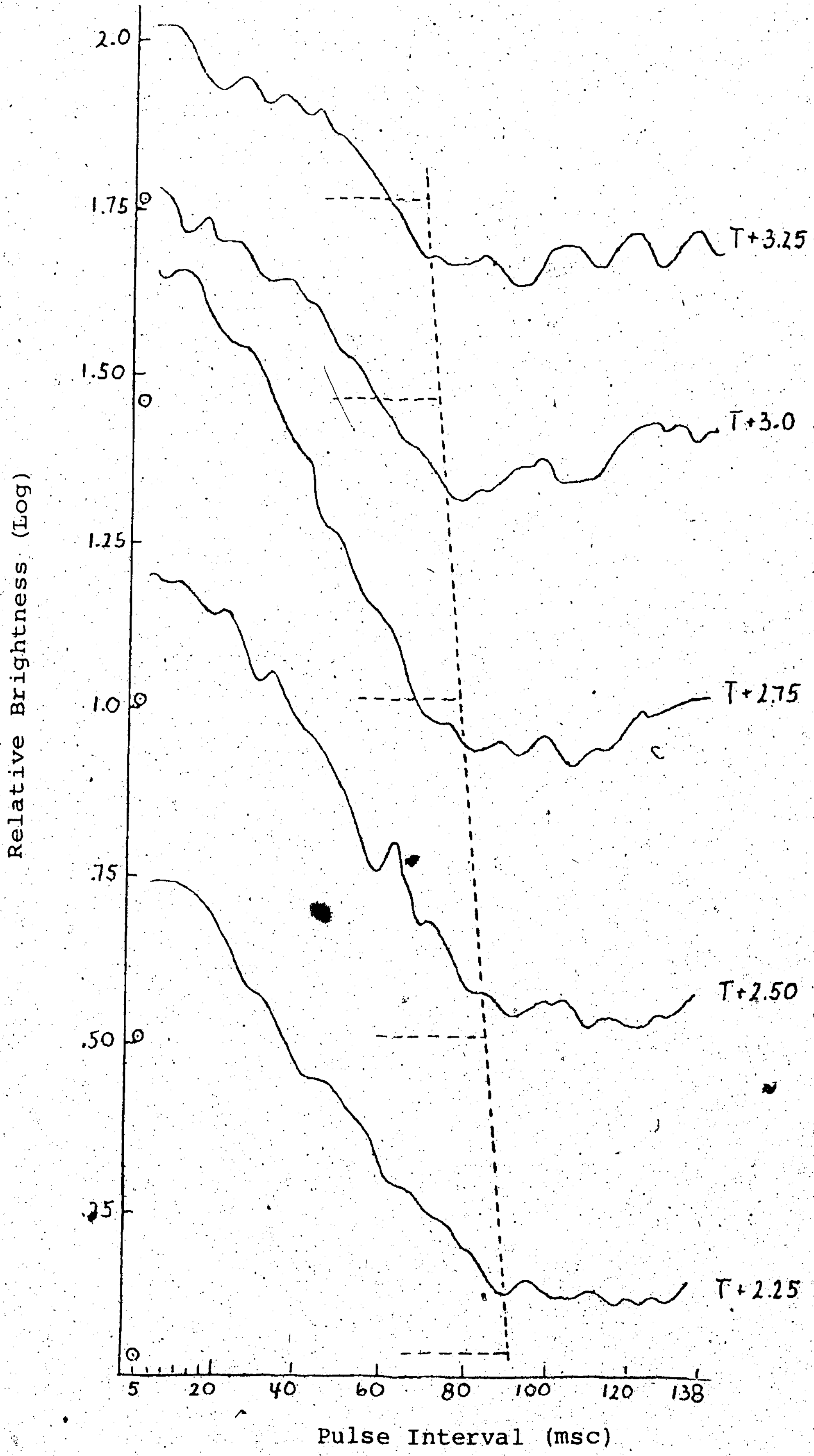


Figure 19 b. Brightness of the fused flash when the pulse interval is smaller than the interval required for optimal interval discrimination

Figure 20: The brightness of a two-pulse stimulus as function of pulse interval and illuminance. Observer T. N. Dashed line segments indicate the brightness of a single pulse


2.0
1.75
1.50
1.25
1.0
.75
.50
.25
Relative Brightness (Log)
T+3.25
T+3.0
T+2.75
T+2.50
T+2.25
5
20
40
60
80
100
120
138
Pulse Interval (msc)

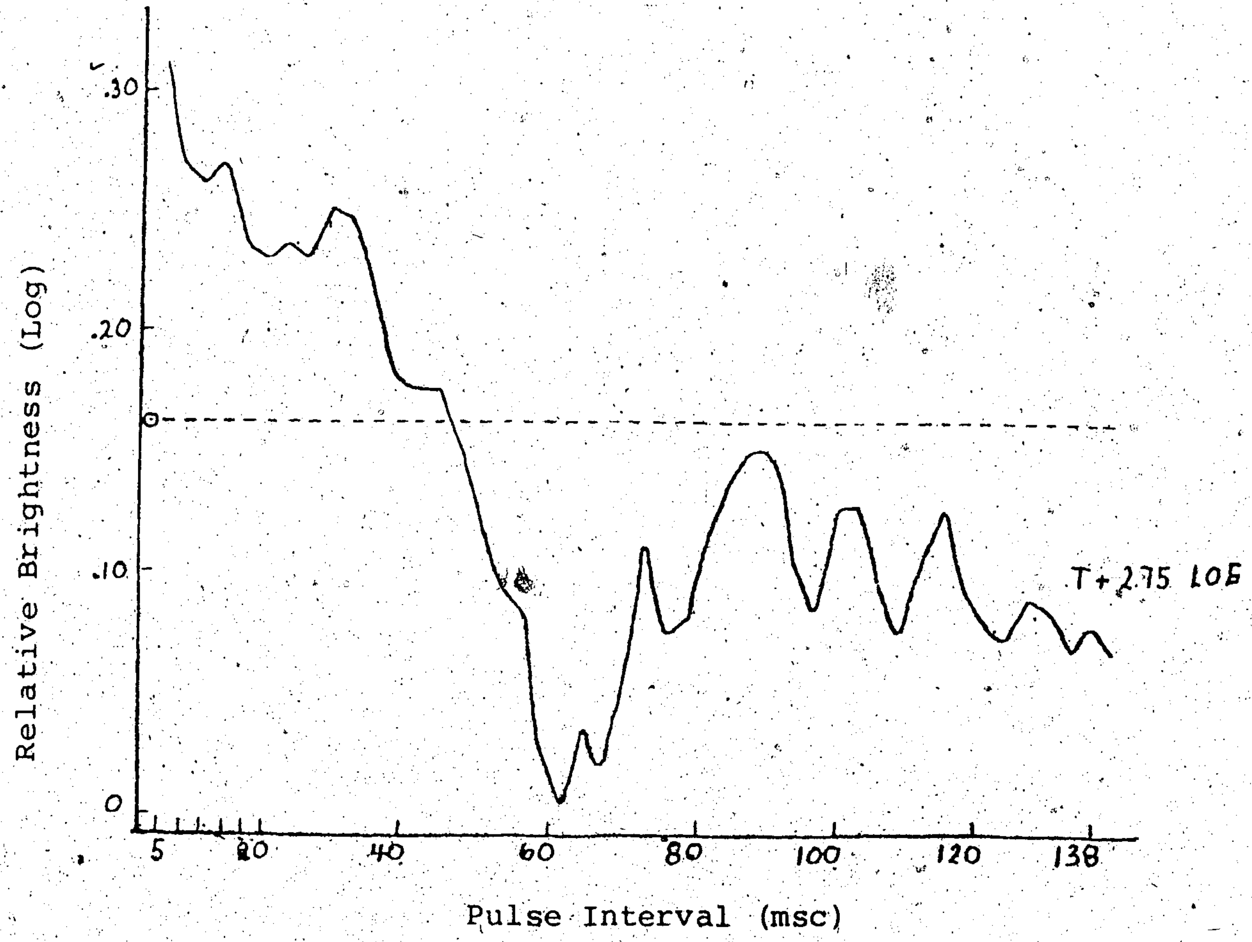


Figure 21: Brightness of a two-pulse stimulus as function of pulse interval. The dashed line indicates the brightness of a single pulse. Observer L. S.

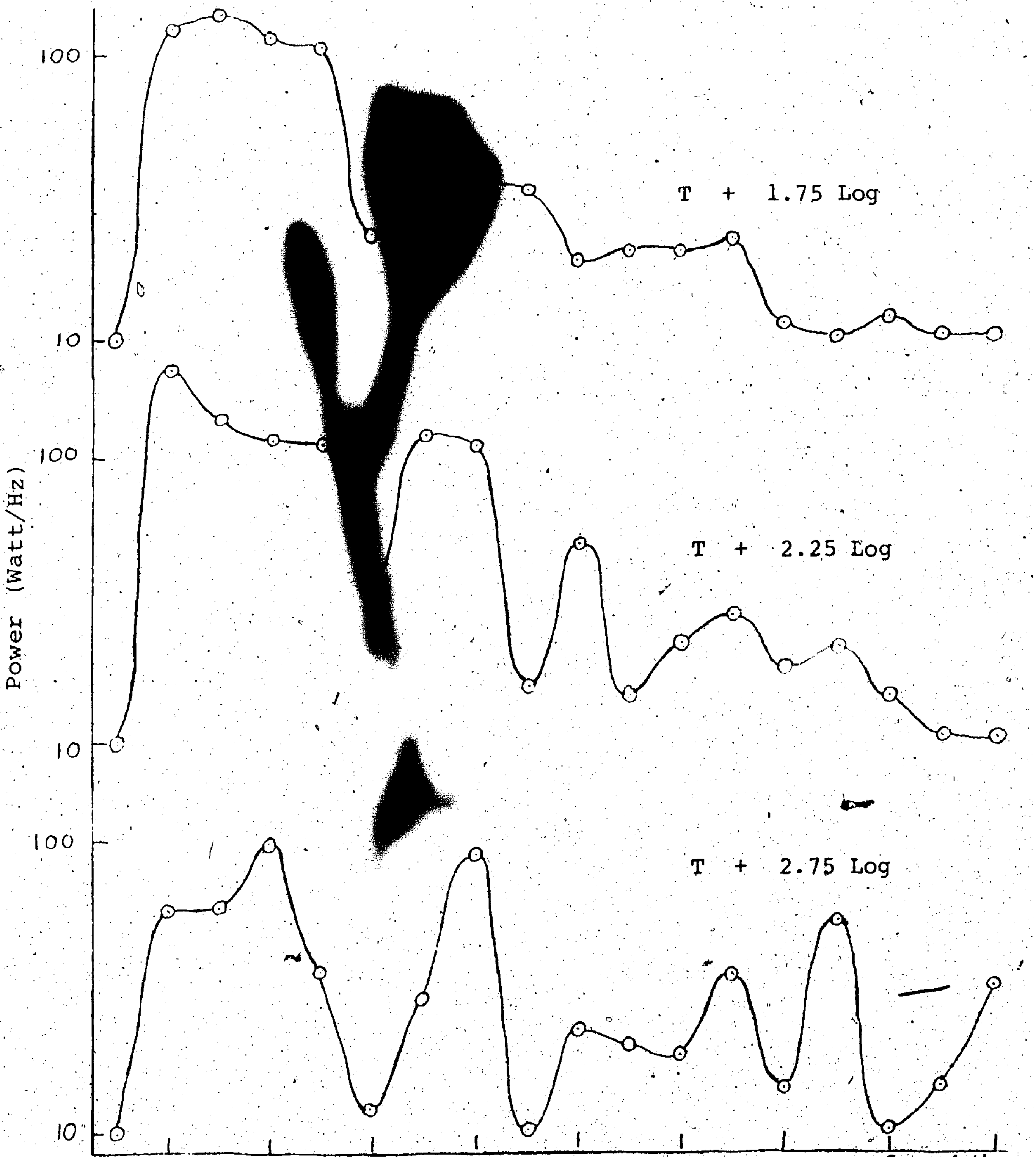
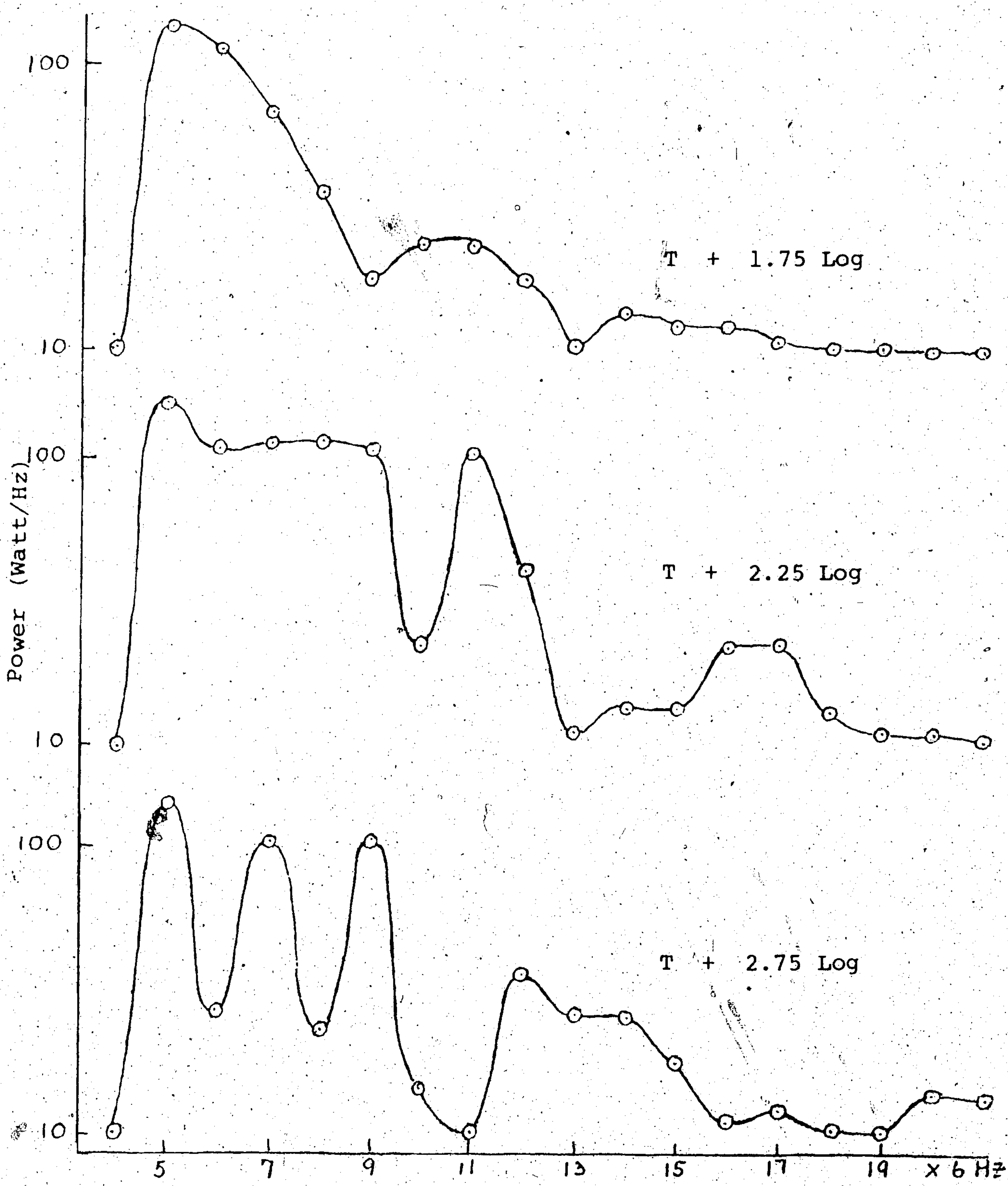


Figure 22: Power density spectra obtained from a frequency analysis of the two-pulse brightness functions for observer L. S.



Frequency (Hz)

Figure 23: Power density spectra obtained from a frequency analysis of the brightness functions for observer H.B.

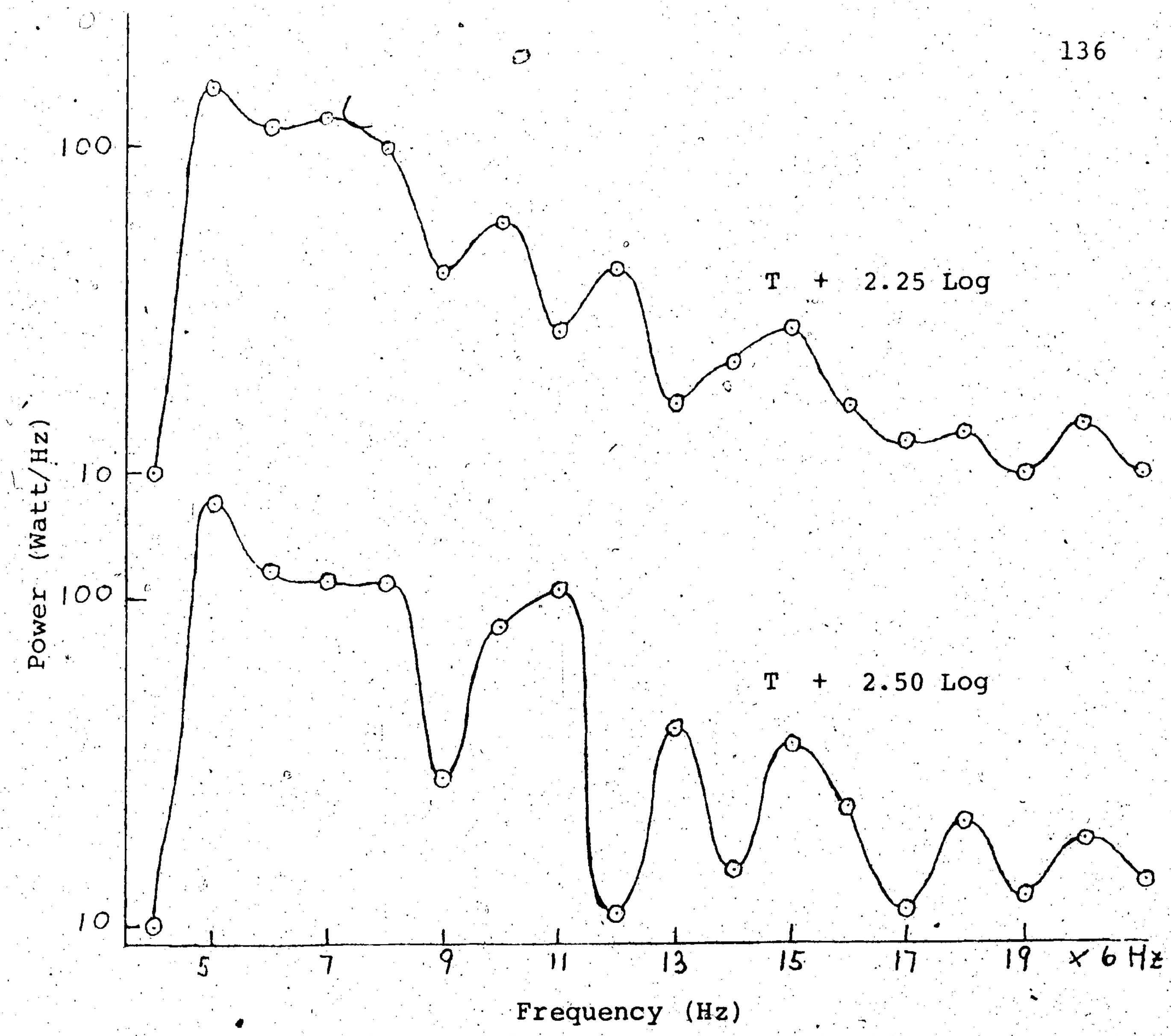


Figure 24: Power density spectra obtained from a frequency analysis of the brightness functions for observer T. N.

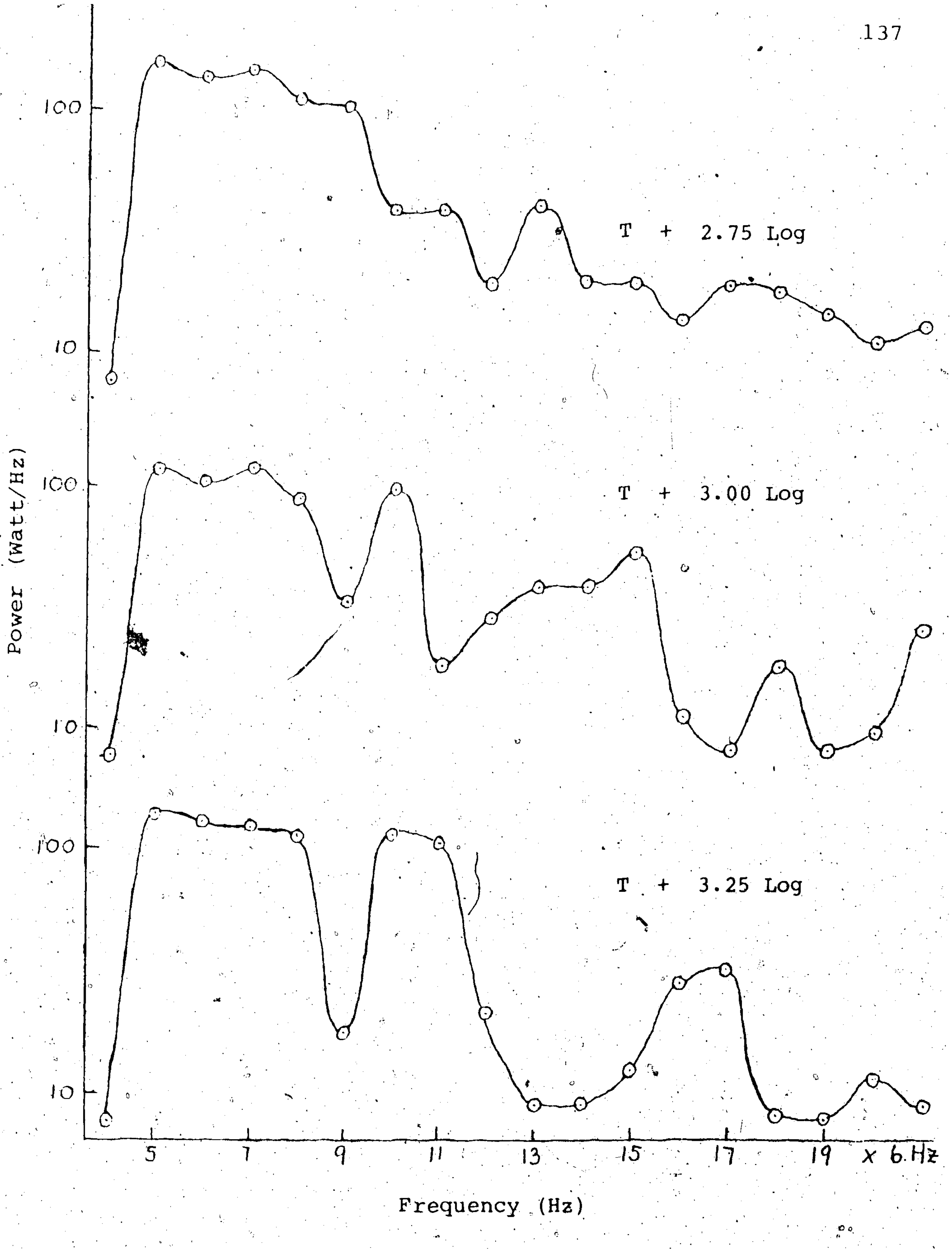


Figure 25: Power density spectra obtained from a frequency analysis of the brightness functions for observer T. N.

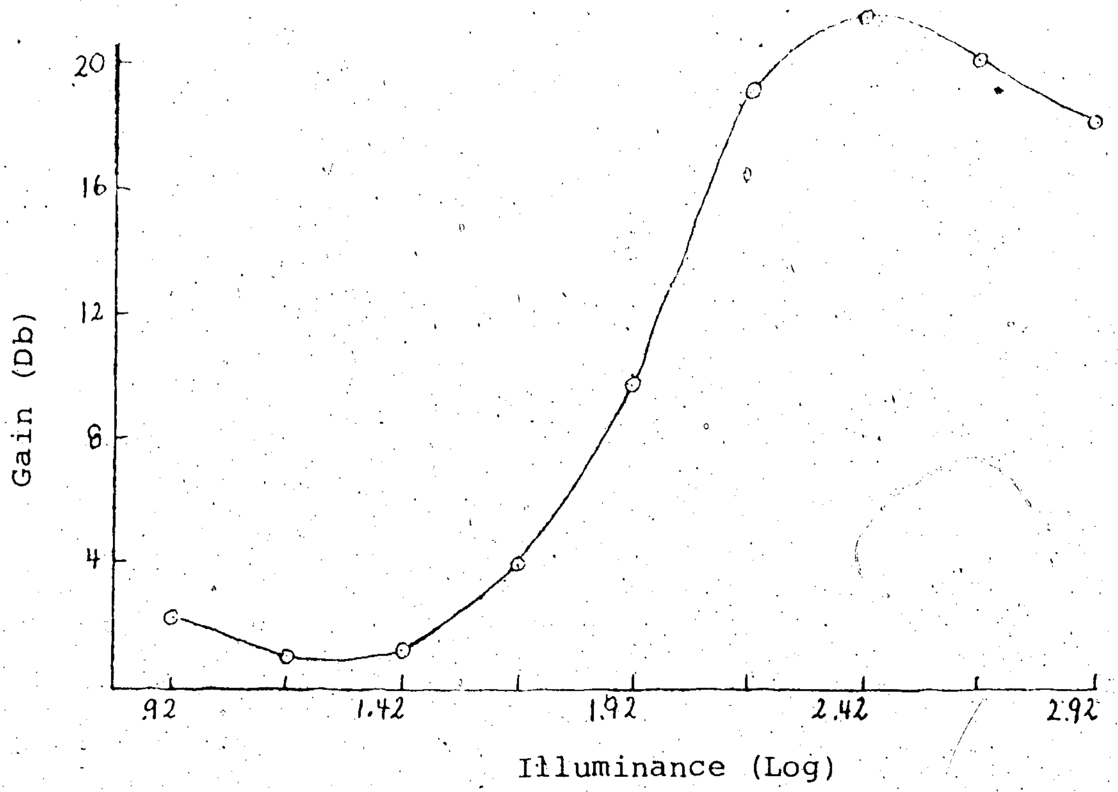


Figure 28: The brightness gain of a one-pulse stimulus as a function of illuminance. Observer L. S.

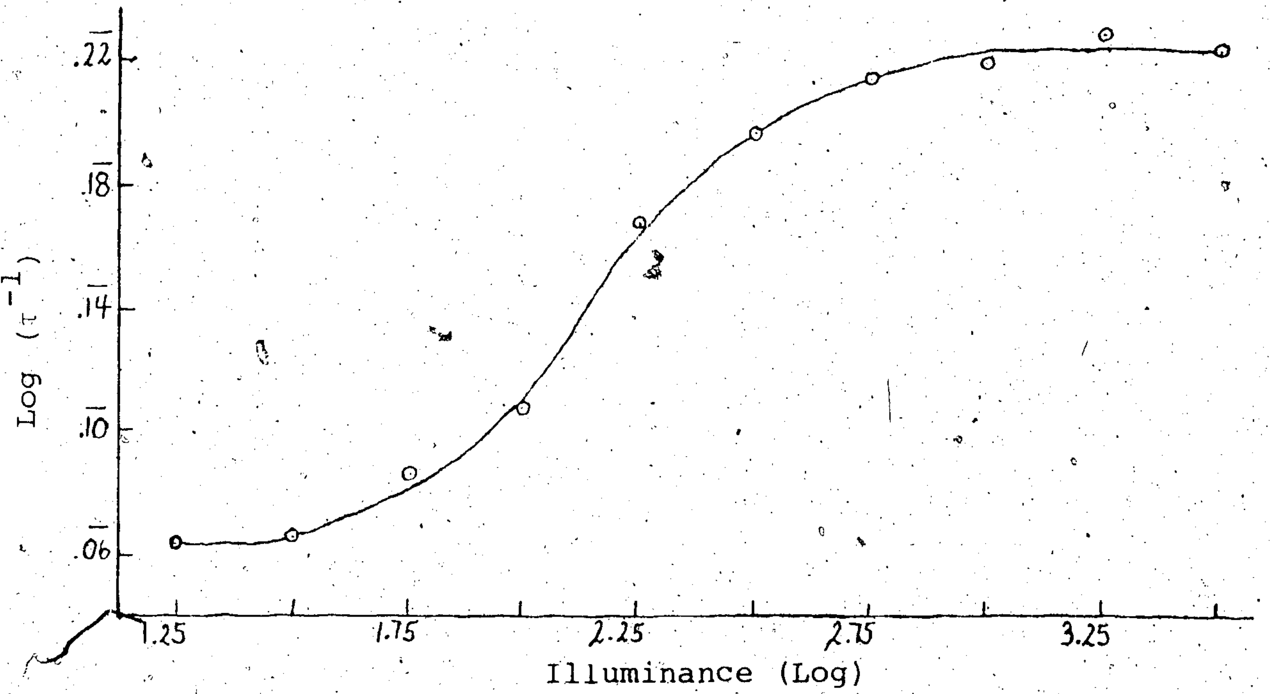


Figure 26: The relationship between the time constant τ as estimated by the two-pulse fusion threshold, and stimulus illuminance.

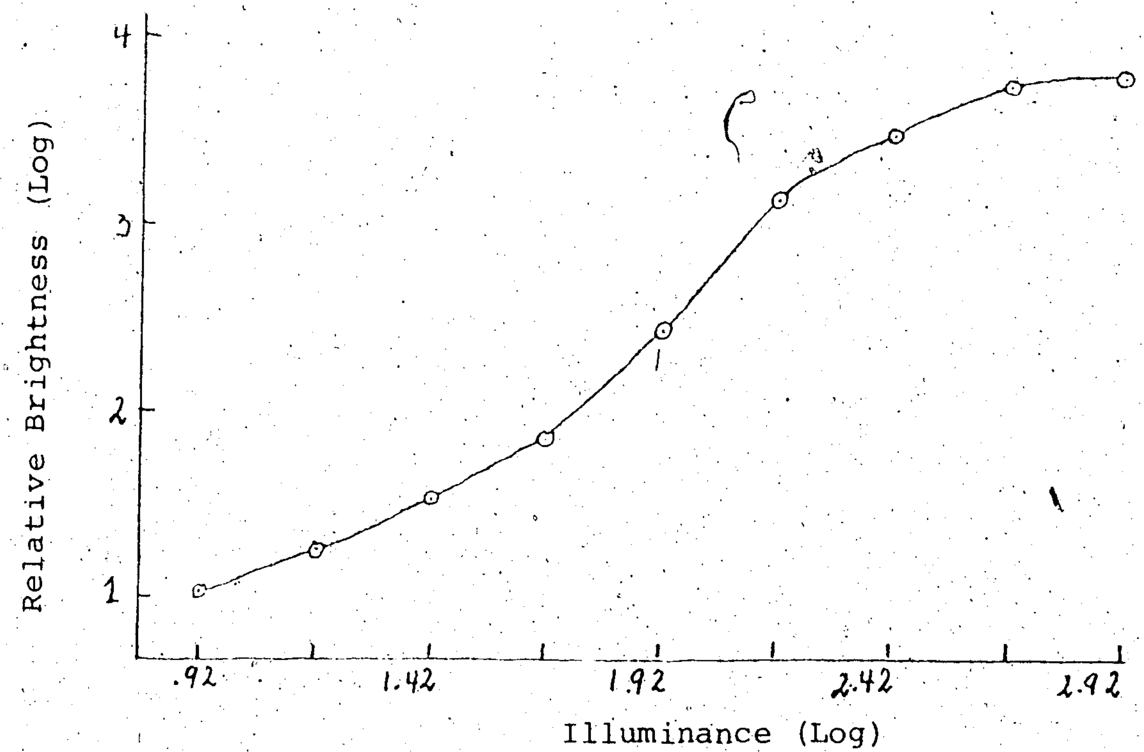


Figure 27: The brightness of a one-pulse stimulus as function of illuminance.

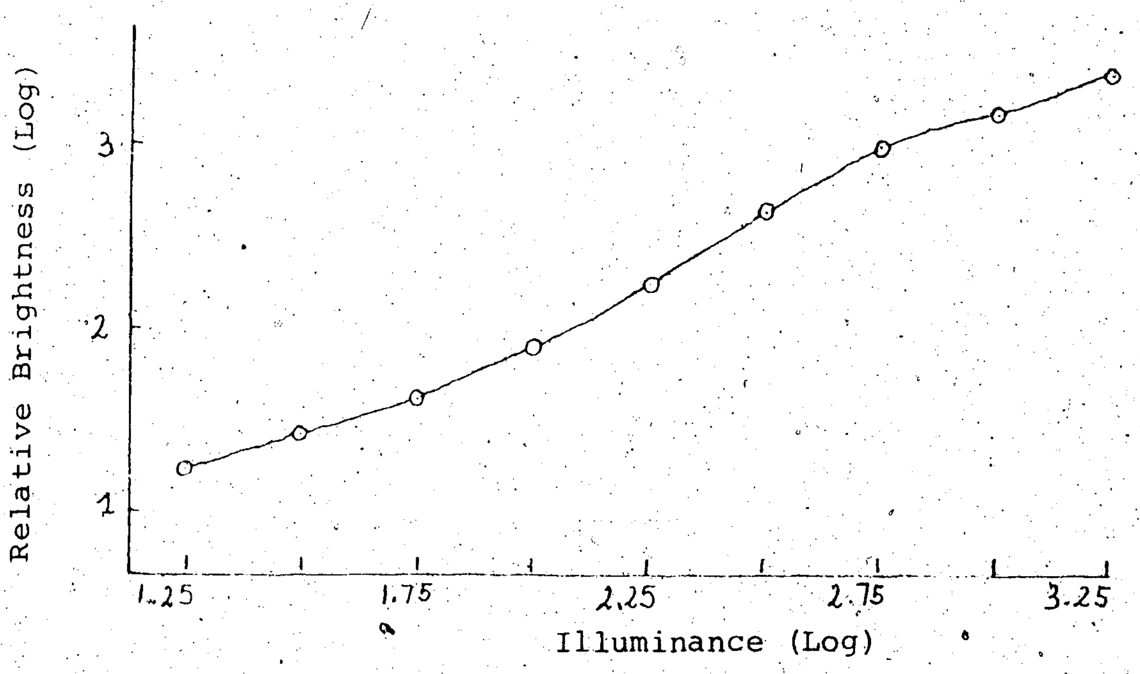


Figure 29: The brightness of a two-pulse stimulus as a function of illuminance when the pulse interval is equal to the time constant τ.

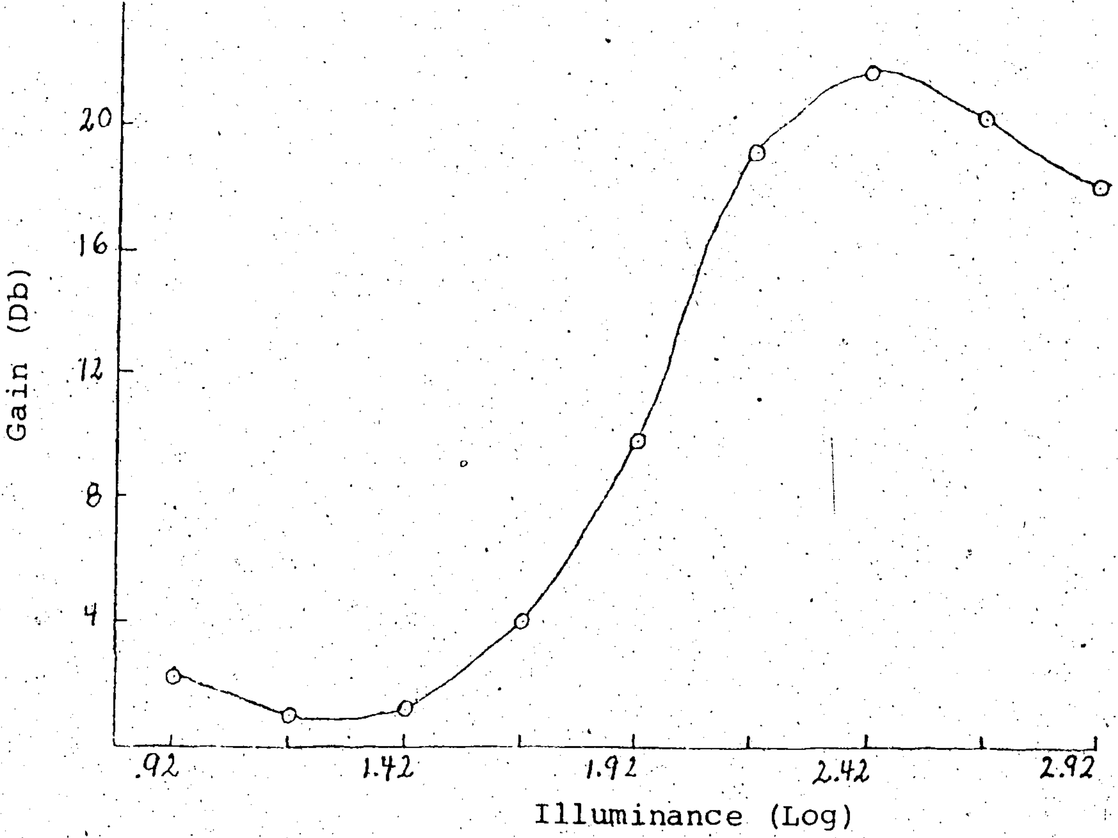


Figure 31: The brightness gain of a one-pulse stimulus as a function of stimulus illuminance. Observer L. S.

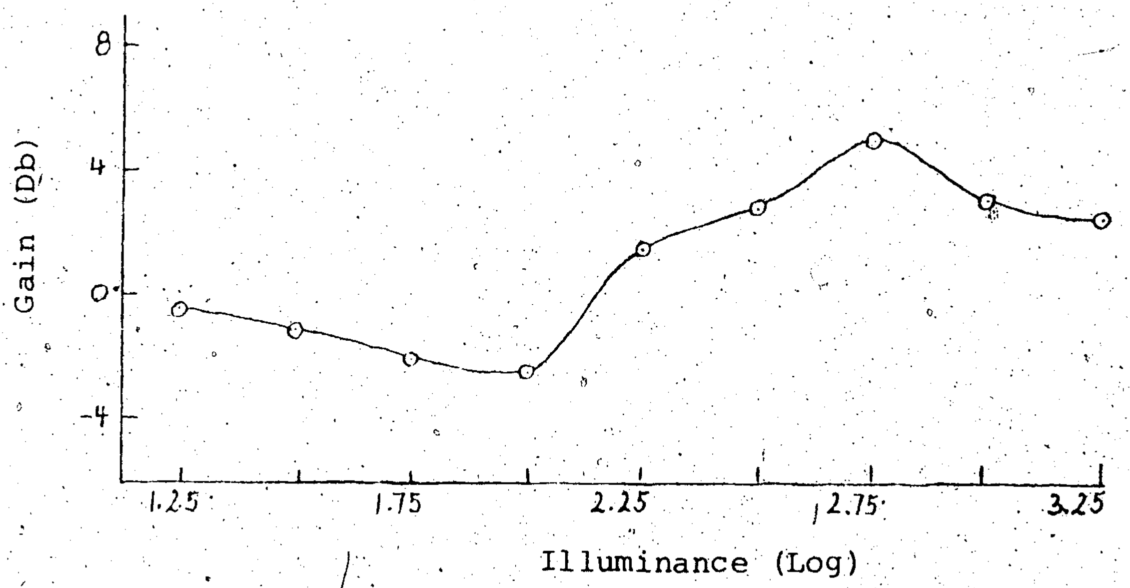
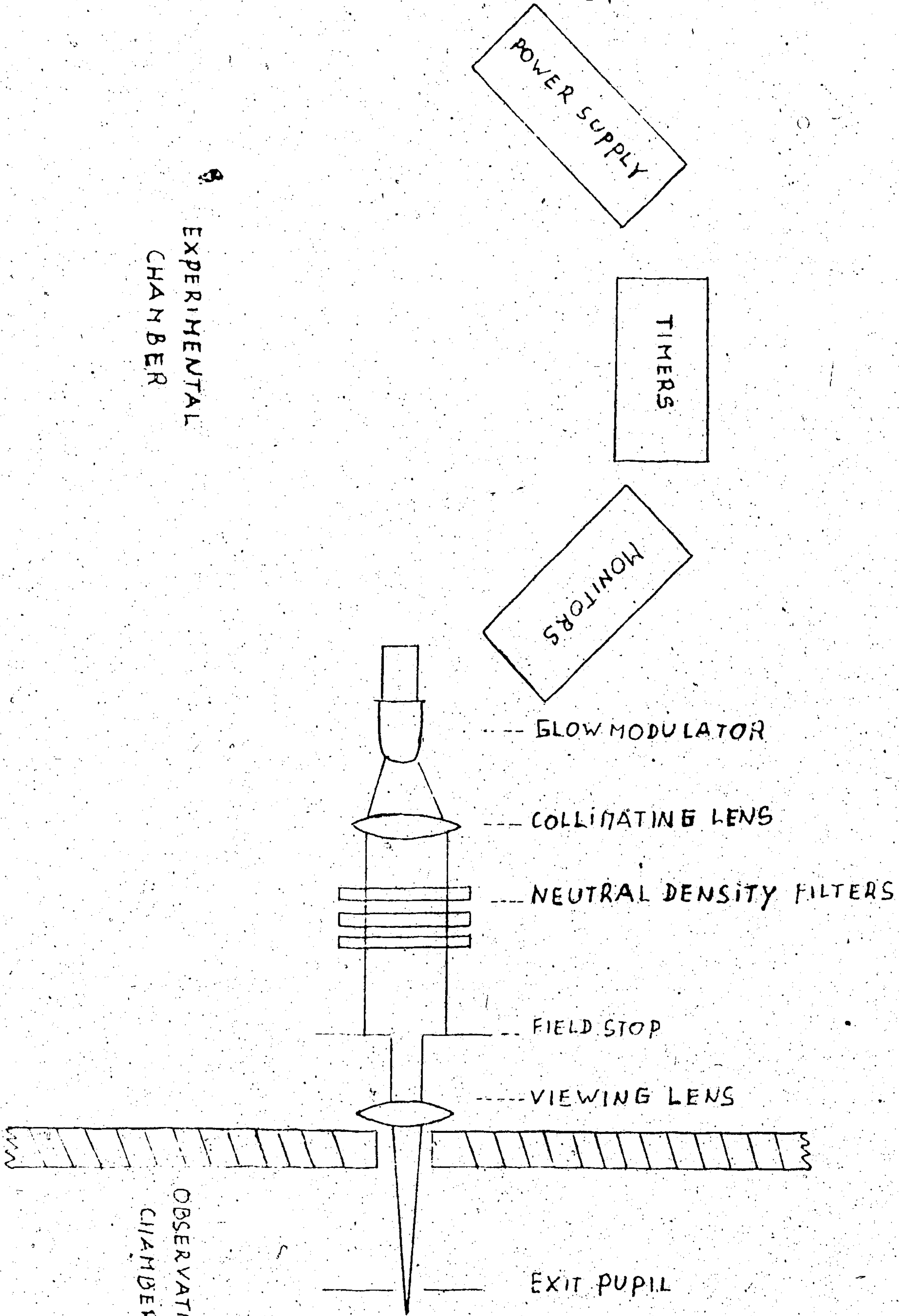


Figure 30: The brightness gain of a two-pulse stimulus as a function of stimulus illuminance when the pulse interval is equal to the time constant τ.

APPENDICES

APPENDIX A

Experimental Arrangement for Experiment I



APPENDIX B

RANGE OF INTERVAL INCREMENTS FOR EACH PULSE INTERVAL

Visual Angle:	10'	25'	1.0°	2.5°	7.5°
Observer: J. P.					
Interval (msc)	Interval Increment (msc)				
3	5-50	5-35	5-35	3-24	5-35
10	5-65	3-20	5-35	3-24	3-20
20	5-65	6-25	3-20	3-20	2-15
30	5-65	5-35	3-20	3-20	2-15
40	5-50	5-35	3-25	3-25	3-20
50	5-50	5-35	3-20	2-15	2-15
60	5-35	3-25	3-20	2-12	1- 9
70	5-35	3-20	2-15	2-12	3-20
80	3-25	3-20	2-12	3-20	3-25
100	5-50	5-35	5-50	5-25	5-35
120	5-50	5-35	5-50	5-50	5-35
140	5-65	5-65	5-50	5-65	5-50
Observer: D. N.					
Interval (msc)	Interval Increment (msc)				
3	20-115	20-95	5-95	5-95	5-95
10	20-115	20-95	5-95	5-75	5-65
20	20-115	20-95	5-65	5-65	5-65
30	20-115	5-75	5-65	5-65	5-50
40	5- 95	5-75	5-50	5-50	5-35
50	5- 75	5-50	5-35	5-35	3-20
60	5- 50	5-65	5-35	3-20	3-20
70	5- 50	5-35	3-25	3-20	3-20
80	5- 50	5-35	5-50	5-50	5-35
100	5- 95	5-65	5-75	5-65	5-65
120	20- 95	5-95	5-95	5-65	5-65
140	20- 95	5-95	5-95	5-95	5-95

APPENDIX B (Continued)

Visual Angle:	10'	25'	1.0°	2.5°	7.5°
Observers: T. G.					
Interval (msc)	Interval Increment (msc)				
3	10-80	5-65	5-65	5-80	5-65
10	10-80	5-65	5-50	5-65	5-65
20	5-65	5-50	5-50	5-65	5-65
30	5-50	5-50	5-50	5-65	5-50
40	5-50	5-35	5035	5-50	5-35
50	5-35	5-35	5-35	5-50	5-35
60	5-35	5-35	3-25	5-50	3-25
70	5-50	3-20	3-25	5-35	3-25
80	5-50	3-20	3-25	5-50	5-35
100	5-65	5-35	5-35	5-50	5-35
120	5-65	5-50	5-50	5-65	5-50
140	5-80	5-65	5-65	5-95	5-50
Observer: H. B.					
Interval (msc)	Interval Increment (msc)				
3	10-80	5-50	5-50	5-50	5-50
10	10-80	5-35	3-25	5-50	5-50
20	5-80	5-35	3-25	5-50	5-50
30	5-65	5-35	3-20	5-50	5-50
40	5-65	5-35	3-20	5-35	5-50
50	5-50	3-25	3-25	5-35	5-35
60	5-50	3-20	3-25	3-20	3-25
70	5-35	3-20	3-20	3-20	3-20
80	5-35	3-25	3-20	3-25	3-25
100	5-35	3-25	3-25	5-35	5-50
120	5-65	5-50	5-35	5-50	5-65
140	20-95	5-65	5-50	5-65	5-65

APPENDIX B (Continued)

Visual Angle:	10'	25'	1.0°	2.5°	7.5°
Observer: L. S.			Constant Brightness		
Interval (msc)			Interval Increment (msc)		
3	5-65	5-35	5-35	5-35	5-50
10	5-80	3-20	4-20	3-35	6-35
20	5-65	3-20	2-15	5-35	5-35
30	5-80	3-25	2-15	3-25	5-35
40	5-65	5-30	2-15	3-25	5-50
50	5-50	3-25	2-15	3-20	5-50
60	5-35	5-30	3-20	3-25	5-35
70	5-35	3-20	2-12	2-15	3-20
80	2-15	2-15	1- 9	2-15	3-20
100	5-45	3-25	3-20	3-25	5-65
120	5-50	5-35	5-35	3-25	5-65
140	5-50	5-50	5-50	5-35	5-65

Observer: L. S.			Constant Luminance		
Interval (msc)			Interval Increment (msc)		
3	5-50		5-30	3-25	3-20
10	5-65		4-20	3-20	2-15
20	5-65		2-15	2-15	2-15
30	5-65		2-15	2-12	2-12
40	5-50	A	2-15	2-12	2-15
50	5-50	S	3-20	2-15	3-20
60	5-50		2-15	1- 9	2-15
70	5-35	A	2-12	2-12	1- 9
80	3-25	B	2-12	2-12	3-25
100	5-35	O	5-30	5-50	5-35
120	5-35	V	5-35	5-30	5-35
140	5-65	E	5-35	5-50	5-65

APPENDIX B (Continued)

Visual Angle: 10'

Observer: L. S. Interval (msc)	T + 3.05 Log Interval Increment (msc)
3	5-35
10	5-50
20	5-65
30	5-65
40	5-65
50	5-50
60	5-35
70	5-35
80	3-25
100	5-35
120	5-50
140	5-50

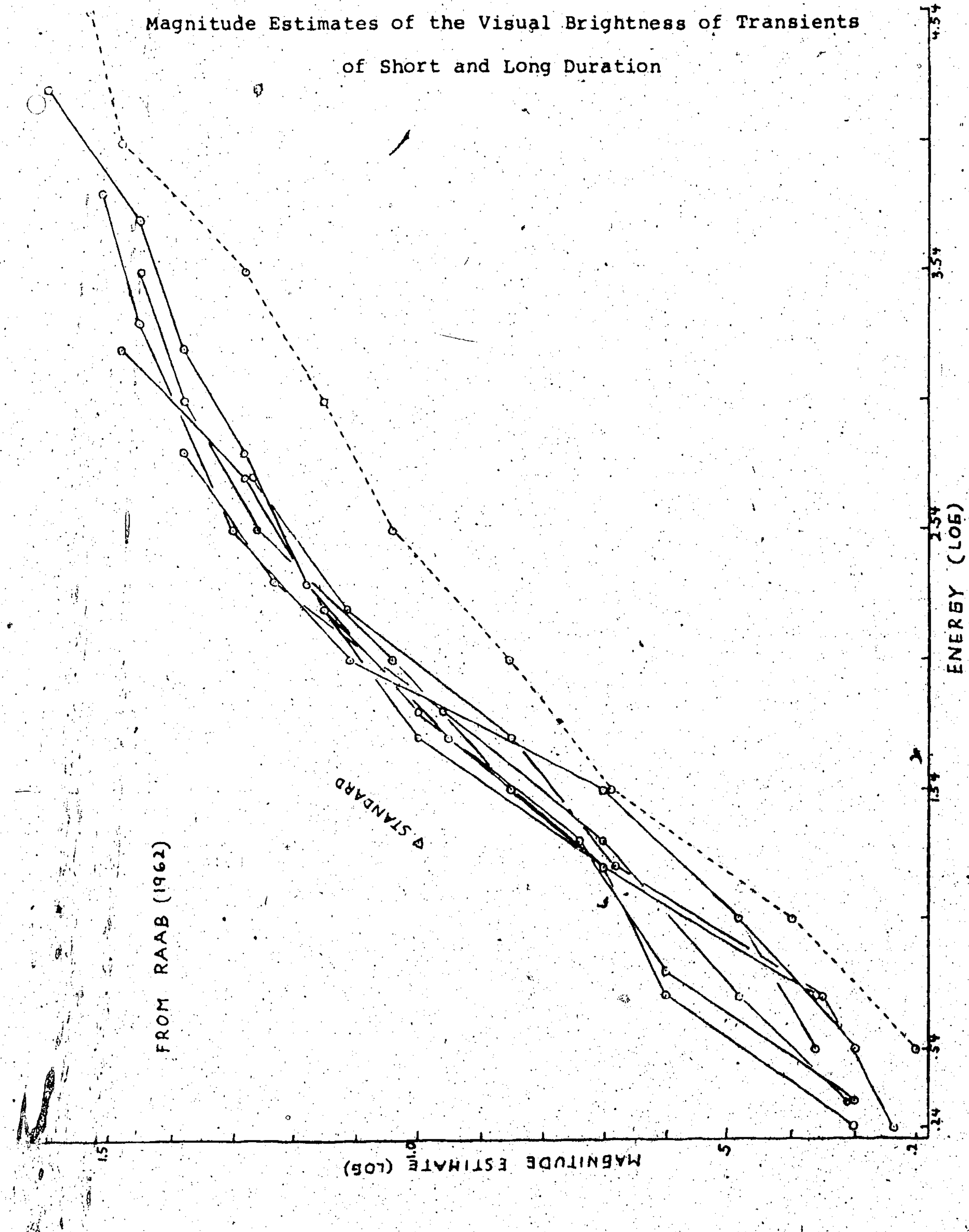
APPENDIX C

RANGE OF INTERVAL INCREMENTS FOR EACH PULSE INTERVALS FOR EXPERIMENT III

Visual Angle:	30'	30'
Observer: L. S.	T + 2.75	T + 1.75
Interval (msc)	Interval Increment (msc)	
3	12-42	6-36
9	12-42	6-36
15	12-48	6-36
21	12-48	6-30
27	12-48	6-36
33	6-36	6-36
39	6-36	6-36
45	6-30	6-36
51	6-24	6-24
57	6-18	6-24
63	4-15	6-36
69	2-12	6-24
75	2-15	4-24
81	4-24	4-24
87	6-36	2-18
93	6-36	4-18
99	6-36	2-18
105	6-36	2-18
111	6-48	6-36
117	6-48	6-36
123	6-36	6-36
129	6-36	6-24
135	12-60	6-48

APPENDIX D

Magnitude Estimates of the Visual Brightness of Transients of Short and Long Duration



APPENDIX E

FOCAL-RT Program for Interval Increment Discrimination

```
*
C FOCAL-RT

01.01 C $MAIN
01.02 O C;O S;A "CAL.?"ANS;I (ANS-0YES)1.03,5.01,1.03
01.03 A "VAL.?"ANS;I (ANS-0YES)1.04,2.05,1.04
01.04 A "MATRIX?"ANS;I (ANS-0YES)1.05,2.06,1.05
01.05 A "GO?"ANS;I (ANS-0YES)1.3,1.08,1.3
01.08 L O,F1,I,FILE1,0;A "SESS.#-A"F1(11) N;S F1(10)=1023
01.09 T "CH.1 WEDGE AT .53 FOR T+2.75 USE 1 2 LOG FILT."
01.10 A "???"ANS;I (ANS-0YES)1.1,1.12,1.1
01.12 S B=F1(3);S D=F1(5);S F1(6)=0;S F1(7)=0;S F1(15)=0;S F1(16)=0
01.13 T "HIT SNS-1",!!!;O I,3;O I
01.14 F J=0,F1(0)-2;D 3
01.15 F J=0,F1(2)-2;D 4
01.16 O T;T "OBSERV.L.S.     T+2.75    30'    SESS.#",F1(11),!!!
01.17 O S;O C;T "ADAPTATION IN PROGRESS";F I=20,56;S F1(I)=0
01.18 S A=FZ(5);I (A)1.18,1.18;S I=0
01.19 O I,1;O I;S A=FX(500);S I=I+1;S A=FZ(4);I (A)1.19,1.19,1.20
01.20 S I=I*1.05;S A=N-I;I (A)1.22,1.22,1.21
01.21 O I,1;F I=1,1,A;D 1.32
01.22 O C;T "EXPERIMENT IN PROGRESS";O T;L G,$TRIALS,0
01.30 L C,F1;O I,2;O I;L E,
01.32 O I

02.05 L G,SVALUES;0
02.06 L G,$MATRIX,0

03.01 S X=F1(3)+F1(0)-FRAN(F1(0)-J)
03.02 S A=F1(X);S F1(X)=F1(B+J);S F1(B+J)=A

04.01 S X=F1(5)+F1(2)-FRAN(F1(2)-J)
04.02 S A=F1(X);S F1(X)=F1(D+J);S F1(D+J)=A

05.01 A "ISOI?"N;O I,.25
05.02 S A=FZ(5)+1;O I;G A,5.02;O I,3;O I
05.03 O I;S A=FX(N*10);O I,1.5;O I;S A=FZ(5)+1;G A,5.03,1.05
*
```

```
*W
C FOCAL-RT

01.01 C $TRIALS
01.05 S F1(6)=F1(6)+1;S E=F1(3)+F1(6);S C=F1(4)
01.06 I (F1(6)-F1(0))1.07,1.07,1.18
01.07 T %3,F1(E-1),!;D 2
01.08 F J=F1(4),F1(4)+F1(1)-1;S F1(J)=F1(I+3)+F1(E-1);S I=I+1
01.09 F I=0,F1(1)-2;D 4
01.10 F J=F1(4),F1(4)+F1(1)-1;T %3,F1(J)
01.11 T " ",!
01.12 F J=F1(5)+F1(7),F1(5)+F1(7)+F1(1)-1;T %3,F1(J)
01.13 T " ",!;O I,3;O I
01.14 O C;O S;T "EXPERIMENT IN PROGRESS",!!!;T %3,F1(E-1);T "    ";O T
01.15 L G,$RUN,0
01.18 S A=FNEW(3000);T "END"!
01.19 T "N0.CORRECT RESPONSES="%3,F1(16),!
01.20 T "N0.ABORTS="%3,F1(15),!!
01.21 A "DATA PRINT?" ANS;I (ANS-0YES)1.27,1.22,1.27
01.22 T %3,"S.# L.S.   T+2.75  30'   SESS.#",F1(11),!!
01.24 F I=F1(10),31,F1(10)+(F1(0)-1)*31;D 3
01.25 S I=F1(10);S F1(I-2)=F1(I-2)+F1(15);T "N0.ABORTS="%3,F1(I-2),!
01.26 S F1(I-1)=F1(I-1)+F1(16);T "N0.OF CORRECT RESPONSES="%3,F1(I-1),!
01.27 T " "!!!!!!!!!!!!;O I,3;O I;L G,$MAIN,0

02.01 S I=F1(5)+F1(2)
02.02 I (F1(I)-F1(E-1))2.04,2.03,2.04
02.03 S F1(8)=F1(I+3)+F1(E-1);S F1(1)=F1(I+1);R
02.04 S I=I+F1(I+1)+3;G 2.02

03.01 T %3,F1(I),!
03.02 F J=I+1,3,I+28;T %3,F1(J)
03.03 T " "!;F J=I+1,3,I+28;T %3,F1(J+1)
03.04 T " "!;F J=I+1,3,I+28;T %3,F1(J+2)
03.05 T " "!!

04.01 S X=F1(4)+F1(1)-FRAN(F1(1)-I)
04.02 S A=F1(X);S F1(X)=F1(C+I);S F1(C+I)=A
*
```

```
C FOCAL-RT

01.02 C $RUN
01.03 S L=20
01.04 S D=F1(3)+F1(6)-1;S E=F1(D);S K=F1(5)+F1(7);S J=F1(4);G 10.09
01.10 F I=12,14;D 1.2
01.20 S D=F1(I)*10;O I,1;O I;S A=FX(D);O I

02.01 F I=1,R;D 2.02
02.02 O I,.125;O I;S A=FNEW(125);O I

03.01 F I=1,R;D 3.02
03.02 O I,.25;O I;S A=FNEW(250);O I
03.03 O I,1;O I;S A=FNEW(200);S F1(15)=F1(15)+1;G 4.01

04.01 S A=FZ(5);S B=F1(J);S F1(L)=F1(J)-E;G 4.02
04.02 I (A)4.01,4.01;S A=F1(K)+1;G A,4.11,4.11,4.12,4.13
04.11 S F1(12)=B;S F1(13)=E;S F1(14)=E;D 1.1;D 6;S R=1;S P=P1;G 7.01
04.12 S F1(12)=E;S F1(13)=B;S F1(14)=E;D 1.1;D 6;S R=2;S P=P2;G 7.01
04.13 S F1(12)=E;S F1(13)=E;S F1(14)=B;D 1.1;D 6;S R=3;S P=P3;G 7.01

05.01 S A=FZ(5)
05.02 I (A)5.01,5.01;S A=K+3+B;S R=F1(A);G R,5.03,5.04,5.05
05.03 S F1(12)=F1(8);S F1(13)=E;S F1(14)=E;G 5.06
05.04 S F1(12)=E;S F1(13)=F1(8);S F1(14)=E;G 5.06
05.05 S F1(12)=E;S F1(13)=E;S F1(14)=F1(8)
05.06 D 1.1
05.07 D 6.01;G A,5.07;D 2.01;S B=B+1;G 10.1

06.01 S P1=FZ(2);S P2=FZ(3);S P3=FZ(4);S A=P1+P2+P3+1
06.02 G A,6.01,6.03;S R=6;D 2.01;G 3.03
06.03 R

07.01 O I,.25;S I=0
07.02 S I=I+1;I (6-I)7.04;S A=FZ(5)+1;O I;G A,7.02,7.03
07.03 S A=FZ(0)+1;G A,3.03
07.04 D 2.01;I (P-1)7.05;S A=1;T %3,A;S K=K+1;S J=J+1;D 7.11;G 7.06
07.05 S A=0;T %3,A;S K=K+1;S J=J+1
07.06 S F1(L+1)=F1(L+1)+A;S L=L+2
07.07 S P1=P1+1;G P1,7.08;S I=1;G 7.10
07.08 S P2=P2+1;G P2,7.09;S I=2;G 7.10
07.09 S I=3
07.10 O S;T %1,I;O T;G 10.11
07.11 S F1(16)=F1(16)+1

10.09 S A=FNEW(250);S B=0
10.10 I (B-3)5.01
10.11 I (J-F1(4)-F1(1))4.01
10.14 S R=3;D 3.01;T " ",!!;S F1(7)=F1(7)+F1(1);L G,$DATA,0
*
```

```
*
C FOCAL-RT

01.01 C $DATA
01.02 O I,.125;S I=0
01.03 S I=I+1;O I;I (R-I)1.05;S A=FZ(5);I (A)1.03,1.03;D 1.1
01.04 O I,1;O I;S A=FX(500);S A=FZ(4);I (A)1.04,1.04
01.05 S E=F1(3)+F1(6)-1;S I=-1;D 5;S X=F1(10);S I=0;S J=0;D 6
01.06 F I=20,56;S F1(I)=0
01.07 O C;O S;T " "!!;T "N0.ABORTS="%3,F1(15),!!
01.08 T "N0.CORRECT RESPONSES="%3,F1(16),!;O T;L G,$TRIALS,0
01.10 O C;O S;T " ",!!!!!!,"READJUSTMENT IN PROGRESS",!;O T

03.01 S F1(X+29-A-2)=F1(X+29-A-5);S F1(X+29-A-1)=F1(X+29-A-4)
03.02 S F1(X+29-A)=F1(X+29-A-3)

05.01 S I=I+2;I (I-F1(1)*2+3)5.02,5.02;R
05.02 S M=20+I-1
05.03 I (F1(M)-F1(M+2))5.01,5.01;S X=F1(M);S F1(M)=F1(M+2);S F1(M+2)=X
05.05 S X=F1(M+1);S F1(M+1)=F1(M+3);S F1(M+3)=X;S M=M-2
05.06 I (M-20)5.01,5.03,5.03

06.01 I (F1(X))6.03,6.02,6.03
06.02 S F1(X)=F1(E)
06.03 I (F1(E)-F1(X))6.04,6.05,6.04
06.04 S X=X+31;G 6.01
06.05 S X=X+1
06.10 I (F1(20+I))6.2,6.2,6.11
06.11 I (F1(X+J))6.14,6.12,6.14
06.12 S F1(X+J)=F1(20+I);S F1(X+J+1)=F1(X+J+1)+F1(20+I+1)
06.13 S F1(X+J+2)=F1(X+J+2)+1;S I=I+2;G 6.1
06.14 I (F1(20+I)-F1(X+J))6.16,6.12;S J=J+3;I (J-27)6.11,6.11;G 6.19
06.15 S F1(X+J+1)=F1(20+I+1);S F1(X+J+2)=F1(X+J+2)+1
06.16 I (J)6.17,6.17;S J=J-3;I (F1(20+I)-F1(X+J))6.16,6.12,6.18
06.17 S M=J-3;S K=5;D 7;G 6.12
06.18 S M=J;S K=6;D 7;S J=J+3;G 6.12
06.19 T "STORAGE OVERFLO AT INC.  ",%3,F1(20+I),!
06.20 R

07.01 F A=0,3,29-J-K;D 3
07.02 S M=M+3;S F1(X+M+1)=0;S F1(X+M+2)=0;S F1(X+M)=0
*
```

```
*W
C FOCAL-RT

02.09 C $VALUES
02.10 O T;G 11.10

06.10 T %3, C, "       "; A N(C),
06.11 T "                    "; A IN(C),

07.10 F A=1,N(C);S F1(I)=IN(C);S I=I+1

11.10 A "NO. COMP. INTERVALS" S,!
11.20 T "ITEM   REPEATS  VALUE",!
11.30 F C=1,S; D 6
11.31 L O,F1,I,FILE1,0
11.40 S F1(0)=0;F C=1,S;S F1(0)=F1(0)+N(C)

12.20 A "STARTING FILE LOC." SC,!;S I=SC
12.30 F C=1,S;D 7

13.09 S F1(3)=SC

17.10 A "NO. TEST INCREMENTS" S,!
17.20 D 11.20
17.30 F C=1,S;D 6
17.40 S F1(1)=0;F C=1,S;S F1(1)=F1(1)+N(C)

18.20 D 12

20.09 S F1(4)=SC

24.10 A "NO. OF TEMPORAL POSITIONS OF TEST INCREMENT" S,!
24.30 D 11.20
24.31 F C=1,S;D 6
24.40 S F1(2)=0;F C=1,S;S F1(2)=F1(2)+N(C)

25.20 D 12
25.41 S F1(5)=SC
25.42 G 27.05

26.10 D 17.10
26.11 A "COMPARISON INTERVAL" CI,!
26.20 D 11.20
26.30 F C=1,S;D 6
26.40 D 12.20
26.45 S F1(SC-3)=CI;S F1(SC-2)=0;F C=1,S;S F1(SC-2)=F1(SC-2)+N(C)
26.50 F C=1,S;D 7.1;S F1(SC-1)=SC

27.05 F M=1,F1(0);D 26
27.10 L C,F1
27.15 O S;L G,$MAIN,0
*
```

```
C FOCAL-RT

09.49 C $MATRIX
09.50 L O,F1;I,FILE1,0
09.51 A "NO. COPIES?" CP
09.52 S B=F1(3);S C=F1(4);S D=F1(5);S E=F1(0);S N=0
09.53 G 11.10

10.10 S X=F1(3)+F1(0)-FRAN(F1(0)-J)
10.11 S A=F1(X);S F1(X)=F1(B+J);S F1(B+J)=A

11.10 T "HIT SNS-1",!!!
11.11 O I,3;O I
11.28 S L=0;S M=0
11.29 F J=0,F1(2)-2;D 24
11.30 F J=0,F1(0)-2;D 10
11.31 T "OBSERVER           CONDITION           DATE                TIME",!!!
11.32 G 20.07

20.05 F I=0,F1(1)-2;D 23
20.07 S L=L+1;S E=F1(3)+L;I (L-F1(0))20.08,20.08,20.27
20.08 T %3,F1(E-1),!
20.11 D 25
20.12 F J=F1(4),F1(4)+F1(1)-1;D 26
20.13 D 20.05
20.15 F J=F1(4),F1(4)+F1(1)-1;S TE=F1(J)+F1(E-1);T %3, TE
20.17 T " ",!
20.20 F K=F1(5)+M,F1(5Y+M+F1(1)-1;T %3, F1(K)
20.21 T " ",!!;S M=M+F1(1)
20.22 G 20.07
20.27 T " ",!!!!!!
20.30 S N=N+1;I (N-CP)11.28,22.10,22.10

22.10 L G,$MAIN,0

23.10 S X=F1(4)+F1(1)-FRAN(F1(1)-I)
23.11 S A=F1(X);S F1(X)=F1(C+I);S F1(C+I)=A

24.10 S X=F1(5)+F1(2)-FRAN(F1(2)-J)
24.11 S A=F1(X);S F1(X)=F1(D+J);S F1(D+J)=A

25.05 S I=F1(5)+F1(2)
25.06 I (F1(I)-F1(E-1))25.10,25.07,25.10
25.07 R
25.10 S I=I+F1(1)+3;G 25.06

26.10 S F1(J)=F1(I+3);S I=I+1
*
```

APPENDIX F

FOCAL-RT Program for Brightness Matching Tasks

```
*W
C FOCAL-RT

01.01 C $MAIN
01.03 A "CAL?"ANS;I (ANS-0YES)1.04,4.02,1.04
01.04 O S;A "PRT?"ANS;I (ANS-0YES)1.05,6.01,1.05
01.05 A "VAL?"ANS;I (ANS-0YES)1.06,4.01,1.06
01.06 O S;A "GO?"ANS;I (ANS-0YES)1.25,1.07,1.25
01.07 D 1.26;A "S#-SES#-A"F1(2) F1(4) N;D F1(2),1.27,1.28,1.29,1.3,1.31
01.09 T "SNS-1",!;O I,3;O I;S L=F1(1);F I=0,F1(0)-3;D 5
01.14 S F1(5)=F1(1)+F1(0);F I=F1(5),F1(5)+2*F1(0)+1;S F1(I)=0
01.15 D 2;S I=F2(509);S F1(I-2)=F1(5);O T;T "GO",!;O I,1;O I;O C;O S
01.16 S I=FZ(5);I (I)1.16,1.16;S J=0;T "ADAPTATION  T.N."
01.17 O I,1;O I;S I=FX(500);S J=J+1;S I=FZ(4);I (I)1.17,1.17
01.18 S J=J*1.05;S I=N-J;I (I)1.19,1.19;O I,1;F J=1,I;O I
01.19 O C;L G,$RUN,0
01.25 O I,3;O I;L C,F1;L C,F2;O T;L E,
01.26 L O,F1,I,FILE1,0;L O,F2,F,#72,0
01.27 S F2(509)=517;S F2(506)=.85;S F2(505)=2.75
01.28 S F2(509)=3388;S F2(506)=1.35;S F2(505)=2.25
01.29 S F2(509)=9130;S F2(506)=1.1;S F2(505)=2.5
01.30 S F2(509)=12001;S F2(506)=.6;S F2(505)=3
01.31 S F2(509)=6259;S F2(506)=.35;S F2(505)=3.25

02.01 O C
02.02 T "CH1. USE TWO  1 LOG FILTERS",!
02.03 T %3.2,"CH1. WEDGE +",F2(506);A "  ??"ANS;I (ANS-0YES)2.03,2.05,20
02.05 R

03.01 I (F1(N))3.02,3.03
03.02 T %4,F1(N),"   ";S N=N+1;G 6.04
03.03 S I=I+61;T " ",!;G 6.02

04.01 O T;L G,$VALUES,0
04.02 L G,$CALIBRATION,0

05.01 S J=F1(1)+F1(0)-FRAN(F1(0)-I)
05.02 S K=F1(J);S F1(J)=F1(L+I);S F1(L+I)=K

06.01 D 1.26;O T;O T;A "CO"F2(509),!;S I=F2(509)
06.02 I (F1(I))6.03,1.25
06.03 T %3,F1(I),"=   ";S N=I+1;S J=0
06.04 S J=J+1;I (J-7)3.01,3.01;T " ",!"          ";S J=0
06.05 I (F1(N))6.04,6.06,6.04
06.06 S I=I+61;T " ",#,;G 6.02
*
```

```
*
C FOCAL-RT

01.01 C $RUN
01.22 O S;S O=F1(5);S M=F1(1);S J=1;S X=F2(509);S F1(6)=0
01.24 I (M-F1(1)-F1(0))1,26;S J=3;S K=.25;D 6.01;D 5.02
01.25 S I=-1;D 7;S I=F1(X-2);D 8;S I=F1(X-2);O T;D 9;D 5.02;G 1.28
01.26 O I,1;O I;S K=.125;D 6.01
01.27 S L=FZ(5);I (L)1.27,1.27;O C;S N=F1(M);D 5.01;T %3,N,"=";G 3.02
01.28 L G,$DATAPLOT,0

02.01 O I,.25;S I=0
02.02 S I=I+1;I (8-I)2.04;S L=FZ(5)+1;O I;G L,2.02,2.03
02.03 S L=FZ(0)+1;G L,1.24
02.04 S F1(O)=N;I (K)2.06,2.05,2.06
02.05 S K=.001
02.06 T %4,K*1000;S F1(O+1)=K*1000;S O=O+2;S M=M+1;S F1(6)=F1(6)+1
02.07 T " ",!!!,"TRIAL NO.",%3,F1(6),!;G 1.24

03.02 O I,1.5;O I;S L=FX(N*10);S L=FZ(5)+1;G L,3.02;S K=FADC(8)
03.03 O I,1;O I;G 2.01

05.01 T "EXPERIMENT IN PROGRESS  L.S.",!!!
05.02 T " "!,"END OF SESSION",!!!

06.01 F N=1,J;D 6.02
06.02 O I,K;O I;S L=FNEW(K*1000);O I

07.01 S I=I+2;I (I-F1(0)*2+3)7.02,7.02;R
07.02 S M=F1(5)+I-1
07.03 I (F1(M)-F1(M+2))7.01,7.01;S J=F1(M);S F1(M)=F1(M+2)
07.04 S F1(M+2)=J;S J=F1(M+1);S F1(M+1)=F1(M+3);S F1(M+3)=J;S M=M-2
07.05 I (M-F1(5))7.01,7.03,7.03

08.01 S J=X;S K=J
08.02 I (F1(J))8.04,8.03,8.04
08.03 S F1(J)=F1(I)
08.04 I (F1(J)-F1(I))8,05,8.06,8.05
08.05 S J=J+61;S K=J;G 8.02
08.06 S J=J+1;I (F1(J))8.06,8.07,8.06
08.07 S F1(J)=F1(I+1);S I=I+2;S J=K;I (F1(I))8.09,8.1,8.09
08.09 I (F1(J)-F1(I))8.05,8.06,8.05
08.10 R

09.01 T %4.2,"S.NO.= L.S.   CONDIT.=T+",F2(505),"   SESS.NO.=",F1(4),!!
09.02 S K=0
09.03 I (F1(I))9.05,9.04,9.05
09.04 R
09.05 S K=K+1;I (F1(I)-F1(I+2))9.07,9.06,9.07
09.06 S I=I+2;S M=K;G 9.03
09.07 T %3,F1(I),"=    ";S M=I-2*K+3;F J=M,2,I+1;T %4,F1(J),"    "
09.09 S I=I+2;T " ",!;G 9.02
*
```

```
*
C FOCAL-RT

01.01 C $DATA PLOT
01.02 O C;O S;A "PLOT?"ANS;I (ANS-0YES)2.26,1.04,2.26
01.04 S F2(508)=F1(2);S F2(507)=F1(4);S K=0;S M=0;O T

02.01 T %4.2,"S.#=L.S.   CO.=T+",F2(505),"   SES.#",F2(507),!!
02.02 S L=F2(509)
02.03 I (F1(L))2.05,2.12,2.05
02.05 S M=M+1;S J=1;S N=0;S ANS=0;S I=1
02.06 S F2(K)=F1(L)
02.07 I (F1(L+J))2.08,2.09,2.08
02.08 S F2(K+I)=F1(L+J);S N=N+F1(L+J);S I=I+1;S J=J+1;G 2.07
02.09 S J=J-1;S N=N/J;S I=0;D 4;F I=K+1,K+J;S ANS=ANS+(F2(I)-N)↑2
02.10 S ANS=FSQT(ANS/J);S F2(K+1)=J;S F2(K+2)=N;S F2(K+3)=ANS
02.11 S F2(K+4)=O;S F2(K+5)=P;S K=K+6;S L=L+61;G 2.03
02.12 S I=-1;D 3
02.13 O S;A "AVR?"ANS;I (ANS-0YES)2.2,2.27,2.2
02.20 A "HI LMT&LO LMT(0-1)"P N;O T;F I=0,6,(M*6)-6;D 5
02.23 O C;O S;D 2.01;S J=1.30/M;F I=0,J,1.3;D 2.42
02.24 F I=0,.125,1;D 2.43
02.25 S K=2;F I=J,J,1.3;S L= FDIS(I,((F2(K)/1000)-N)/(P-N));S K=K+6
02.26 O T;S F2(506)=M;S F2(504)=M;L G,$GRAPH,0
02.27 S F2(506)=M;L G,$AVR,0
02.42 S L=FDIS(I,0)
02.43 S L=FDIS(0,I)

03.01 S I=I+6;I (I-M*6+7)3.02,3.02;R
03.02 S N=I-5
03.03 I (F2(N)-F2(N+6))3.01,3.01;S J=F2(N);S F2(N)=F2(N+6)
03.04 S F2(N+6)=J;S J=F2(N+1);S F2(N+1)=F2(N+7);S F2(N+7)=J
03.05 S J=F2(N+2);S F2(N+2)=F2(N+8);S F2(N+8)=J;S J=F2(N+3)
03.06 S F2(N+3)=F2(N+9);S F2(N+9)=J;S J=F2(N+4);S F2(N+4)=F2(N+10)
03.07 S F2(N+10)=J;S J=F2(N+5);S F2(N+5)=F2(N+11);S F2(N+11)=J
03.08 S N=N-6;I (N)3.01,3.03,3.03

04.01 S I=I+1;I (I-J)4.03;S O=F2(K+1);S P=F2(K+J);R
04.03 I (F2(K+I)-F2(K+I+1))4.01,4.01;S ANS=F2(K+I);S F2(K+I)=F2(K+I+1)
04.04 S F2(K+I+1)=ANS;S I=I-1;I (I)4.01,4.01,4.03

05.01 T %5.2,F2(I),"   ",F2(I+1),"   ",F2(I+2)," ",F2(I+3)
05.02 T %5.2," ",F2(I+4)," ",F2(I+5),!
*
```

```
*W
C FOCAL-RT

01.01 C $GRAPH
01.02 O T;A "GRAPH?"ANS;I (ANS-0YES)1.27,1.05,1.27
01.05 A "HI LMT-LO LMT" H L,!;S ANS=F2(504)
01.06 T %4.2,"S.#=L.S.   CO.=T+",F2(505),"   SESS.#",F2(507),!
01.07 T "      ";F I=4,72;T "-"
01.08 T " ",!
01.10 S SC=(H-L)/68
01.25 F I=2,6,F2(504)*6-4;T %3,F2(I-2);T "!";;D 2
01.26 D 1.07;T " ",!!!!!!!!!!!
01.27 A "EST.DISCRIM.FUNC.?"ANS;I (ANS-0YES)1.44,1.28,1.44
01.28 A "CRITERION"C;S I=8;S J=I;S K=0;S ANS=F2(504)
01.30 I (I-(ANS*6-10))3.01,3.01,1.31
01.31 A "WRITE?"ANS;I (ANS-0YES)1.35,1.32,1.35
01.32 D 1.06;S K=0;S I=6;S ANS=F2(504);G 3.1
01.35 T " ",!!!!;A "GRAPH FUNC.?"ANS;I (ANS-0YES)1.27,1.36,1.27
01.36 D 1.05;T %2,"CRITERION",C,!;D 1.06;D 1.07;D 1.08;S I=ANS*6+1;S M=6
01.37 I (ANS*6-12-M)1.41;T %3,F2(M);T "!";I (F2(I))1.38,1.42,1.38
01.38 I (H-F2(I))1.39;S SC=(H-L)/68;D 2;G 1.4
01.39 T ">HI LMT",!
01.40 S M=M+6;S I=I+1;G 1.37
01.41 D 1.26;G 1.27
01.42 T " EXCEEDS RANGE";!;G 1.41
01.44 A "AVR?"ANS;I (ANS-0YES)1.5,1.49,1.5
01.49 L G,$AVR,0
01.50 L G,$MAIN,0

02.01 S J=FITR((F2(I)-L)/SC)
02.02 F K=1,J-1;T " "
02.03 T "*",!

03.01 I (C-FABS(F2(I)-F2(J+6)))3.03,3.08;S J=J+6
03.02 I (J-(ANS*6-10))3.01,3.01;S F2(ANS*6+1+K)=0;G 3.09
03.03 I (F2(I)-F2(J+6))3.04,3.04,3.05
03.04 S H=1*C;G 3.06
03.05 S H=-1*C
03.06 S X=(F2(I)+H-F2(J))/(F2(J+6)-F2(J));S X=X*(F2(J+4)-F2(J-2))
03.07 S X=X+F2(J-2);S F2(ANS*6+1+K)=X-F2(I-2);G 3.09
03.08 S F2(ANS*6+1+K)=F2(I+4)-F2(I-2)
03.09 S K=K+1;S I=I+6;S J=I;G 1.3
03.10 I (ANS*6-12-I)1.35;T %3,F2(I),"="
03.12 I (F2(ANS*6+1+K))3.14,3.14;T  %4.2,F2(ANS*6+1+K),!;S K=K+1;S I=I+[illegible]
03.14 T " EXCEEDS RANGE",!;S K=K+1;S I=I+6;G 3.1
*
```

```
*W
C FOCAL-RT

01.01 C $AVR
01.02 S F2(504)=F2(506)-1;S M=F2(504);F I=6,6,M*6-6;D 2
01.03 O T;D 4
01.05 T " ",!!!;D 4.02;O I,2;O I;L G,$GRAPH,0

02.01 S F2(I)=(F2(I)+F2(I+6))/2
02.02 S F2(I+2)=(F2(I+2)+F2(I+8))/2

03.01 T %5.2,F2(I),"   ",F2(I+1),"   ",F2(I+2),!

04.01 A "PRINT VAL?"ANS;I (ANS-0YES)1.05,4.02,1.05
04.02 T "LINEAR INTERPOLATION",!
04.03 F I=0,6,M*6-6;D 3
*
```

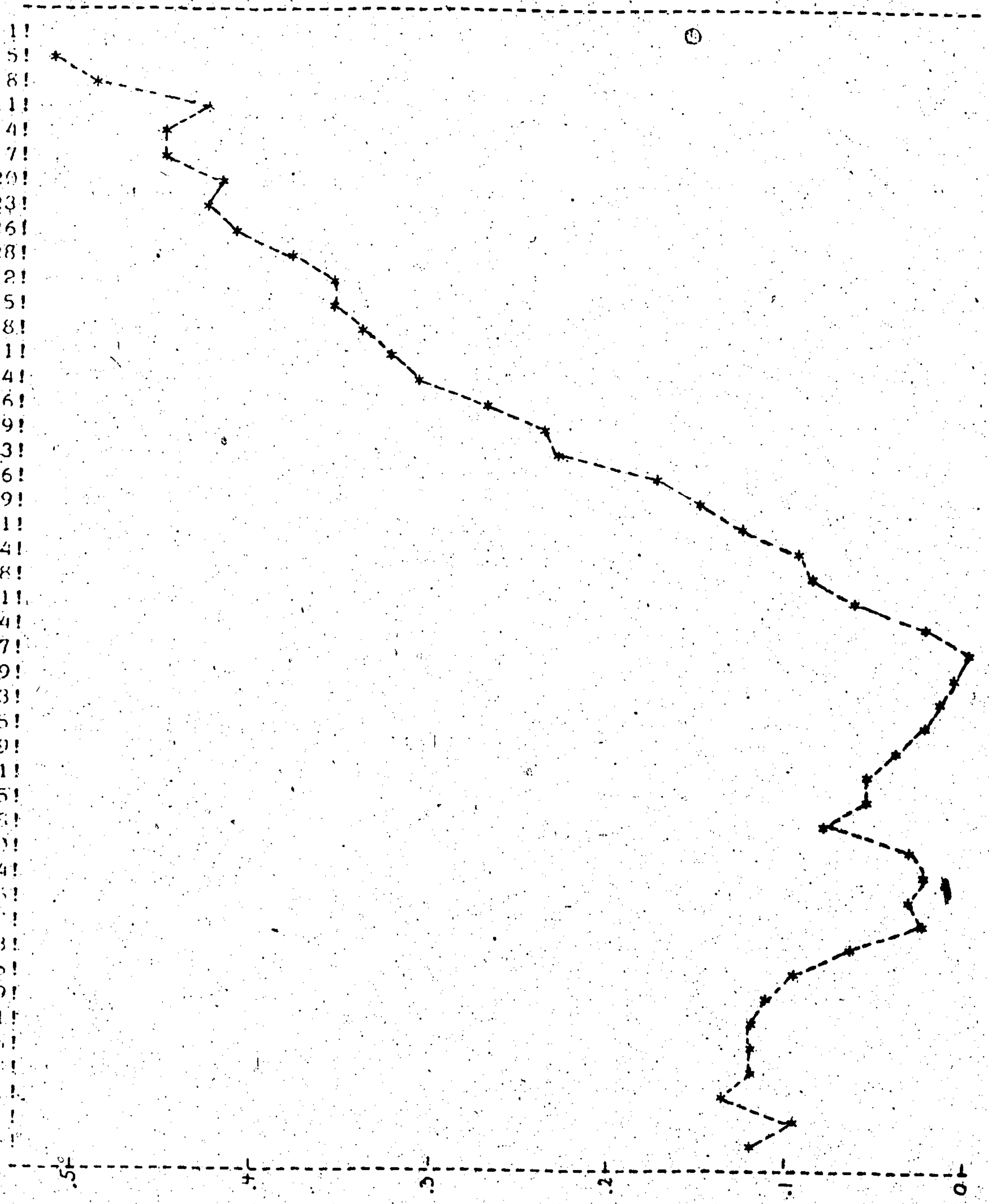
```
*W
C FOCAL-RT

03.01 C $VALUES

04.01 L O,F1,I,FILE1,0;A "N0.DIFFERENT STIMULUS VALUES?"I,!
04.02 T "ITEM   REPEATS   VALUE",!
04.03 F J=1,I;D 4.10
04.04 S F1(0)=0;F J=1,I;S F1(0)=F1(0)+N(J)
04.05 A "STARTING FILE LO.?"F1(1),!;S J=F1(1);F C=1,I;D 4.11
04.06 L G,$MAIN,0
04.10 T %3,J,"        ";A N(J),;T "   ";A N1(J)
04.11 F A=1,N(C);S F1(J)=N1(C);S J=J+1
*
```

```
C FOCAL-RI

01.01 C $CALIBRATION

02.01 O C;O S;A "GM PH"ANS;I (ANS-0YES)3.01,2.04,3.01
02.04 A "ISOI"N;O I,.25
02.05 S A=FZ(5)+1;O I;G A,2.05;O I,3;O I
02.06 O I;S A=FX(N*10);O I,1.5;O I;S A=FZ(5)+1;G A,2.06,3.01

03.01 A "MT PH,"ANS;I (ANS-0YES)7.1,3.05,7.1
03.05 O S;A "POT"P;I (P-0)3.06,3.07,3.06
03.06 S Z=P
03.07 A "ILL"L;I (L-0)3.08,3.09,3.08
03.08 S T=L
03.09 S A=FADC(8);S N=FITR(1000*A);T %3,N;I (Z-N)3.10,4.1,3.2
03.10 S A=FNEW(75);DO 3.31
03.11 G 3.09
03.20 S A=FNEW(300);DO 3.31
03.21 G 3.09
03.31 F I=0,30;O D

04.10 O C;S A=FNEW(1000);S A=0
04.11 F I=0,255;S A=A+FADC(9)
04.20 S B=A/256
04.30 S N=FITR(100*B);S U=5+(N*10)
04.32 S V=FITR(1000*B)
04.34 I (V-U)4.8,4.5,4.5
04.50 S N=N+1;G 4.8
04.80 I (N-T)5.01,6.1,5.01

05.01 F I=0,15;S A=FNEW(50);D 5.3
05.02 O T;T %4.4 "POT",Z,"   ILL",B,!;G 3.05
05.30 F J=0,12;O D

06.10 O T;S A=FNEW(1000);T %4.4 "POT",Z,"   ILL",B,!;O S

07.10 A "ADC OUTPUT MONITOR"ANS;I (ANS-0YES)8.01,7.11,8.01
07.11 S A=0;F I=0,255;S A=A+FADC(15)
07.12 S A=A/256;O C;O T;T %5.4,"ADC#15=",A,!;O I,1.5;O I

08.01 O S;L G,$MAIN,0
*
```

APPENDIX G

Sample Print-Out of a Two-Pulse Brightness Function.

```
LINEAR INTERPOLATION
GRAPH?:YES
HI LMT-LO LMT:335 :230
S.#=T.N.   CO.=T+ 3.000   SESS.# 5.000
```



Log Relative matching luminance

APPENDIX H

INTERVAL DURATIONS FOR THE STANDARD AND TEST STIMULUS IN EXPERIMENT IV

Luminance (Log)	Standard (msc)	Test (msc)									
T + 1.25	70	73	76	79	82	85	88	91	94	97	100
T + 1.50	70	AS ABOVE									
T + 1.75	70	AS ABOVE									
T + 2.00	65	67	69	71	73	75	77	79	81	83	85
T + 2.25	60	62	64	66	68	70	72	74	76	78	80
T + 2.50	55	57	59	61	63	65	67	69	71	73	75
T + 2.75	50	52	54	56	58	60	62	64	66	68	70
T + 3.00	50	AS ABOVE									
T + 3.25	48	50	52	54	56	58	60	62	64	66	68
T + 3.50	48	AS ABOVE									

APPENDIX I

SUMMARY OF MEASURED AND EFFECTIVE LUMINANCE

Observer	Experiment	Conditions (log)	Visual* Angle	Channel	Measured Luminance (nit)	Density (log)	Effective Luminance (nit)
	I	Calibration	30'	Main	1.74×10^3 #		
	I	"	10'	"	1.05×10^3 #		
	I	"	24'30"	"	1.22×10^3 #		
	I	"	58'30"	"	1.12×10^3 #		
	I	"	2.5°	"	1.35×10^3 #		
	I	"	7°26'	"	1.23×10^3 #		
	II	"	1°7'	"	7.26×10^2 ##		
	II	"	"	Match	1.16×10^2 ##		
	II-VI	"	30'	Main	1.42×10^3 ###		
	"	"	"	Match	1.62×10^2 ####		
L. S.	II	T + 2.25	1°7'	Main		3.17	4.91×10^{-1}
T. N.	II	T + 2.25	"	"		3.17	$4.91 - 10^{-1}$
L. S.	I	T + 3.05	10'	"		1.71	2.05×10^1
L. S.	I C	T + 2.91	10'	"		2.91	1.29×10^0
D. N.	I O	T + 1.86	"	"		2.55	2.96×10^0
J. P.	I	T + 1.76	"	"		2.76	2.10×10^0

APPENDIX I (Continued)

Observer	Experiment	Condition (log)	Visual Angle*	Channel	Measured Luminance (nit)	Density	Effective Luminance (nit)
L. S.	I N	T + 2.25	24'30"	"		2.91	1.50×10^0
D. N.	I S	T + 2.25	"	"		2.55	3.44×10^0
J. P.	I T	T + 2.25	"	"		2.70	2.44×10^0
L. S.	I	T + 2.41	58'30"	"		2.91	1.38×10^0
D. N.	I A	T + 3.05	"	"		2.55	3.16×10^0
J. P.	I N	T + 2.56	"	"		2.70	2.24×10^0
L. S.	I T	T + 3.34	2.5°	"		2.91	1.66×10^0
D. N.	I	T + 3.76	"	"		2.55	3.80×10^0
J. P.	I L	T + 3.04	"	"		2.70	2.70×10^0
L. S.	I U	T + 4.55	7°26'	"		2.91	1.51×10^0
D. N.	I M	T + 4.86	"	"		2.55	3.47×10^0
J. P.	I	T + 4.46	"	"		2.70	2.46×10^0
L. S.	I C	T + 2.25	10'	Main		2.51	3.24×10^0
T. G.	I O	"	"	"		1.63	2.46×10^1
H. B.	I N	"	"	"		2.32	5.03×10^0
L. S.	I	"	24'30"	"		2.91	1.50×10^0
T. G.	I S	"	"	"		3.04	1.11×10^0
H. B.	I T	"	"	"		3.04	1.11×10^0
L. S.	I	"	58'30"	"		3.29	5.74×10^{-1}

APPENDIX I (Continued)

Observer	Experiment	Condition (log)	Visual Angle*	Channel	Measured Luminance (nit)	Density (log)	Effective Luminance (nit)
T. G.	I A	T + 2.25	58'30"	Main		3.33	5.24×10^{-1}
H. B.	I N	"	"	"		3.13	8.32×10^{-1}
L. S.	I T	"	2.5°	"		4.12	1.02×10^{-1}
T. G.	I	"	"	"		4.49	4.37×10^{-2}
H. B.	I I	"	"	"		3.92	1.62×10^{-1}
L. S.	I L	"	7°26'	"		5.11	9.54×10^{-3}
T. G.	I L	"	"	"		5.11	9.54×10^{-3}
H. B.	I .	"	"	"		4.91	1.51×10^{-2}
L. S.	II/III	T + 1.75	30'	"		3.75	2.53×10^{-1}
"	II	T + 2.25	"	"		3.25	7.98×10^{-1}
"	II/III	T + 2.75	"	"		**2.61	3.48×10^{0}
H. B.	II	T + 1.75	"	"		3.66	3.11×10^{-1}
"	II	T + 2.25	"	"		3.16	9.84×10^{-1}
"	II	T + 2.75	"	"		2.66	3.11×10^{0}
T. N.	II	T + 2.25	"	"		3.35	6.35×10^{-1}
"	II	T + 2.50	"	"		3.10	1.13×10^{0}
"	II	T + 2.75	"	"		2.85	2.00×10^{0}
"	II	T + 3.00	"	"		2.60	3.56×10^{0}

APPENDIX I (Continued)

Observer	Experiment	Condition (log)	Visual Angle*	Channel	Measured Luminance (nit)	Density (log)	Effective Luminance (nit)
T. N.	II	T + 3.25	30'	Main		2.35	6.35×10^{0}
L. S.	IV/V/VI	T + 1.25	30'	"		4.20	8.96×10^{-2}
"	"	T + 1.50	"	"		4.00	1.42×10^{-1}
"	"	T + 1.75	"	"		3.75	2.53×10^{-1}
"	"	T + 2.00	"	"		3.50	4.49×10^{-1}
"	"	T + 2.25	"	"		3.25	7.98×10^{-1}
"	"	T + 2.50	"	"		***2.86	1.96×10^{0}
"	"	T + 2.75	"	"		2.61	3.47×10^{0}
"	"	T + 3.00	"	"		2.36	6.21×10^{0}
"	"	T + 3.25	"	"		2.11	1.10×10^{1}
"	"	T + 3.50	"	"		***2.08	1.18×10^{1}

* Nominal values. ** Due to an inaccuracy in the calibration of 2 Log neutral density Filter, the increase in effective luminance from T+2.25 to T+2.75 is .64 Log for this observer.

*** Due to an inaccuracy in the calibration of a 2 Log neutral density filter, the increase in effective luminance from T+2.25 to T+2.50 and from T+3.25 to T+3.50 is .39 Log and .03 Log respectively.

\# Refer to Laboratory Log 10/7/73
\## Refer to Laboratory Log 27/1/74
\### Refer to Laboratory Log 8/7/74
\#### Refer to Laboratory Log 14/9/74