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TACHISTOSCOPIC THRESHOLDS AND INTENSITY-TIME FUNCTIONS USING PATTERN STIMULI IN MONKEYS AND HUMANS

by

Andrew A. Glover

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in partial fulfillment of the
requirements for the degree of
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Aug. 29th, 1982

Date

Chairman of Examining Committee

Date

Executive Officer

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The City University of New York

ABSTRACT

TACHISTOSCOPIC THRESHOLDS AND INTENSITY-TIME FUNCTIONS USING PATTERN STIMULI IN MONKEYS AND HUMANS

by

Andrew A. Glover

Advisor: Professor Pedro Pasik

In this investigation, tachistoscopic thresholds for pattern stimuli as well as intensity-time functions are obtained for monkeys and human observers at several luminance levels. The stimuli are simultaneously presented triangle-circle pairs. Subjects initiate their own trials and are required to respond during each trial.

In Experiment I, thresholds are obtained for two monkeys using the descending staircase procedure as well as the method of constant stimuli. Two levels of luminance are used. For each level, adapting and stimulus fields are flux-equated. Psychometric functions are constructed from the constant stimuli data. Threshold values, as well as energy required at threshold, are comparable across methods. Attenuating the luminance by 1.2 log units results in an increase of threshold duration, but of only 0.4 log units magnitude. In addition, less energy is required at threshold for the lower values of luminance. Qualitative observations in a human subject are consistent with these findings. The results indicate that duration plays a more significant role than intensity for obtaining the criterion response, which suggests a supersummation effect.

In Experiment II, thresholds are obtained for three monkeys and one other human subject using only the descending staircase procedure. Eight stimulus luminances are used at a constant light adaptation level. Stimulus and adapting fields are flux-equated only in the condition utilizing the highest luminance. The other several levels are attenuated in 0.3 log steps. Intensity-time functions are constructed from these data. Slopes of these functions are steeper than -1.0, again indicating supersummation, i.e., duration is more effective than intensity in eliciting the criterion response. Function analyses show a region of reciprocity at briefer durations followed by supersummation. Response latency values remain relatively constant for stimuli of high luminance and brief duration, and become progressively longer at lower luminances and longer durations. Similarly, the stimulus energy at threshold results in comparable latencies at higher levels, and an increment in latency at lower levels.

The results of both Experiments I and II indicate that duration is more effective than luminance for a threshold pattern discrimination task, i.e., supersummation is demonstrated in both studies. The magnitude of the phenomenon is not the same across experiments, indicating that the level of light adaptation may have an effect.

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Chapter I

INTRODUCTION

In 1885 Bloch described a reciprocal relationship between intensity (I) and duration (T) in a visual detection task (Bloch, 1885). Bloch's Law, as extended by Charpentier (1890), states that luminance and duration of a visual stimulus can be interchanged reciprocally below a certain critical duration (tc) to produce a constant behavioral response, such as 50% frequency-of-seeing. This law implies that the visual effect is solely dependent on the total energy (E) of the stimulus (E=IT), so that luminance is fully integrated over time. The above relationship has been termed complete temporal integration or summation. For durations greater than tc, increases in time are not fully compensated by corresponding decreases in intensity.

Although Bloch's Law was assumed to hold only for elementary processes such as brightness discrimination, a number of other measures of visual functions such as visual acuity, motion perception, digit identification, and numerosity have been shown also to follow this law (Brown, 1955; Graham & Cook, 1937; Hunter & Sigler, 1940; Kahneman & Norman, 1964). Perception of shape is similarly influenced by intensity and time, but the precise nature of the relationship is not clear. Shape matching functions have been obtained (Leibowitz & Bourne, 1956; Leibowitz, Toffey & Searle, 1966) and the findings indicate that shape constancy does not result solely from the total excitation produced by the stimulating energy, but depends strongly on exposure time. Assuming adequate energy to permit discrimination, the tendency towards shape constancy seems to depend on additional mechanisms involving stimulus exposures that are longer than tc. Similarly, the findings of a forced-choice task in which subjects have to choose between linear displays of dots, arranged in pairs or evenly spaced, presented at different exposure times and intensities, indicate that perception becomes differentiated over time. Intensity has little effect on the discrimination of pairs of dots, whereas exposure time and spatial distance between and within pairs of dots increases the percent of correct responses (Kaswan & Young, 1963).

The lower and upper limits of complete integration have been difficult to define. Most investigators find that Bloch's Law holds for stimuli in the microsecond range (Beams, 1935; Brindley, 1952; Dawson & Harrison, 1973; Gilmer, 1937; but see Pulling, 1951). With prolonged stimuli, however, the results are more controversial, because difficulty arises in judging when the slope of the function log I vs log T changes from -1.0 to 0.0, i.e., from complete integration to no integration (see segments b and d of Figure 4). This problem can be overcome, however, by using two light pulses separated by various time intervals. With this procedure, tc is clearly demarcated by an abrupt inflexion in the function (Clark & Blackwell, 1959). A region of partial integration may exist beyond tc for some range of stimulus durations (Sperling and Jolliffe, 1965). In this case, increases in time do not fully compensate for corresponding decreases in luminance. Partial integration exists when a progressively less luminance decrement is required as duration is increased to maintain the same response level. The longest stimulus duration at which partial integration can no longer be demonstrated is called utilization time (Piéron, 1952). Some investigators (e.g., Karn, 1936; Long, 1951; Ronchi, 1974; Herrick, 1973; Levinson, 1979) choose to ignore partial integration altogether. When this phenomenon is not observed, i.e., when there is a sharp demarcation between complete reciprocity and failure of reciprocity, utilization time coincides with critical duration.

Critical duration and utilization time may take on different values depending on the experimental conditions and the method of data analysis. The form of the temporal integration function is, however, generally agreed upon. It has been proposed that experimental factors and/or manipulations that change the values of critical duration or utilization time, and/or alter the form of the function, may yield information relevant to understanding temporal integration and its importance in perception (Wasserman & Kong, 1979).

Despite the consistent findings in temporal summation research (complete summation, critical duration, partial integration, utilization time), no satisfactory theoretical interpretation of the reciprocal relationship exits. Boynton (1961) notes that what causes reciprocity to fail beyond tc is not known. Moreover, it is not clear how a complex and generally nonlinear system follows such a linear principle as Bloch's Law (Kahneman, 1979).

Most previous studies on temporal integration have utilized single and double flashes of light and human subjects. The present investigation seeks to obtain temporal-integration functions for pattern discrimination in the normal monkey (Macaca mulatta) and in the human observer. Since patterns are closer to natural stimuli, the obtained functions may add significantly to understanding the visual properties of the normal subject. The monkey is selected because there is an absence of data about this animal, and investigations with monkeys would have potentially fewer experimental restrictions than with humans. For example, the effects of cerebral lesions or of neuropharmacological agents, such as neurotransmitter agonists and antagonists, on the intensity-time function may be investigated in the future. The intensity-time function is also obtained in a human observer under essentially identical conditions to confirm the animal data. Comparable results would give more weight to the animal model for investigations of temporal integration.

Traditionally two methods have been used to study intensity-time relationships in vision: an equal-energy paradigm and an equal-performance paradigm. With the equal energy method, the independent variables consist of intensity-duration combinations whose luminous energy product is constant (IT=K). The dependent variable is the level of performance selected (e.g., absolute threshold). With the equal performance method, a criterion value of performance is chosen (e.g., 50% detection) and either luminance or duration is held constant while the other parameter is varied in order to elicit the criterion response. Two psychophysical procedures are used in the present study: the descending staircase method and the method of constant stimuli. Both are of the equal performance type.

Experiment I contrasts the two psychophysical methods: descending staircase and constant stimuli procedures. Two luminance levels are used, with the adapting and stimulus fields equated for total luminous flux. Experiment II is conducted using only the descending staircase procedure with light adaptation held constant. The stimuli are at the same level of the adapting field, or at seven other lower values. Additionally, latency data are collected to confirm appropriate performance and to ascertain the relationship of this measure to parameters of the obtained temporal summation functions. In both experiments, subjects are required to initiate trials to minimize motivational variables and inattention.

Chapter II

RELEVANT LITERATURE

A. Time and Intensity Variables Affecting Temporal Integration

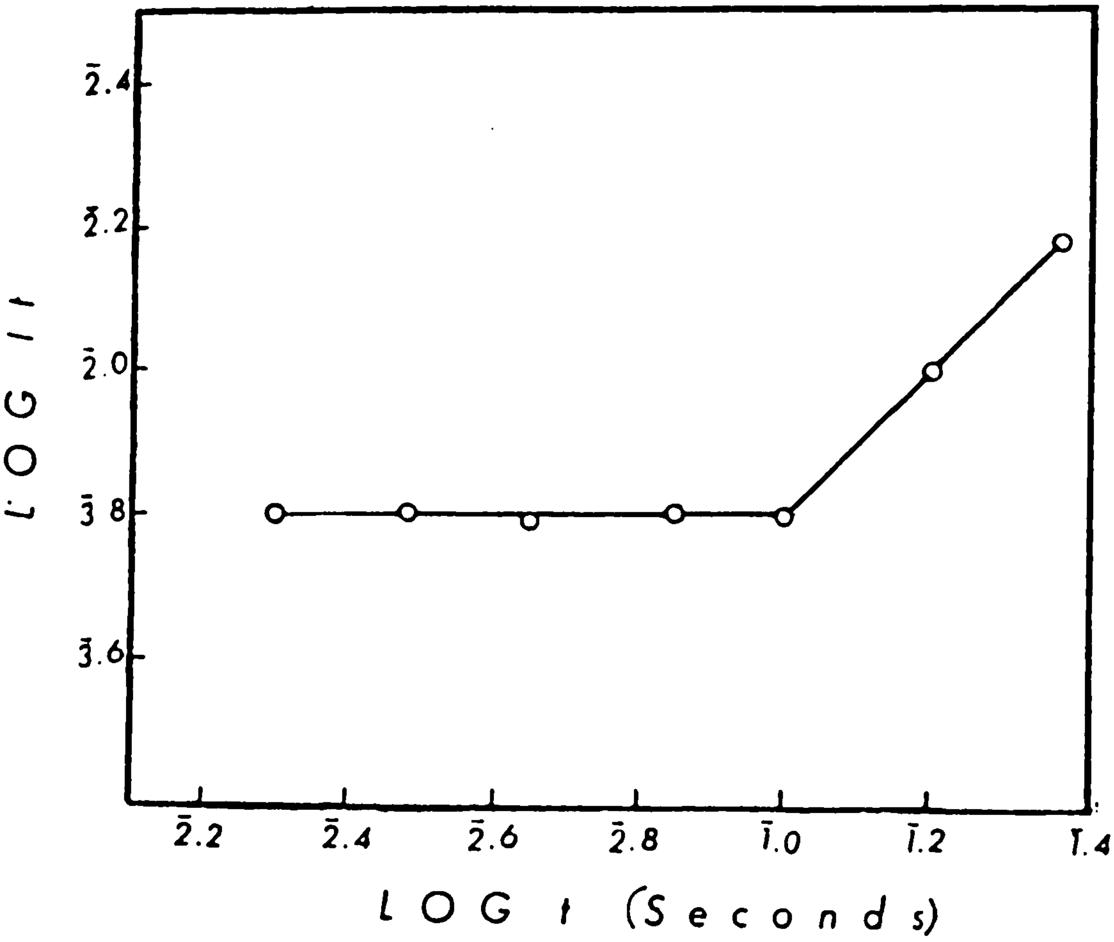
According to the psychophysical law of reciprocity (Bloch, 1885) a constant visual effect is dependent only upon the total stimulus energy ($E = IT$), if the duration is less than a critical time (Le Grand, 1968), i.e., $IT = K$ for a criterion response. If intensity and duration are plotted logarithmically, a straight line with negative unit slope is obtained, and this relationship would exactly satisfy the complete integration predicted by Bloch's Law.

Temporal integration can also be expressed in terms of log IT vs log T. An example from the human literature is taken from Long (1951) and shown in Figure 1. In this case, log IT instead of log I is displayed on the ordinate. The stimuli are square pulses of white light presented at 15 degrees eccentricity. For flashes shorter than critical duration, the obtained slope is zero, indicating that the log IT at threshold is constant. Critical duration is the upper limit of perfect summation. Beyond this value, the function exhibits a positive unit slope, which shows that the visual effect is solely dependent on the luminance ($I = K$).

A similar function, also obtained from human observers by Sperling and Jolliffe (1965), is shown in Figure 2. In this study, square pulses of light are presented foveally to the dark-adapted eye. Unlike Figure 1, this function shows a region of partial integration between complete summation and no-summation. This gradual transition from complete integration to no integration, which suggests that increases in stimulus duration are not compensated by corresponding decreases in intensity for a constant visual

Figure 1.

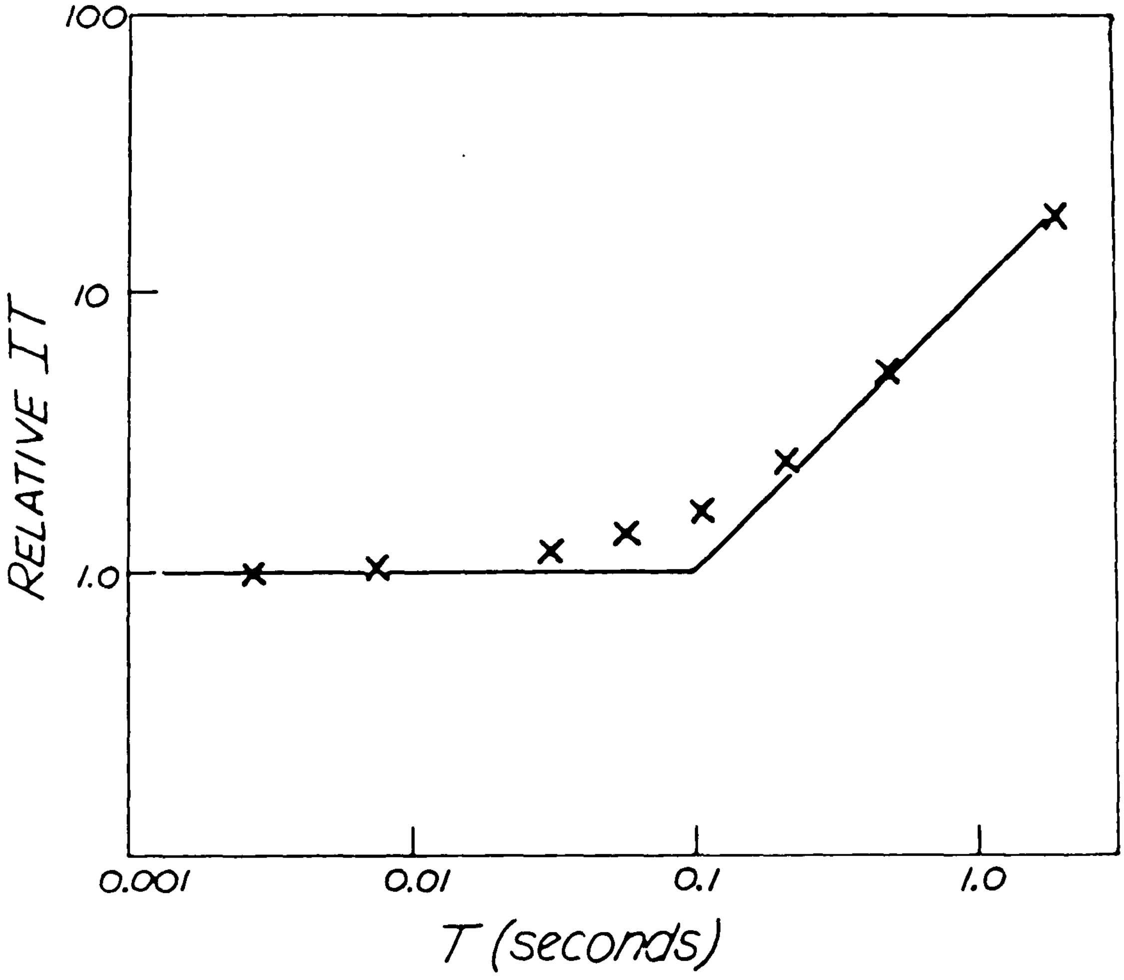
The intensity-time curve obtained by Long (1951) showing log IT vs log T for the human observer. Note that a region of partial integration is not found.



LOG It
$\bar{2}.4$
$\bar{2}.2$
$\bar{2}.0$
$\bar{3}.8$
$\bar{3}.6$
$\bar{2}.2$
$\bar{2}.4$
$\bar{2}.6$
$\bar{2}.8$
$\bar{1}.0$
$\bar{1}.2$
$\bar{1}.4$
LOG t (Seconds)

Figure 2.

The log IT vs. Log T function reproduced from Sperling and Jolliffe (1965). Values are averages of three subjects for foveally presented stimuli, 45 degrees in diameter, with a wavelength of 650 millimicrons, against a dark surround. The solid line represents the predicted values from a model based on Hartline's single receptor results. Note a region of partial summation for the four stimulus durations between complete summation (represented by the two briefest stimuli) and no summation (represented by the two longest stimuli).


100
10
1.0
RELATIVE IT
0.001
0.01
0.1
1.0
T (seconds)

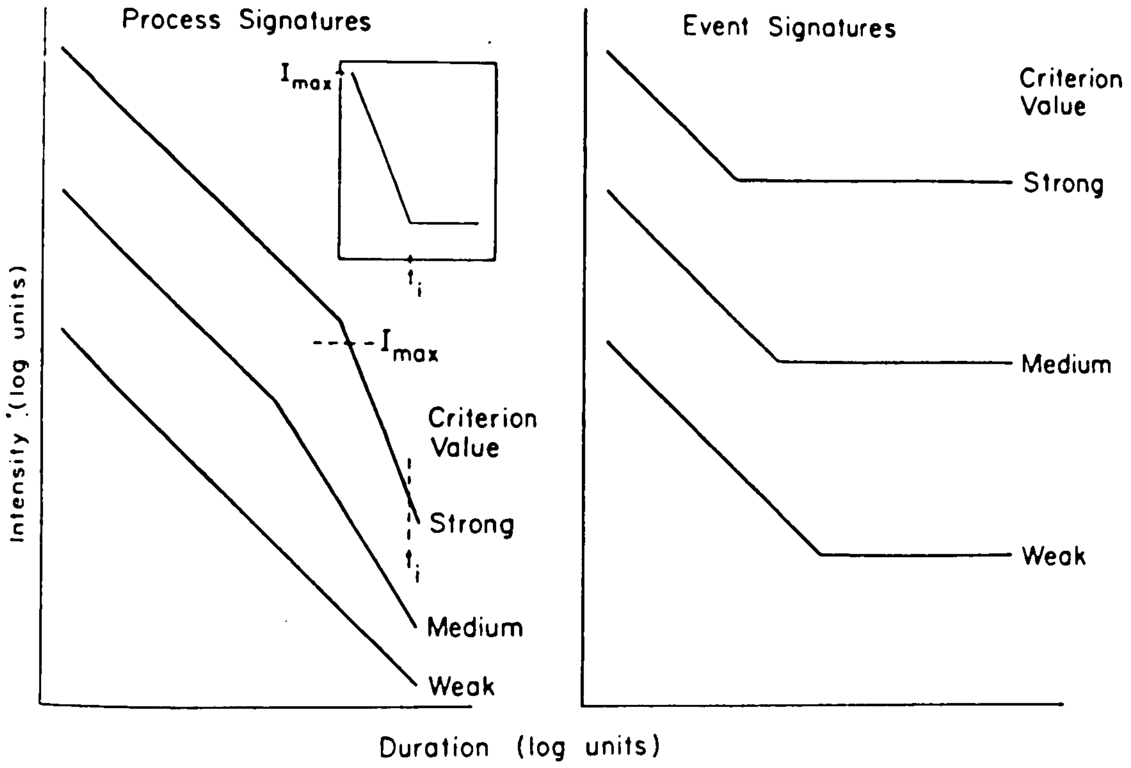
effect, has been noted by several investigators (Baumgardt & Hillman, 1961; Blondel & Rey, 1912; Clark & Blackwell, 1959; Kietzman & Gillam, 1972). Other authors ignore partial integration and as in Figure 1, estimate critical duration from the intersection of the line of zero slope and the line of unit positive slope (Biersdorf, 1955; Herrick, 1973; Karn, 1936; Levinson, 1979; Long, 1951; Nolan, 1957; Ronchi, 1974). The upper limit of partial integration is called utilization time; beyond it, integration fails completely. For stimulus durations greater than utilization time, luminance must remain constant for the subject to maintain the same level of responding.

In addition to the five characteristics of single flash studies of temporal summation outlined above (complete integration, critical duration, partial integration, utilization time, and no summation), two other phenomena have been considered: supersummation (Kong & Wasserman, 1978) and subsummation (Kietzman, 1979). Supersummation occurs when longer durations require disproportionately lower intensities for the same criterion response with a consequent slope that is steeper than -1.0, in log I vs log T functions. Since these intensity-time combinations result in a lower energy requirement, the effect can be construed as facilitatory. One such effect has been reported by Wasserman and Kong (1979) and is shown in Figure 3, left. Working with Limulus eye, receptor and spike potentials from the retinula cell and the axon of the eccentric cell, respectively, were recorded under various combinations of intensity and time to elicit a criterion response. The data are

analyzed in terms of latency or amplitude of the graded receptor potential, latency to the first spike, peak spike frequency, area under the amplitude/time function of the receptor potential, and total number of spikes. Bloch's law is confirmed for all these measurements for brief durations. With longer stimuli,

Figure 3.

Functional relationships (signatures) found in physiological experiments on the trade-off of intensity and duration to produce a criterion sensory signal in Limulus. The "process" function is obtained when the area under a receptor potential or the total number of spikes is considered. The "event" function is obtained when either the peak of the receptor potential or the peak frequency of spikes is the measured parameter. Note that the "process" relationships show a region of complete summation followed by <u>supersummation</u>. The "event" functions depict a region of complete summation followed by no-summation. Additionally, "process" signatures are modified by criterion changes whereas "event" signatures are not. The inset on the left shows the function derived from a behavioral experiment where supersummation is followed by no-summation (from Wasserman & Kong, 1979).


Process Signatures
I_{max}
t_i
I_{max}
Criterion Value
Strong
t_i
Medium
Weak
Event Signatures
Criterion Value
Strong
Medium
Weak
Intensity (log units)
Duration (log units)

however, the last two measures require relatively less intensity and, therefore, exhibit the supersummation phenomenon after complete integration. The authors interpretation of these findings will be given in the next Section.

Other instances of supersummation effects are suggested in the literature. For instance, in a study by Hunter and Sigler (1940), the subject judges the number of dots in a visual display under various time-intensity combinations. When there are eight or less dots, complete summation is evident up to a critical duration. When the number of dots is nine or more, supersummation functions (slopes steeper than -1.0) become apparent. A significant effect of duration over intensity is also reported, as noted earlier, by Kaswan and Young (1963), Leibowitz and Bourne (1956), as well as Leibowitz, Toffey and Searle (1966).

In spite of the above findings, some investigators question supersummation on empirical and/or theoretical grounds. The data of Hunter and Sigler (1940) are interpreted in the context of probability summation and/or the possibility of counting the stimuli one at a time at the longer durations (Schlosberg, 1948). Kahneman (1966) suggests also that the findings of Kazwan and Young (1963) may be attributed to artifacts caused by masking. The issue, therefore, remains open.

Log I vs log T functions with slopes steeper than -1 have also been obtained in auditory psychophysics. In these cases, however, they occur at brief stimulus duration and, therefore, are thought to be due to a non-linear loss of information as duration is decreased. Greater intensity increments are required to compensate for relatively smaller decrements in duration to elicit the criterion response. Because of these considerations, this phenomenon is interpreted as inhibitory (Babkoff, 1979). For an extensive review of auditory temporal integration functions see Krooss-Glover, 1980.

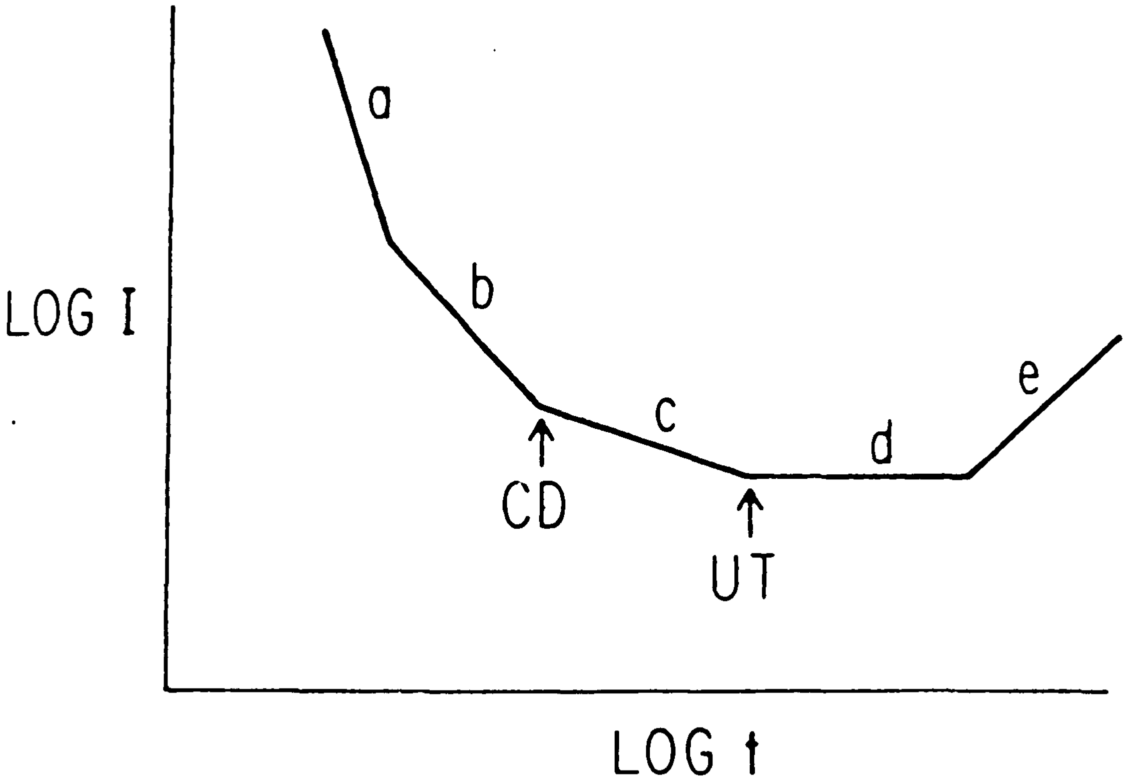
Finally, subsummation refers to intensity-time relations with a positive slope, i.e., that increasing the stimulus duration above some value requires additional increases in intensity to maintain a constant response. It is well known that to keep suprathreshold brightness constant, it is necessary to decrease luminance as stimulus exposure duration is increased. Beyond a certain duration, however, luminance must also be increased to maintain the same effect. This is the classic Broca-Sulzer effect (Kietzman, 1979), which some authors have interpreted to suggest an inhibitory process.

Figure 4, taken from Kietzman (1979) gives a summary of the seven characteristics of the temporal summation function. The sequence of the segments is *arbitrary*. For instance in visual psychophysics, segment a, representing supersummation, occurs usually after segment b (see Fig. 3) i.e., at *longer* stimulus durations, whereas in auditory experiments, segment a, with slope steeper than -1, results with *briefer* stimuli.

Temporal summation of photic energy has been studied electrophysiologically at different levels: single cell, electroretinogram, and evoked potentials (Johnson & Bartlett, 1956; Wasserman & Kong, 1975; Wicke, Donchin & Lindsley, 1964). It has also been studied in a number of neural structures: photoreceptor, retinal ganglion cell, lateral geniculate nucleus, and visual cortex (Baker, Sanseverino, Lamarre, & Poggio, 1969; Levick & Zachs, 1970; Wasserman & Kong, 1975). Finally, temporal summation has been shown to occur in a variety of species: horseshoe crab, conger eel, goldfish, rabbit, cat, and humans (Adrian & Mathews, 1927; Bartley, 1934; Hartline, 1934; Levick & Zachs, 1970; Wasserman & Kong, 1975). The observed temporal integration functions are very similar in all species including man, and provide

Figure 4.

The seven characteristics of temporal summation (from Kietzman, 1979). Supersummation, complete summation, partial summation, non-summation, and subsummation are shown by segments a, b, c, d, and e, with slopes of > -1.0, -1.0, < -0.1, 0.0, > 0.0, respectively. CD and UT signify critical duration and utilization time, respectively. The sequence of the segments is *arbitrary*.


LOG I
a
b
c
d
e
CD
UT
LOG t

a physiological substrate for behavioral psychophysical investigations. The criterion response may be a given electrophysiological parameter, for instance, some feature of a graded receptor potential, or of the electroretinogram, or some behavior, e.g. 50% frequency-of-seeing or tail movement response to light in limulus (Wasserman & Kong, 1979).

B. Other Variables Affecting Temporal Integration

A number of factors and/or their interaction are thought to influence temporal integration in addition to the inherent time-intensity relationships. These other variables can be various stimulus attributes, organismic conditions, response requirements, and methods of response analysis.

It has been shown in behavioral studies that critical duration exhibits a non-linear increase as a function of spatial frequency between two and ten cy/deg (Brown and Black, 1976). Contrariwise, lower values of tc have been reported for higher levels of light adaptation (Barlow, 1958; Clark & Blackwell, 1959; Graham & Kemp, 1938; Herrick, 1973; Keller, 1941; Van den Brink & Bouman, 1954), and for larger size stimuli (Barlow, 1958; Graham & Margaria, 1935; Karn, 1936). These latter findings, however, are not confirmed by other investigators who find that light adaptation, size, as well as wavelength have no effect on critical duration (Ikeda, 1965; Meijer, Van der Wildt & Van den Brink, 1978; Rouse, 1952; Uetsuki & Ikeda, 1970). The period of partial integration is prolonged with increases in spatial frequency (Legge, 1978) and size of the stimulus (Baumgardt & Hillman, 1961; Meijer, Van der Wildt & Van den Brink, 1978; Sperling & Joliffe, 1965) whereas light adaptation has the opposite effect (Ikeda, 1965; Utesuki and Ikeda, 1970).

Organismic variables such as age, brain damage, psychopathology and response criterion have been shown to influence critical duration. Older adults (30-55 years old) matched with younger individuals on standard tests for visual acuity have longer tc's for form discrimination (Eriksen, Hamlin & Breitmeyer, 1970). Postgeniculate rather than pregeniculate lesions prolong critical duration (Wilson, 1967), while schizophrenics have shorter tc's than normals and subjects with other types of psychoses (Collins, Kietzman, Sutton & Shapiro, 1978).

The importance of response requirements on temporal integration have also been established. Kahneman and Norman (1964) find that different critical durations are related to differences in perceptual function. For example, under identical stimulus conditions, they report tc values of approximately 80 msec when the observer has to judge the relative brightness of two stimuli whereas values of about 300 msec are obtained when triads of digits have to be discriminated. Similar effects are reported in an experiment involving stroboscopic illumination of a moving radius. The subject's task is either to count the number of visible radii or estimate the angle subtended by the leading and trailing edges of the radii. Despite of the fact that the stimuli are the same, obtained limits of phenomenal simultaneity, which apparently is related to tc, are longer in the counting task than those for estimating the angle (Allport, 1970). Bruder and Kietzman (1973) compare characteristics of temporal summation for three responses measures: frequency-of-seeing, signal detectability, and simple reaction time. Reciprocity is always followed by partial integration, but critical duration and utilization time are shorter for simple reaction time than for the other measures.

It appears from the preceding examples that some features of temporal integration are modified by response requirements in the presence of invariate stimuli. These findings suggest that temporal summation cannot be fully explained by early sensory processes (Wasserman & Kong, 1979). The conclusion that feedback modulation is provided by more central levels, however, cannot be ruled out. In fact, there is abundant anatomical and physiological evidence in lower vertebrates, and in some mammals, that the retina indeed receives fibers of central origin which modify its activity (Cowan, 1970; Miles, 1972; Powell, Downer & Brooke, 1965).

Choice of response analysis also influences temporal summation characteristics. As pointed out earlier, it has been shown that a fixed peripheral neural signal does not make the time course of the phenomenon invariate. The response characteristic chosen for analysis may determine such course (Kong & Wasserman, 1978). When time-locked features of the graded receptor potential in Limulus retinula cell (such as latency or peak amplitude) are analyzed, the expected temporal integration function becomes evident and the shape is unaffected by changes in the response criterion. The above authors define this sort of approach as an "event" analysis (Figure 3, right). Otherwise, when aspects reflecting the entire response are considered, such as area under the receptor potential waveform, a different sort of relationship is obtained with a region of complete summation followed by supersummation. In this case the form of the function varies with criterion shifts. These authors designate this approach as a "process" analysis (Fig. 3, left). Based upon experiments involving the Limulus tail flick response to light they suggest that when supersummation is found behaviorally, the nervous system is performing a "process" analysis. In this case, supersummation is followed by a region of no-summation (Fig. 3, left inset). Wasserman and Kong (1979) find a correspondence between response latency and critical duration, which they label ti, and conclude that for a process analysis, they are of the same magnitude. For an event analysis, these authors suggest that critical duration is shorter than latency by a constant.

C. Conceptual Approaches to Temporal Integration

Two approaches have been proposed to account for temporal summation characteristics: a peripheral one involving photochemical integration in visual pigments (Hartline, 1934), and a central one based on evidence that when the stimulus is fixed, critical duration varies with the observer's task (Bruder and Kietzman, 1973; Kahneman & Norman, 1964; Raab & Fehrer, 1962). The first approach suggests that the characteristics of temporal summation can be accounted for solely at the receptor level; the second viewpoint implies that a more central processing is involved. For example, brightness discrimination data and the b wave of the ERG are comparable, which suggests that the response requirement is mediated peripherally (Biersdorf, 1958). Similar correlates for form discrimination have not been noted. Central nervous system involvement in temporal integration has its roots in the fact that task requirements, in the presence of relatively invariate stimuli, have an effect on critical duration.

System operating characteristics for brightness and pattern discrimination are different, i.e. for the former, tc decreases monotonically with increasing energy (Graham & Kemp, 1938); for the latter, tc describes a U-shaped function with respect to stimulating energy, i.e., tc first decreases as energy is increased then rises sharply with further increments in energy (Kahneman, 1964). Critical time is also shorter for the intensity task (Kahneman, Norman and Kubovy, 1967). These authors conclude that temporal integration for different tasks may be mediated differently.

Based on earlier data, Kahneman (1979) proposes two models to account for IT failure at tc when different responses are required: 1) latency cut-off and 2) excitation leakage. The first model would apply to brightness discrimination tasks, and involves the notion of an "accumulator" which is addressed at a given time after stimulus onset. The response is only determined by what is in the "memory" up to a cut off period, which is tc. This model could explain short tc's, the abrupt transition from complete summation to no summation, as well as accomodate the common finding that tc is inversely related to energy. The second model would relate to visual acuity situations, but involves an accumulator which begins losing some of the stored information at some time. In this case, partial summation would be evident after tc. This model accomodates the U-shaped relation between tc and energy where the longest critical durations are obtained for the most intense stimuli. Very long tc's probably reflect a real failure of integration.

Wasserman and Kong (1979) seek to integrate the two approaches by suggesting that, even though the peripheral neural signal is invariate, the nervous system can analyze the input in different ways. Furthermore, critical duration gives an indication of the type of analysis the central nervous system is performing. Kong and Wasserman (1978) state that, receptors function linearly in weak light, and non-linearly in the more intense photopic range, i.e., in the latter condition duration has more of an effect on the width of the receptor potential than intensity has on the amplitude. Behavioral supersummation may reflect the way the central nervous system analyzes sensory signals.

Chapter III

GENERAL METHODS

A. Subjects

1. Monkeys

Three experimentally naive, male adolescent rhesus monkeys (Macaca mulatta) with no apparent visual defects, ranging in weight from 2.0 to 2.5 kg at the beginning of the experiment, served as psychophysical observers. Subjects were fitted with restraining collars, caged individually in the colony room, and given a diet consisting of Purina Monkey Chow micromixture. Fresh fruit was offered during the weekend. The colony room temperature was regulated between 68 and 72 degrees Farenheit. During formal training and testing, animals were maintained between 85-90% of their free feeding weight which was initially determined upon entry into the colony. Between experiments animals were fed 20-30 chow pellets daily, and returned to the previous regimen prior to resumption of testing..

2. Humans

One male (VR) and one female (TG), 37 and 28 years old, respectively also participated in the study. Both were in good health and had normal uncorrected vision.

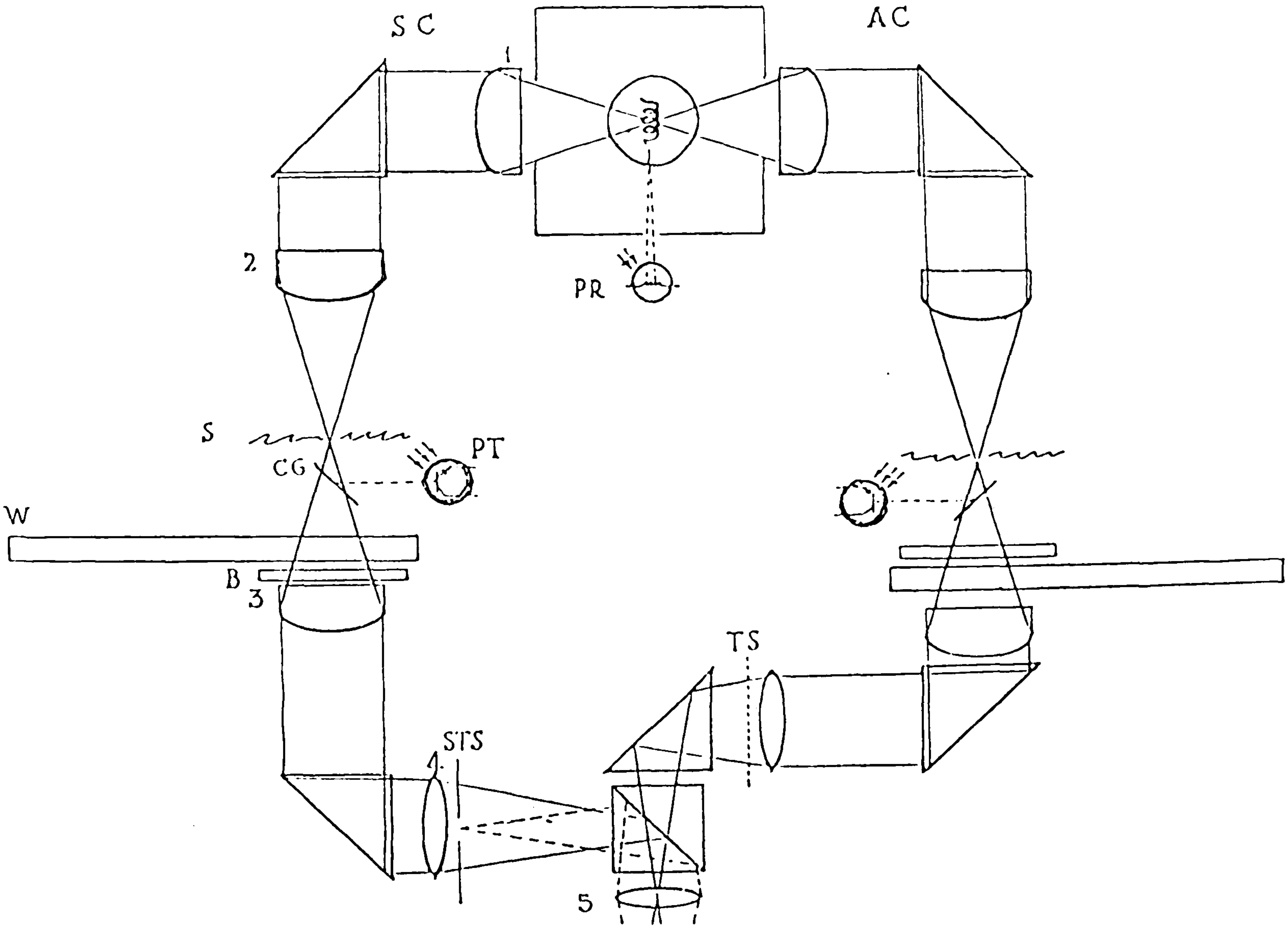
B. Apparatus

1. Dual channel optic stimulator

A two-channel optic stimulator was used to present both the adapting field and the stimuli as illustrated in Figure 5. It consisted of a simplified

Figure 5.

Dual channel optic stimulator. SC, stimulus channel; AC, adapting channel; 1, 2, 3, collimators; 4, 5, projection lenses; W, wedge; B, balancer; CG, cover glass; STS, stimulus slide; TS, texture slide; S, shutter; PR, photoresistor; PT, phototransistor.


S C
1
A C
2
PR
S
PT
CG
W
B
3
TS
STS
4
5

version of that designed by Battersby and Wagman (1959). The light source was a General Electric vertical coiled tungsten filament lamp (CPR, 6 volt, 18 amp), powered by a heavy duty 6-volt storage battery (75 amp/hr). The battery was continuously trickle-charged by a filtered D.C. power supply, thereby stabilizing the lamp power consumption. The lamp was housed in a compartment with three ports and was cooled by forced air from an outside fan, guided by a vibration dampened, flexible duct. The flux was monitored by a photoresistor placed at the front housing aperture, and could be adjusted through a milliameter by modifying the filament current and/or rate of charge of the battery.

All testing was conducted with the milliameter indicator maintained at the preset value at which luminance calibrations were made (see below). Two symmetrical and optically identical beams of light were obtained from the side ports of the lamp housing. Each beam was collimated, redirected 90 degrees by a prism, and focused by another lens on the aperture of a Vincent Associates (Rochester, N.Y.) electromechanical shutter (23X0A3X5). Each shutter was mounted on a stage that could be moved in the vertical, lateral, and anterior-posterior directions, allowing the aperture to be positioned where the image of the source filament was in sharp focus. The shutter apertures were decreased in size so as to eliminate the upper and lower regions of the filament to reduce "hot" spots.

A minimum amount of light was deflected by a coverslip placed at 45 degrees to the axis of the optical system, distal to the shutter openings. This light controlled the base current of phototransistors, the output voltage of which was monitored with an oscilloscope. The main portion of the light beams passed through neutral density circular wedges and balancers providing a zero to 4.0 log unit attenuation. The wedges were mounted on shafts such that luminance could be changed in 0.02 log discrete steps by means of 4 inch diameter, 200-division, dials fitted with verniers. After passing through the filters the beams were recollimated and deflected 90 degrees by prisms, and then passed through the first projection lens: one beam traversed a slide containing the stimulus figures, and the other produced the adapting field by passing through a slide devoid of figures.

The slides were mounted in an electromechanical device that allowed positioning from side to side within the path of light, thereby reversing the position of the stimuli (see below). The slide changer excursion was adjusted so that the stimuli were projected on to the center of rear projection screens. A combining prism redirected both beams to a common front lens which focused each figure on the centers of circular screens, 25 mm in diameter, located in the testing chamber, vertically separated by 57 mm. The vertical display took advantage of the most homogenous region of the field which was eliptical with a vertical major axis due to the oblong shape of the source filament.

The stimuli were an upright equilateral triangle and a circle. These figures were selected because both are easily discriminable compact polygons. In addition, they have traditionally been used in discrimination studies. The stimuli were produced by projection of a specially constructed slide which contained two sets of vertically displayed figures: a circle in the upper position and a triangle in the lower position on the right half, and the reverse on the left half.

2. Construction of stimulus and adapting field slides

Color-Aid paper was used to construct the figures, one triangle and one circle, as well as the background. The forms were approximately the same area, and 20% darker than the ground. A figure and its background constituted a target. The figures were slightly brighter than the surrounds. Relatively low contrast stimuli were selected for the experiments because pilot data using higher contrast black or white figures (triangles, circles or Landolt C's) against the opposite ground were discriminable at the highest luminance and shortest durations available. Each figure-ground was placed at the center of a copying-stand and photographed numerous times at a preselected exposure and f stop settings. This procedure controlled for subtle differences in illumination on the stand as well as exposure error introduced by using mechanical shutters. Kodak Panatomic X film (ASA, 32) was used to obtain sharp images at low contrast.

Each negative containing a figure was placed in an anti-Newton slide binder and inserted into the stimulus channel slide changer. Sorting of final targets was accomplished by a series of photometric measurements sampling the luminance and homogeneity of figures and backgrounds, made on the projection screens with a photometer (Gamma Scientific Corp., model 700 log-linear photomultiplier). The device employed a photopic filter and fiber optic probe. A plexiglas template insured that the fiber optic probe was positioned in a consistent manner. Two targets of each type, with approximately the same luminance and homogeneity, were selected for stimuli in the experiment and placed in an anti-Newton slide binder. A negative with a density similar to the background of the figures was placed in the adapting channel to achieve balance of texture. Differences in luminance between upper and lower screens was minimized by appending mylar sheets to the slide binders. For absolute measurements of the stimuli and adapting field, the photometer was calibrated against a radioactive krypton source, the half life of which was taken into account for final numerical calculations. Measurements were taken in a counterbalanced order to control for fluctuations of light over time.

3. Stimulus dimensions

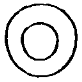
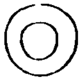
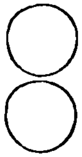
Table 1 contains the area and photometric measurements (luminance, L; contrast, C; total luminous flux, F) of both the figure (f) and background (g) of each target (t) as well as of the adapting field. The length of the side of the triangle and diameter of the circle were 13.03 mm and 9.78 mm, respectively, resulting in areas (A) of 73.52 mm^2 and 75.12 mm^2, respectively. Measurements were taken with vernier callipers on the projected images. Viewed from the 20 cm approximate corneal testing distance, the visual angles subtended by the circles approximated 2.9 degrees. As expected, there were some minimal differences in stimulus parameters which ideally should have been identical. However, all of these differences were not target-bound. Thus, stimuli which appeared on the bottom screen in every trial had a slightly higher luminance, flux, and contrast. Therefore, these differences could not be used as cues for the discrimination. Additionally, the subject's visual field was always larger than the angle subtended by both screens together, so that differences in flux between the two targets could not be sampled independently. Finally, the possibility that animals could solve the problem on the basis of absolute total flux from trial to trial (last column in Table 1) was safely ruled out because the differences gave an extremely low Weber fraction ($\Delta F/\bar{F} = 0.04$).

4. Relative calibrations of the filters

The photometer was set at 100 percent when attenuation was at a

TABLE 1

Dimensions of Stimuli and Adapting Fields

		Figure (f) and Ground (g)			Target (t)				Both Targets	
		A	L	F	A	C	L	F	L	F
Trial A										
	f	73.52	3.536	0.000817	490.87	11.16	2.932	0.004522	2.977	0.009181
	g	417.35	2.826	0.003705						
	f	75.12	3.817	0.000901	490.87	13.91	3.021	0.004659		
	g	415.75	2.885	0.003758						
Trial B										
	f	75.12	3.426	0.000809	490.87	12.05	2.802	0.004321	2.851	0.008791
	g	415.75	2.689	0.003512						
	f	73.52	3.659	0.000845	490.87	13.92	2.899	0.004470		
	g	417.35	2.765	0.003625						
Adapting field									2.926	0.009024
										

Notes:

A = area (mm2)
L = luminance (cd/m2)
F = luminous flux (lumen) = $\pi A(m2)\, L(cd/m2)$
C = contrast = $\frac{Lf - Lg}{Lf + Lg} \times 100$
L = mean luminance = $\frac{Ff + Fg}{\pi A}$
Photometric values are given for the highest L used.
The formula to compute total luminous flux is that applied to Lambertian (as opposed to point) sources.

minimum. Measurements were taken with the fiber optic probe, placed at the center of the rear projection screen, each time the circular wedge filters were advanced fifteen divisions (one division was 0.02 log units). Figure 6 shows photographs of the photometer voltage output at seven levels of luminance. Because of the gain used as well as the dimensions of the oscilloscope display, the lowest level, 0.23 cd/m^2, cannot be visualized.

5. Shutters calibrations

Shutter operation was controlled by a custom designed microprocessor and modified Vincent Associates shutter drivers (model 200). During stimulus presentation, leading and trailing edges of the adapting field shutter (normally open) and stimuli presentation shutter (normally closed) were phase-locked such that the half closed point of the adapting shutter coincided with the half open position of the stimuli shutter and vice versa. The available stimulus durations decreased from 4000 to 4 msec in a harmonic series that approximated 0.1 log steps to within 1%. Figure 7 shows photographs of the light output from the shutters at 4, 40, 400 and 4000 msec, as monitored through the phototransitors on an oscilloscope.

6. Microprocessor control of experimental conditions

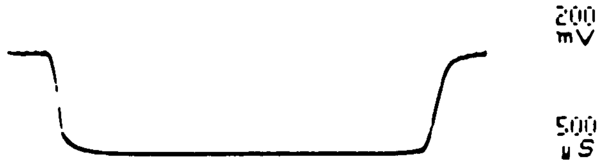
The microprocessor functions were subdivided into three categories: event sequence control, shutter timing, and psychophysical procedure implementation. The event sequence control consisted of cascaded monostable multivibrators, which allowed or denied trial initiation, locked out premature and multiple responses, controlled the slide changer, provided the master command logic pulse for shutter operation, and determined whether the trial

Figure 6.

Photometer voltage output for the seven highest luminance levels used. Note that each successive level is one half the height of the preceding one. The lowest level used could not be resolved.

Figure 7.

Sample records of light pulses as seen on monitor oscilloscope. Each record contains five superimposed sweeps to illustrate the reliability of shutter operation. The sweep speed of each tracing corresponds to the scale bar appearing below the column of numerals.


200 mV
500 μS


200 mV
5 mS


200 mV
50 mS


200 mV
500 mS

initiation light emitting diode (see below) was on or off. The shutter timing circuit incorporated a 2.52 megahertz "clock" providing pulses which were subdivided to achieve different stimulus durations. The specific duration presented, however, depended on software which determined the number of pulses "counted" and, therefore, the time the shutters were activated. Trimming circuits allowed for adjustment of the leading and trailing edges of the stimulus and adapting field shutters. Variation in shutter phase timing did not exceed 1%. The microprocessor section committed to psychophysical procedure implementation addressed the shutter timing circuit and determined whether or not the subject's responses affected the stimulus time. In the case of constant stimuli, exposure time was independent of the observer's responses; with the descending staircase procedure the subject's responses set the stimulus durations. Options included: external trial presentation, self-initiated trial presentation, obligatory or non-obligatory responding during a trial, preselection of stimulus duration, preselection of correct figure position independent of the four preprogrammed Gellerman's schedules, and control of reinforcement.

Displayed data included: 1) trial number; 2) trials remaining; 3) number and position of correct and incorrect responses, stimulus duration; 4) and response latency. The latter value represented the time lapse between stimulus onset and response to within 0.1 msec. Figure 8 is a flow diagram of the microprocessor operation using the descending staircase procedure.

7. Testing chamber

The testing chamber consisted of a wooden box, 66 cm wide, 68.6 cm long, and 112.5 cm high, which was acoustically isolated by two inch thick foam

Figure 8.

Flow diagram of microprocessor control of experimental conditions (descending staircase procedure).

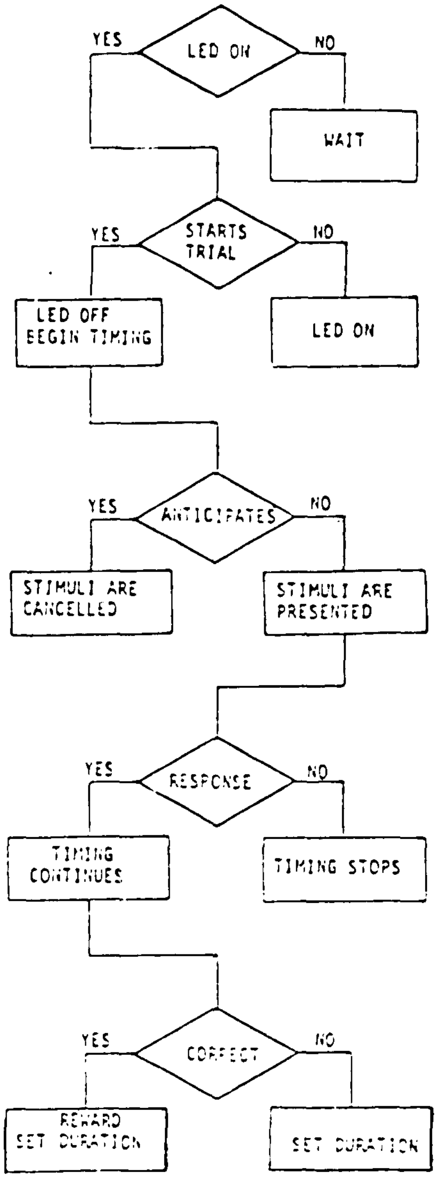
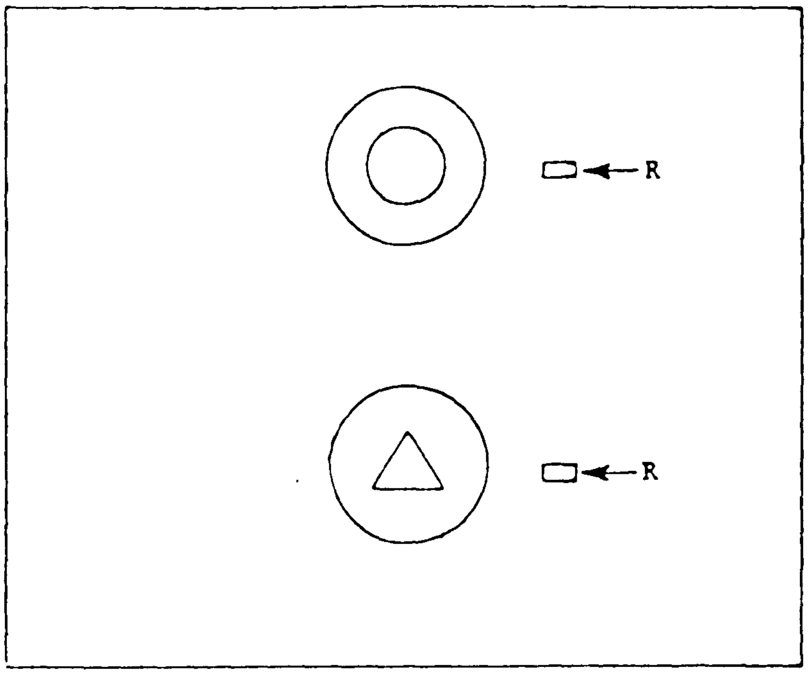
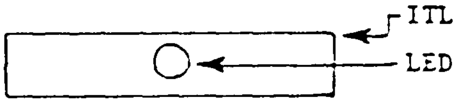
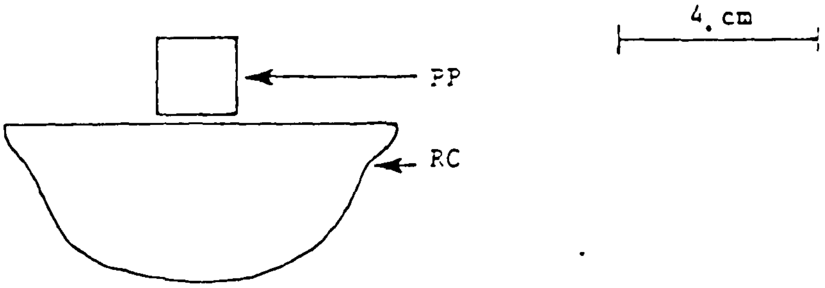

YES
LED ON
NO
WAIT
YES
STARTS TRIAL
NO
LED OFF
BEGIN TIMING
LED ON
YES
ANTICIPATES
NO
STIMULI ARE CANCELLED
STIMULI ARE PRESENTED
YES
RESPONSE
NO
TIMING CONTINUES
TIMING STOPS
YES
CORRECT
NO
REWARD
SET DURATION
SET DURATION

Figure 9.

Testing panel. R, response lever; ITL, initiation trial lever; LED, light emitting diode; PP, pellet port; RC, reward cup.


R
R


ITL
LED


4. cm
PP
RC

rubber and placed within a larger enclosure. Access to the testing chamber was through a hinged outer and removable inner door, both having plexiglas viewing ports. When the outer port was covered, the testing box was light tight. The chamber interior was painted flat black, and illumination was provided by a 15-watt red bulb located at the ceiling center. Channels with bolts to secure the restraining chair insured consistent subject positioning during testing sessions. Vacuum ventilation was continuous, and masking noise was provided by an overhead fan as well as by rapidly forcing air through water in a container. Three human observers were not able to detect cues from the slide changer when the masking noise was present.

The testing panel shown in Figure 9 consisted of two circular rear-projection screens placed one above the other, two associated response levers placed to the right of each screen, a trial initiation lever with an indicator light emitting diode (LED), and a reinforcement cup.

A Gerbrand feeder (M65110) was secured on an outside wall of the testing box, and was used to deliver Noyes dextrose pellets (4.0 mm x 3.3 mm x 45 mg) as reward for correct responses.

C. General Procedures

Procedures outlined here are applicable to Experiment I and Experiment II. Details specific to each study will be given in the results section.

1. Testing chamber familiarization

The monkey was placed in a plexiglas restraining chair and positioned in the testing compartment approximately 20 cm (corneal distance) from, and directly facing, the testing panel. Eye level position was centered midway between the upper and lower rear projection screens. No stimulus was exposed. The head was free to move in every direction. Access doors were left open, the chamber red light on, the optical bench, microprocessor, and room light off. Dextrose pellets were initially offered to the subjects by hand, and later delivered to the reinforcement cup by activating the feeder. The monkey was considered to be familiarized with the testing chamber when pellets were readily taken from the reinforcement cup.

2. Response lever training

The conditions were similar to the above except that the access doors were closed and monkeys were observed through the viewing ports. They were shaped to manipulate the response levers. When either lever was depressed, reinforcement occurred on a fixed ratio (FR 1:1) schedule. Criterion for completion of lever training was 200 rewarded responses within a given session.

3. Discrimination training

At this stage, the chamber red light was off, and the optical bench was on and placed under microprocessor control. For the duration of the study only responses made to the "correct" figure were rewarded. Training consisted of two stages: 1) learning to discriminate between the correct figure and a darkened screen, and 2) learning to discriminate between the correct and incorrect figures presented simultaneously. Only one correct response per trial was reinforced. In the first phase, incorrect figures were masked at the slide with opaque photographic tape. On any training trial, therefore, only the correct figures appeared on either the upper or lower rear projection screen.

Adapting channel and stimulus channel were set at the highest output available under the experimental conditions (see Table 1). In both stages, trials were presented every seven seconds and resulted in the following sequence of events: 1) trial onset (adapting channel shutter open, stimulus channel shutter closed), 2) stimulus onset (adapting channel shutter closed in phase with opening of stimulus channel shutter), 3) stimulus offset (stimulus channel shutter closed in phase with adapting channel shutter opening). Stimulus onset began 200 msec after trial onset thereby insuring that vibration from the slide changer was not transmitted to the figure.

Stimulus offset occurred 4000 msec after stimulus onset with the following qualifications: Lever responses after trial onset but before stimulus presentation (anticipatory responses) cancelled the trial, and subjects were required to wait until the next trial before a response could have a consequence. A response made during the 4000 msec stimulus presentation immediately recalled the adapting field and was reinforced if correct. Responses made after the stimulus offset but before trial onset had no effect. The location of the correct stimulus on each trial was determined by one of four preprogrammed Gellerman's schedules. Using these schedules, position habit, alternation, or double alternation resulted in chance performance. Position habit, defined in terms of incorrect responses to three consecutive identical trials, were corrected by repeating the same trials ten times before returning to the Gellerman's series. Each session was terminated after 140 responses. This phase of training was considered mastered when the animal made at least 90% correct responses on each of two consecutive sessions. The same criterion was used in other training phases unless otherwise noted.

4. Trial initiation training

During this stage of training, subjects were shaped to start trials in response to the illumination of the LED on the initiation lever. The subject's control of trial onset was used to minimize inattention. No fixation light was used in this study. In general, however, direct observation of the animals indicated that their gaze was directed toward the testing panel. In addition, trial initiation could be used as an index of the subject's motivation, i.e., monkeys tried to initiate trials while they were being placed in the testing box as well as during the intertrial interval.

Subjects were positioned in the illuminated testing chamber and observed through the viewing ports. One minute later the LED was turned on. Trial onset was used as a secondary reinforcer in shaping the pressing of the trial initiation lever. Manipulating this lever turned off the LED and resulted in the event timing sequence outlined in discrimination training. At the end of the timing period, the LED was again turned on regardless of whether the animal responded to the targets. For the duration of the study, subjects were required to initiate the trials.

5. Descending staircase (adaptive) procedure training.

Subjects were trained to respond to progressively shorter stimulus durations. This training phase had two aspects: 1) familiarization with the procedure; and 2) making trial initiation contingent upon a response in the preceding trial. The forced response procedure was used because during adaptive training, the subjects responded inconsistently to brief stimuli after initiating a trial. Subjects were placed in the testing chamber with the red light off. Light adaptation time was 20 minutes, and was held constant for the rest of the study. Thereafter, the LED was illuminated. The initial stimulus presented to the subjects was 4000 msec long, but subsequent exposures were controlled by the microprocessor according to the following stepping rules: at a given duration, two successive correct responses decreased the exposure time by 0.1 log unit; one incorrect response increased the duration by 0.1 log unit. Using these rules, the obtained thresholds are equivalent to those reflecting a 70.7% level of correct responses (Levitt, 1971).

At times, behavior became disorganized. This deterioration included cessation of responding, failure in discrimination, as well as responding before the stimulus appeared. When the above occurred, the stimulus duration was set at 4000 msec and held constant until the subject performed properly. If the animal failed to respond, dextrose pellets were delivered by the experimenter to reinstitute behavior. These procedures were used until the monkeys performed appropriately to durations of 100 msec or less for two consecutive testing sessions of 147 trials each.

After the completion of staircase training, illumination of the LED (and, therefore, the possibility of starting a new trial) was made contingent upon the subject's making a choice during a trial. If the animal made a response within the trial period (any time following stimulus onset but before termination of the trial), the LED would be turned on according to the original timing sequence. If a response did not occur, the LED could be illuminated by pressing any response lever within 15 seconds after termination of the trial. After that time, the experimenter turned on the LED. Responses made during the normal trial period or the following 15 seconds, were regarded as correct or incorrect,and subsequent durations were set depending on this evaluation. If the subject did not respond, the subsequent duration was not changed.

Three criteria were used to determine whether the observers performed improperly: 1) occurrence of anticipatory responses; 2) latencies under 100 msec and; 3) unsystematic response profiles. In the adaptive procedure, durations to which the subject was exposed depended upon the previous responses. If the subject performed adequately, the stimulus durations were decreased in a systematic manner and then oscillated above and below threshold as shown in Figure 10. Random behavior would result in unsystematic presentation of stimulus durations. The adaptive staircase response profile, therefore, gave a continuous behavioral assessment of proper task performance.

Chapter IV

RESULTS

A. Experiment I: Tachistoscopic Thresholds for Pattern Discrimination at Two Luminance Levels

In this experiment, thresholds were obtained by two methods: the descending staircase procedure and the method of constant stimuli. This was to insure that the former procedure could confidently be used to generate temporal summation functions.

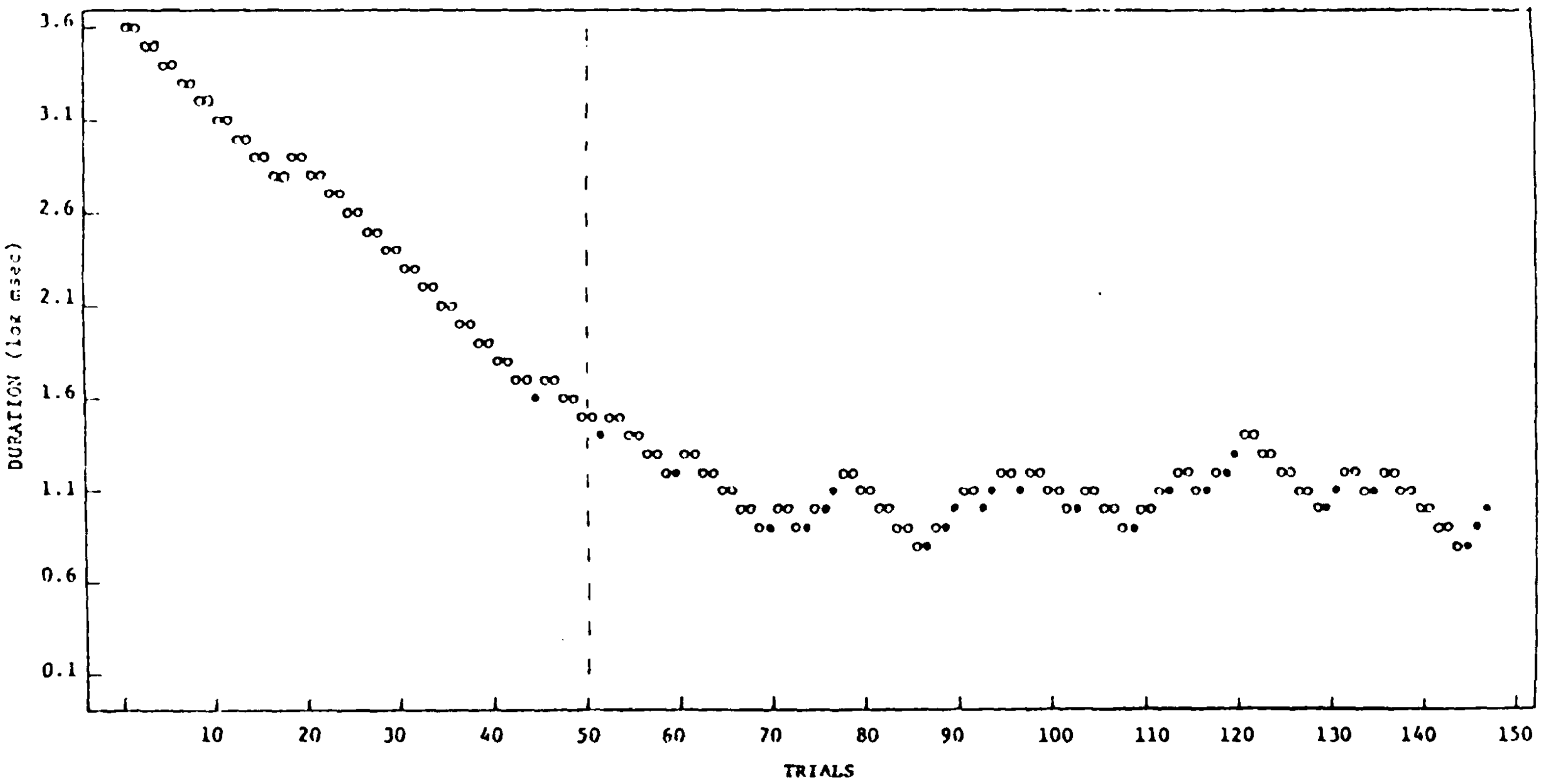
1. First Phase: Descending Staircase Procedure

Monkeys #883 ("circle correct") and #886 ("triangle correct") were positioned in the testing apparatus and light adapted to either of two luminance levels. The lower level represented a 1.2 log attenuation of the higher level. Adapting and stimulus fields were flux equated at 0.004508 or 0.000281 lumen for the high and low luminance levels, respectively. Monkeys were tested once at each level during each daily testing session. Light level presentation was counterbalanced over days.

The first 50 presentations of each session were considered warm-up trials and allowed assessment of performance; the following 97 trials were used to calculate daily thresholds in terms of the stimulus duration which corresponded to the median of revisitations (Levitt, 1971). Visitations to a given duration were of three types: (1) two successive correct responses, (2) a correct and incorrect response sequence; and (3) one incorrect response. A cumulative frequency distribution of the revisitations was constructed in order to determine the median. Figure 10 depicts an illustrative session which gave a

Figure 10.

Profile obtained in the first session with the descending staircase procedure for subject 883 at the highest luminance level. Stimulus durations are shown on the ordinate and consecutive trials on the abscissa. Open and closed circles indicate correct and incorrect responses, respectively. For threshold computation, the first 50 trials are discarded.


3.6
3.1
2.6
2.1
1.6
1.1
0.6
0.1
DURATION (log msec)
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
TRIALS

threshold value of 1.08 log msec or 12.02 msec. Thresholds were considered stable if over six daily testing sessions, daily values did not vary by more than 0.2 log units from the mean of six successive sessions.

During this phase of the experiment, five human observers empirically assessed ways for regarding the testing panel to determine the best "looking" strategy. In addition, one human subject (VR) was tested in an abbreviated manner (once at each luminance level) to compare staircase profiles and thresholds against those obtained in the monkey.

Table 2 shows the data for monkeys #883 and #886 at the high and low luminance levels. For #883, thresholds were 1.02 and 1.43 log msec, and the energy required at threshold was -4.03 and -4.82 log Talbots, respectively. For animal #886, the threshold durations for the high and low luminance level were 1.26 and 1.62 log msec, and the energy was -3.82 and -4.63 log Talbots, respectively.

In general, for both animals, decreasing the luminance by 1.2 log units resulted in only a 0.4 log increase in threshold duration. Furthermore, less energy was required at the lower luminance level than at the higher, the difference being approximately 0.8 log Talbots.

Humans reported that both screens could be scanned during long stimulus durations. This was not possible, however, for brief stimuli in which the optimal strategy consisted in regarding only one screen. Profiles for one human observer (VR) were evaluated qualitatively to confirm the animal's performance, and it was found that they conformed to the criterion mentioned above in the adaptive method training.

2. Second Phase: Method of Constant Stimuli

TABLE 2

Experiment I. Tachistoscopic Thresholds (Adaptive Procedure)

	Monkey #883		Monkey #886	
	High L	Low L	High L	Low L
Sessions	θ	θ	θ	θ
1	9.82	27.51	14.52	38.86
2	9.03	28.78	14.19	37.40
3	14.82	28.94	19.35	31.77
4	7.02	26.97	20.93	42.20
5	10.87	22.75	16.29	41.76
6	10.71	26.54	14.79	57.43
Mean	10.38	26.92	16.68	41.57
SD	2.59	1.43	2.82	8.36
Log θ	1.02	1.43	1.22	1.62
log $E\theta$	-4.03	-4.82	-3.82	-4.63

High L, 2.929 cd/m2

Low L, 0.183 cd/m2

θ, threshold (msec)

E, energy of the Lambertian source is computed by

E (Talbot) = F (lumen) x T (sec). See note in Table 1.

The average thresholds determined by the staircase procedure for the high and low luminance level, were used to select a range of stimulus values spanning 0.7 log units in 0.1 log steps to be used in the constant stimuli procedure. The stimulus duration closest to the average threshold was used as the midpoint of the range. The microprocessor was programmed daily to present the seven stimuli in a quasi-random manner. Each duration in the bracket had to occur the same number of times when the correct figure was in the upper as well as lower position.

Subjects were placed in the testing chamber, and light adapted for 20 minutes to either the high or low luminance values used in a counterbalanced order over days. Subjects were tested once at each level during each daily session.

All subjects started with 20-30 trials on the adaptive procedure until the longest duration in the preselected bracket was reached; durations were then chosen for the method of constant stimuli. Initial use of the descending staircase procedure allowed the experimenter to monitor the response profile, and thus, insure that the animal was performing properly.

Each one of the seven durations was presented 20 times during a session for a total of 140 trials. The few trials in which no response was made were noted, and, at the end of the session, missing values were obtained from the reiterated original series of constant stimuli presentations. Data were collected over six successive days, 120 responses per duration, and were used to construct psychometric functions. The percent correct responses at each duration were averaged for the six testing sessions at each luminance level (120 responses per duration). A chance correction factor was not used. In general, as stimulus duration was increased, percent correct responses also increased.

Figures 11 and 12 illustrate the frequency-of-seeing curves for monkeys #883 and 886, respectively. Using threshold values in msec, rather than log msec, the slope and y intercept were determined by the method of least squares. The threshold values for the 70.7% correct response level were then calculated for each luminance by using a linear equation of the form $Y=\underline{m}X+\underline{b}$. The 70.7% value was chosen to facilitate comparison with data obtained using the adaptive procedure, which converged on this level. The obtained threshold values for #883 were 1.09 and 1.48 log msec, for the high and low levels of luminance, respectively. Energy values at threshold were -3.96 and -4.77 log Talbots. For #886, the thresholds were 1.25 and 1.58 log msec and the corresponding energies -3.80 and -4.67 log Talbots.

For both monkeys, attenuating the luminance by 1.2 log units was not paralleled by the same increase of threshold duration; less energy was required at the lower luminance level, the difference being 0.8 log Talbots.

Table 3 shows the summary of threshold values for both subjects using the adaptive procedure and method of constant stimuli. In general, the magnitudes are similar. Both methods gave only a 0.35-0.40 log increase in duration for a 1.2 log decrement in luminance.

B. Experiment II. Tachistoscopic Thresholds for Pattern Discrimination at Eight Luminance Levels

In this experiment, thresholds were determined by the adaptive method to obtain temporal integration functions and to explore more fully the lack of complete reciprocity obtained in Experiment I. In addition, latency data were collected for each response and analyzed as a function of stimulus energy at threshold.

The adapting field channel was maintained at 2.926 cd/m2 and remained

Figure 11.

Psychometric functions for Monkey #883 at the high (open circles) and low (closed circles) luminance levels.

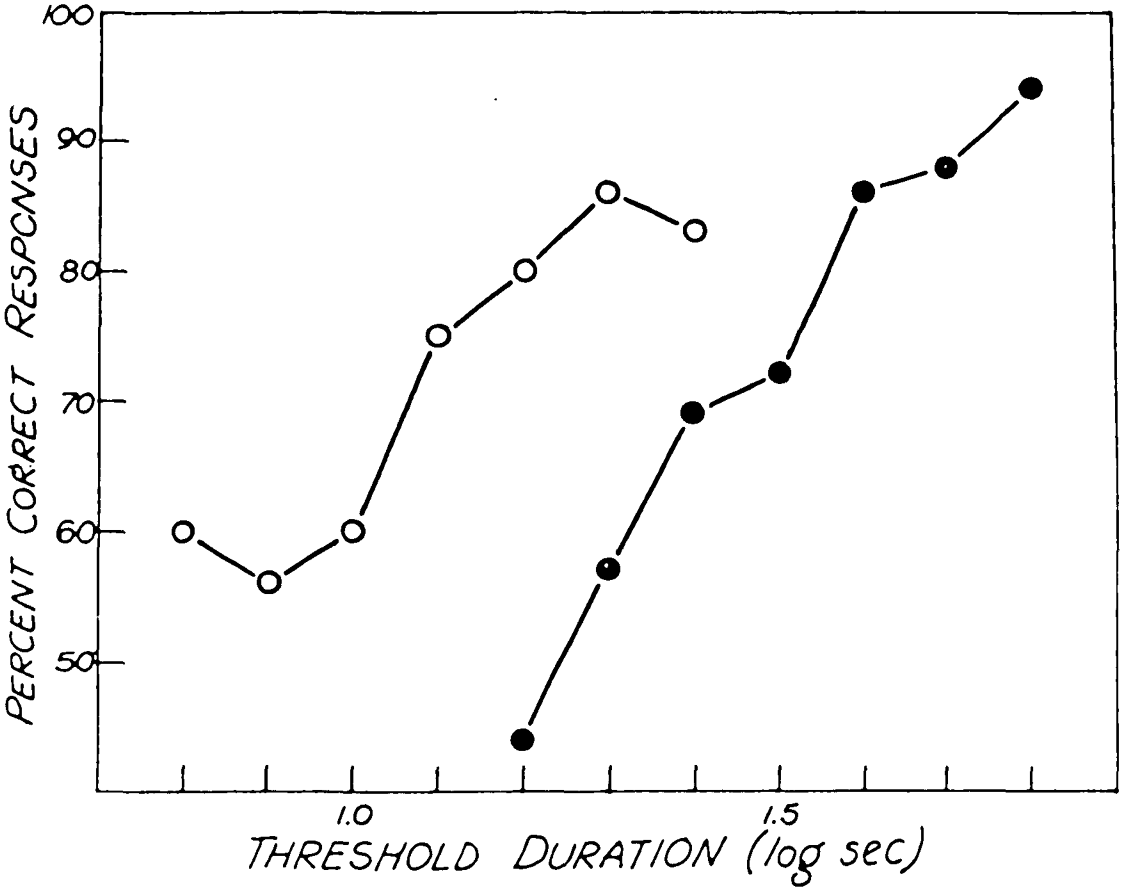

100
90
80
70
60
50
PERCENT CORRECT RESPONSES
1.0
1.5
THRESHOLD DURATION (log sec)

Figure 12.

Psychometric functions for Monkey #886 at the high (open circles) and low (closed circles) luminance levels.

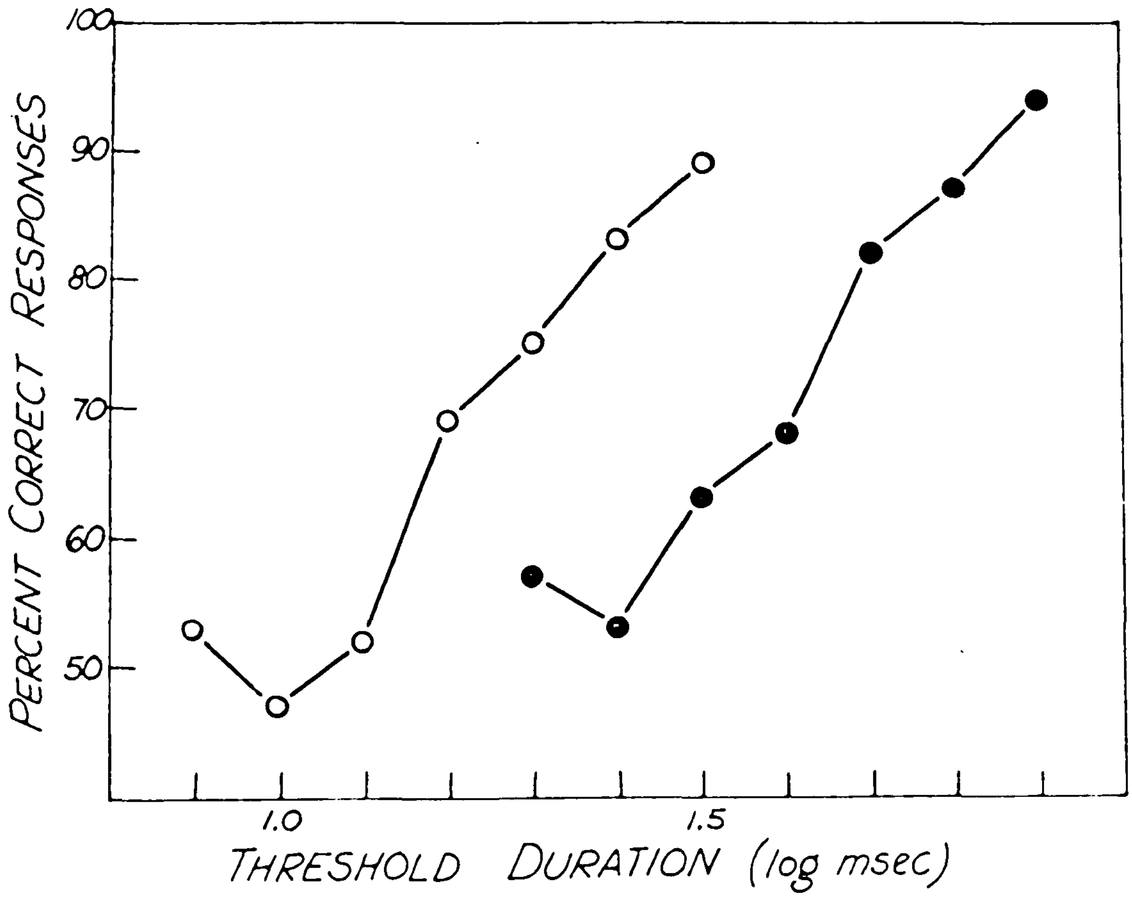

100
90
80
70
60
50
PERCENT CORRECT RESPONSES
1.0
1.5
THRESHOLD DURATION (log msec)

TABLE 3

Experiment I. Comparison of Results Across Procedures

Thresholds in Log msec

	#883		#886	
	High L	Low L	High L	Low L
Adaptive Procedure	1.02	1.43	1.22	1.62
Constant Stimulus Procedure	1.09	1.48	1.25	1.58

such for the duration of the experiment. The mean luminance levels for the targets was set at one of the following values: 2.926, 1.461, 0.731, 0.365, 0.183, 0.091, 0.046, and 0.023 cd/m2. Beginning with the first value, each successive level represented a 0.3 log attenuation, or halving, of the previous luminance level. Stimulus and adapting fields were equated for total luminous flux only for the stimuli of highest luminance. Full attenuation was 2.1 log units. The first level was photopic, the last scotopic, and the others were in the mesopic range.

The order of presentation of luminance level was selected quasi-randomly. Each value had to occur an equal number of times. Correct stimulus position was determined by one of four Gellerman's schedules and was changed randomly each time a different level was used.

Monkeys #883, 886, and 894 and one human observer participated in this experiment. The human observer (TG) was familiarized with the apparatus, given verbal instructions ("choose the assigned figure, guess if you are not sure"), and warm-up sessions at the highest, intermediate, and lowest luminance level. Delivery of dextrose pellets indicated correct responses for the human. Subjects were light adapted in the testing apparatus for 20 minutes. Threshold and latency data were then collected for the two luminance levels, the second determination immediately following the first. Monkeys were then returned to the colony. Three hours later, the animals were retested at two more levels of luminance, returned to the colony and fed. The human subject, when possible, adhered to the same temporal testing schedule.

During training, all monkeys showed a deterioration in performance at 0.183 cd/m2 and below. The deterioration included failure in discrimination as well as responding before the stimulus appeared. To improve the animal's behavior, the luminance of the stimulus channel was set at the highest level and the monkey was allowed to make five correct responses. The luminance was then decreased by 0.3 log units and the subject required to make five correct responses, before attenuating by still another 0.3 log units. This procedure was iterated until the level of luminance was reached at which performance initially deteriorated. The staircase method was then resumed.

The experimental design, for the monkey, called for a minimum of five testing sessions at each level, i.e. a total of 40 sessions. Monkey #883 died during the study, after completing all but one of the sessions. For this animal the data at 0.183 cd/m2 is based on only four testing sessions.

The human observer was given only three testing sessions at each level.

Table 4 contains the summary data for all subjects in terms of threshold duration, log threshold duration, log E at threshold, response latency, and log latency for each of the eight luminance levels used.

1. Monkeys

a. General data analyses. As indicated in Table 4, decreasing luminance resulted in increased threshold durations for all animals. For monkey #883 these values for the highest and lowest luminances used were 1.17 and 2.71 log msec, respectively. For animal #886 the respective thresholds were 1.40 and 2.84 log msec. The obtained values for monkey #894 were 1.25 and 2.70 log msec, respectively. In general, a 2.1 log attenuation in luminance was associated with a threshold duration increment of approximately 1.50 log msec. Log E magnitudes for monkey #883, for the same two luminance levels, were -3.88 and -4.45 log Talbots, respectively. For animal #886 the values were -3.64 and -4.31 log Talbots. The obtained values for monkey #894 were -3.81 and -4.45 log Talbots, respectively. For all monkeys, as luminance was attenuated less energy was required at threshold. The difference was

TABLE 4

Experiment II. Summary Data For All Subjects

L	log L	θ	log θ	log E	Lat	Log Lat	θ	log θ	log E	Lat	log Lat
				#883					#886		
2.926	0.466	14.77	1.17	-3.88	449	2.65	24.93	1.40	-3.65	380	2.58
1.461	0.165	40.28	1.61	-3.74	492	2.69	45.11	1.65	-3.69	433	2.63
0.730	-0.137	62.08	1.79	-3.85	503	2.70	77.16	1.89	-3.77	477	2.68
0.365	-0.438	85.94	1.93	-4.02	529	2.72	123.31	2.09	-3.87	543	2.73
0.183	-0.738	145.61	2.16	-4.09	574	2.76	176.62	2.25	-4.01	485	2.69
0.091	-1.041	173.57	2.24	-4.32	598	2.78	338.94	2.53	-4.03	644	2.81
0.046	-1.337	292.66	2.47	-4.39	659	2.82	463.60	2.67	-4.19	786	2.90
0.023	-1.638	507.10	2.71	-4.45	807	2.91	696.36	2.84	-4.31	914	2.96
			#894						TG		
2.926	0.466	17.84	1.25	-3.81	422	2.62					
1.461	0.165	48.99	1.69	-3.66	393	2.59	12.99	1.11	-4.25	687	2.84
0.730	-0.137	84.65	1.93	-3.72	411	2.61	46.02	1.66	-3.99	612	2.79
0.365	-0.438	118.95	2.08	-3.87	391	2.59	86.19	1.94	-4.02	579	2.82
0.183	-0.738	244.94	2.39	-3.87	507	2.70	179.73	2.25	-3.99	854	2.93
0.091	-1.041	305.84	2.49	-4.07	667	2.82	157.48	2.20	-4.35	724	2.87
0.046	-1.337	409.88	2.61	-4.24	724	2.86	205.39	2.31	-4.54	681	2.93
0.023	-1.638	499.11	2.70	-4.45	801	2.90	342.34	2.53	-4.61	802	2.91

approximately 0.6 log Talbots. Additionally, latency increased as luminance was attenuated, the difference between the extreme levels being approximately 0.30 log msec.

b. Analyses of Log Luminance (L) and Log Energy (E) vs Log Threshold Duration (T) Functions. Figures 13, 15 and 17 depict graphs of log L as a function of log T, and Figures 14, 16 and 18 the log E vs lot T plotted for the monkeys. Inspection of these graphs suggested that linear analyses of full as well as partial functions might be appropriate. A general linear model (GLM, SAS, 1979) was used to test these hypotheses, and revealed that indeed it could predict most features of the obtained functions.

Table 5 gives the slope values of the two functions resulting from both full and partial analyses. The full analyses yielded slopes steeper than -1.0 for the log L vs log T and close to -0.5 for the log E vs log T function. Both of these results indicated the occurrence of supersummation, i.e., that the stimulus duration was more effective than luminance in determining tachistoscopic thresholds for pattern discrimination. For further analyses, the data were divided by inspection of Figures 13, 15 and 17 into thresholds for the briefer and longer stimulus durations. The criterion for this grouping was the deviation from the theoretical line of unit negative slope. This partial analysis suggested that a certain degree of reciprocity appeared at the briefer durations whereas the longer durations contributed maximally to the supersummation effect. This was again shown by the slopes of the functions which at shorter durations approached -1.0 for the log L vs log T plots, and 0.0 for the log E vs log T functions. Similarly, at the longer durations it was steeper than -1.0 and between -0.5 and -1.0, respectively. The threshold values at the inflexion point of these functions were 86, 123 and 245 msec for monkeys #883, 886 and 894,

Figure 13.

Log luminance vs log threshold duration for Monkey #883. Each point represents the mean of at least five determinations. The dashed line indicates negative unit slope representing complete reciprocity (temporal summation). Note that at high luminances there is complete summation. Note that the points at brief durations fall close to this line indicating complete summation. Longer durations result in a derivation with a slope steeper than -1.0 demonstrating supersummation.

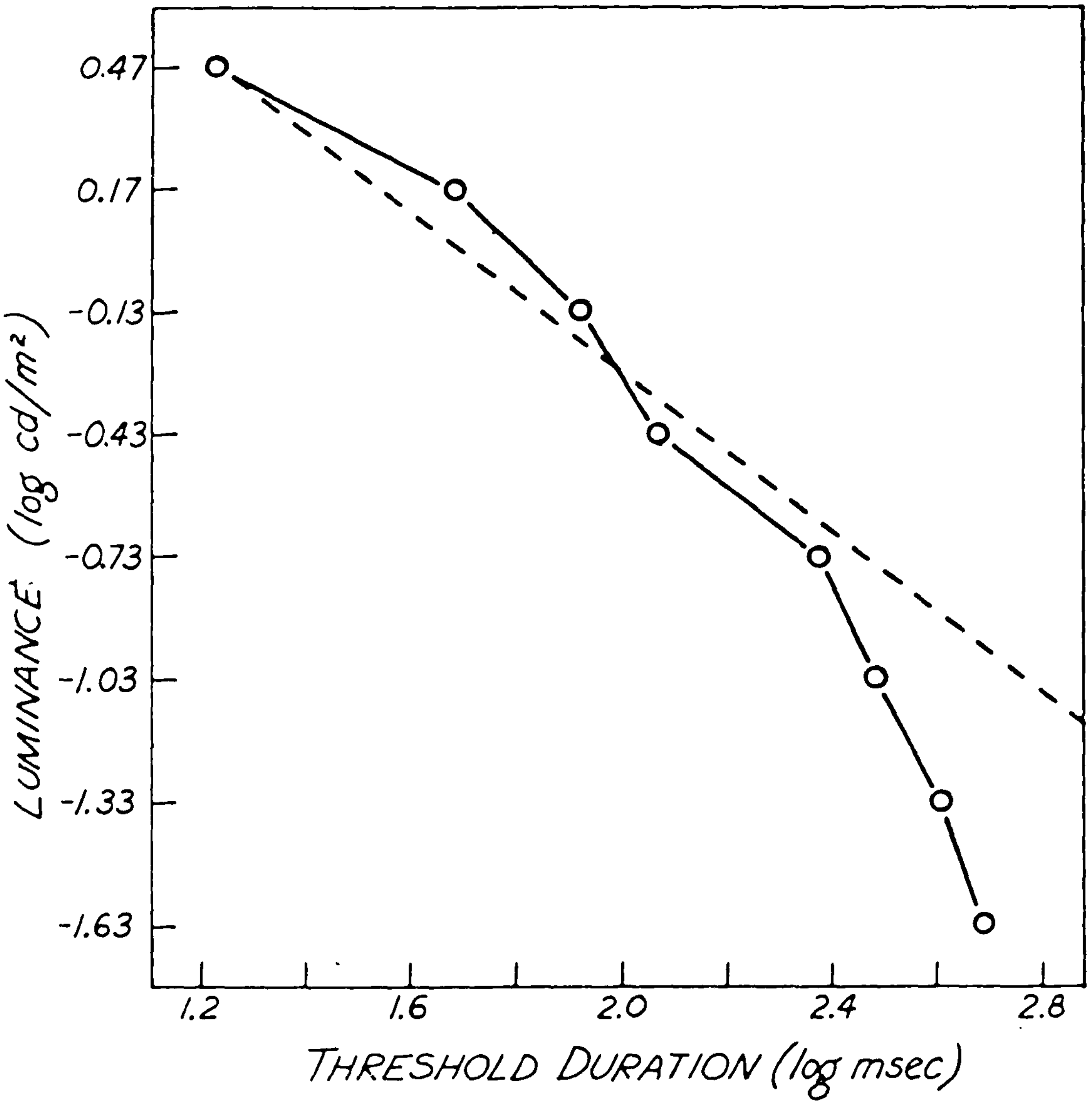

0.47
0.17
-0.13
-0.43
-0.73
-1.03
-1.33
-1.63
LUMINANCE (log cd/m²)
1.2
1.6
2.0
2.4
2.8
THRESHOLD DURATION (log msec)

Figure 14.

Log energy vs log threshold duration for Monkey #883. Each point represents the mean of at least five determinations. The dashed line represents 0.0 slope which indicates total summation. Note that reciprocity is present at brief durations, and is followed by a negative slope indicative of supersummation.

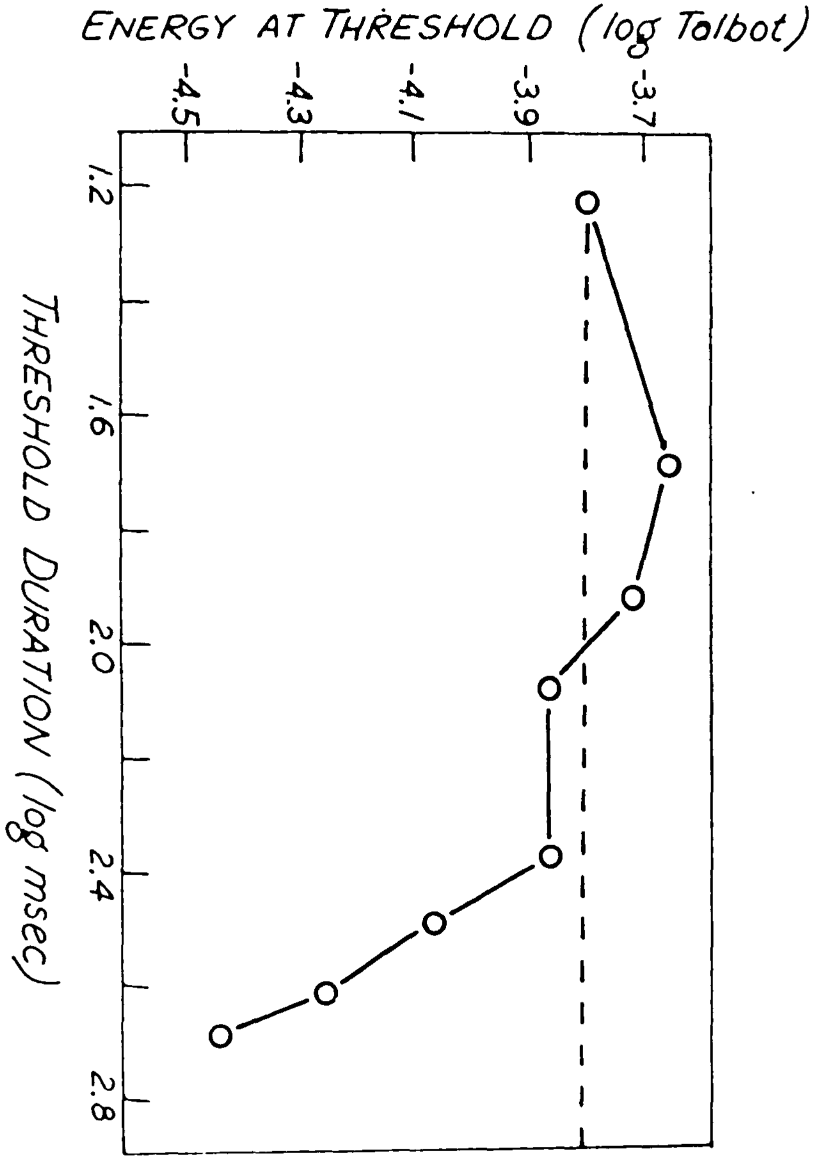

ENERGY AT THRESHOLD (log Talbot)
-4.5
-4.3
-4.1
-3.9
-3.7
THRESHOLD DURATION (log msec)
1.2
1.6
2.0
2.4
2.8

Figure 15.

Log luminance vs log threshold duration for Monkey #886. Notes as in Fig. 13.

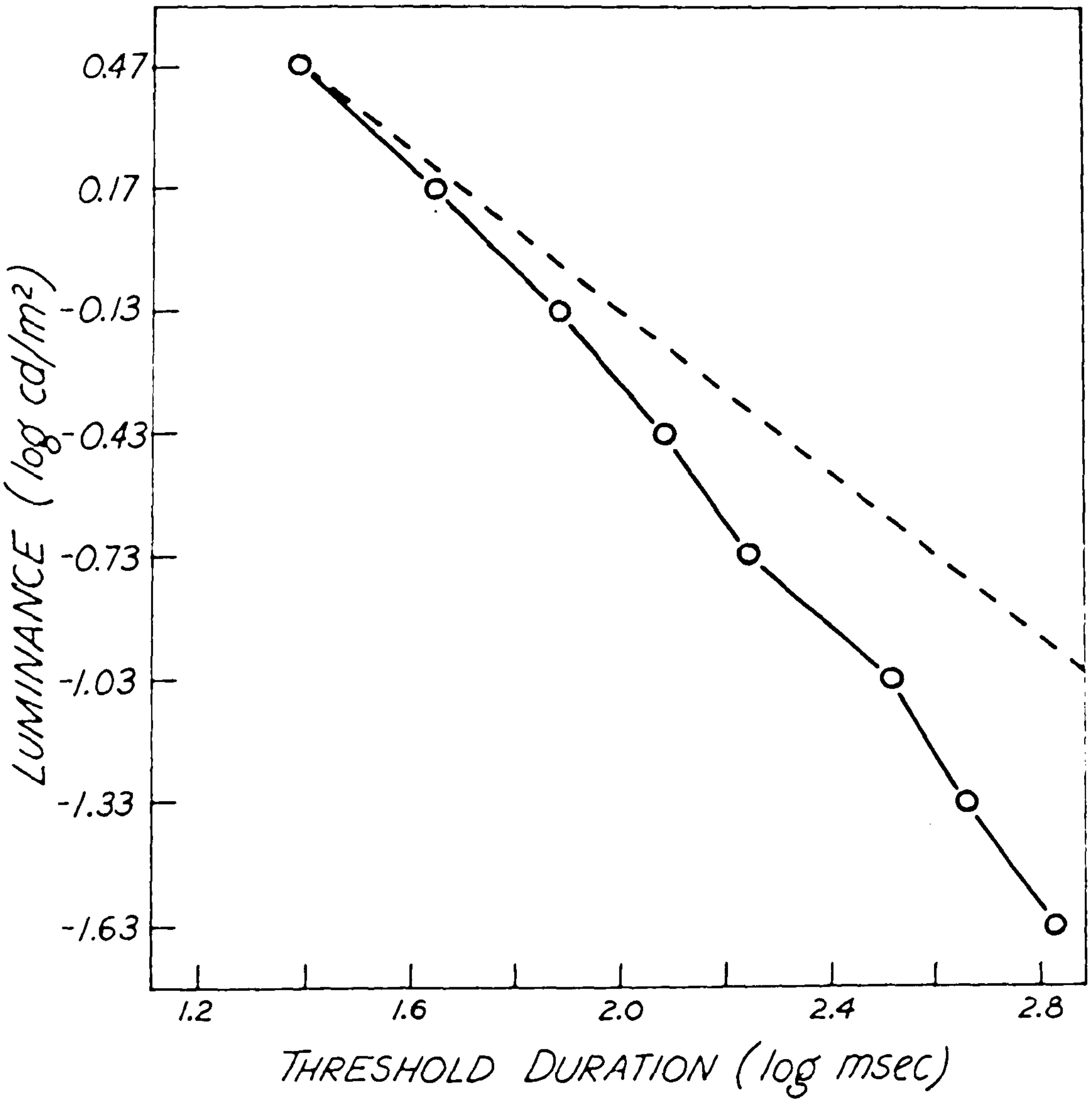

0.47
0.17
-0.13
-0.43
-0.73
-1.03
-1.33
-1.63
LUMINANCE (log cd/m²)
1.2
1.6
2.0
2.4
2.8
THRESHOLD DURATION (log msec)

Figure 16.

Log energy vs log theshold duration for Monkey #886. Notes as in Fig. 14.

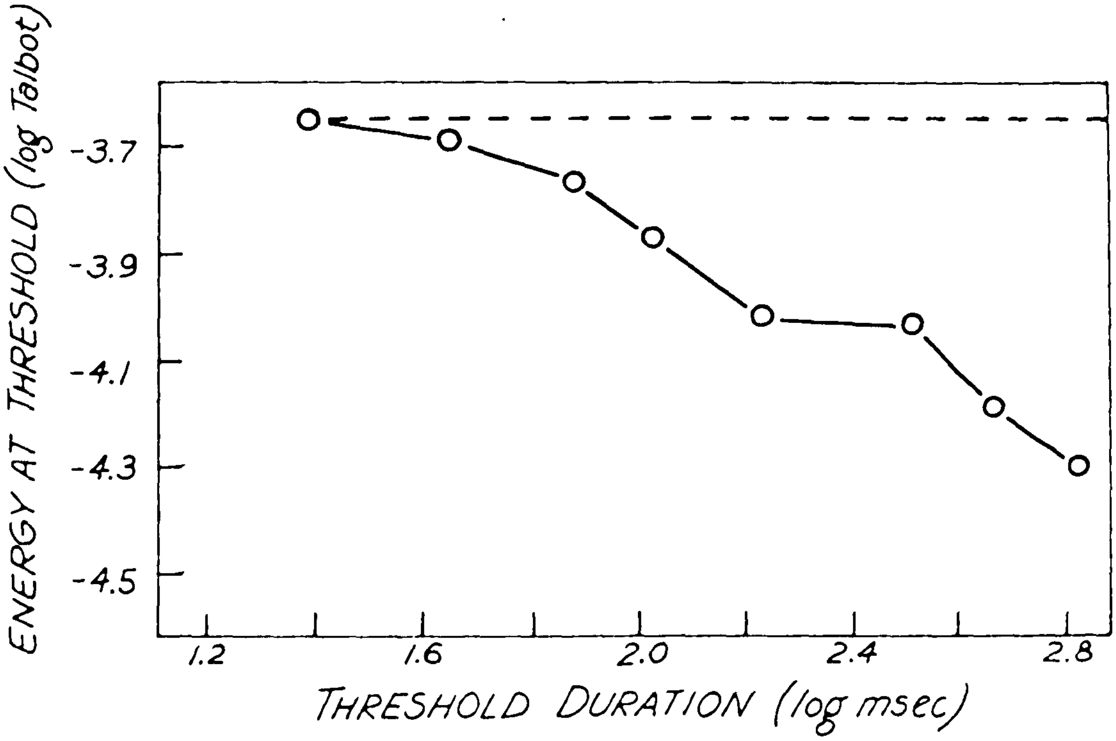
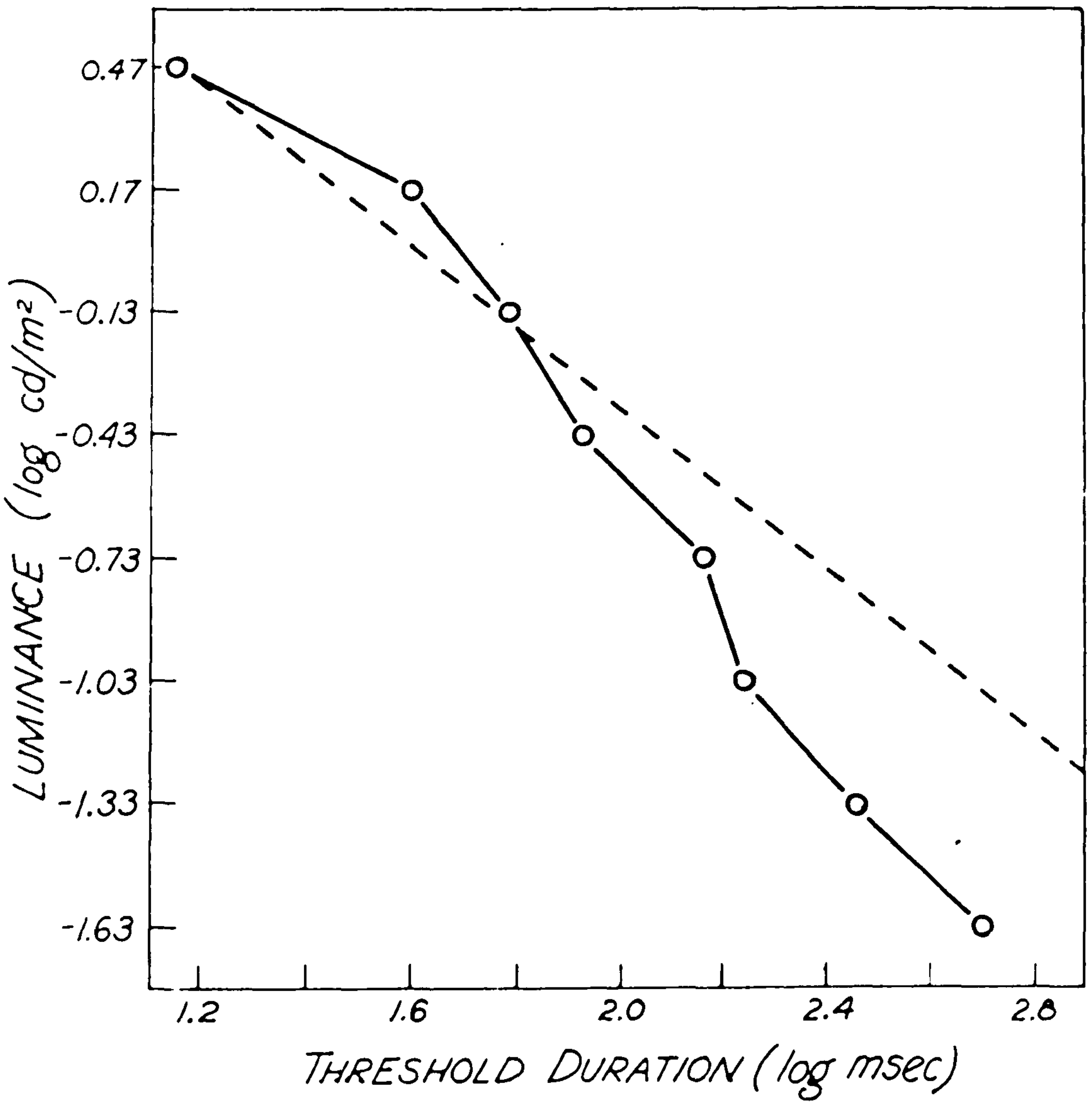

ENERGY AT THRESHOLD (log Talbot)
-3.7
-3.9
-4.1
-4.3
-4.5
1.2
1.6
2.0
2.4
2.8
THRESHOLD DURATION (log msec)

Figure 17.

Log luminance vs log threshold duration for Monkey #894. Notes as in Fig. 13.



LUMINANCE (log cd/m²)
0.47
0.17
-0.13
-0.43
-0.73
-1.03
-1.33
-1.63
1.2
1.6
2.0
2.4
2.8
THRESHOLD DURATION (log msec)

Figure 18.

Log energy vs log threshold duration for Monkey #894. Notes as in Fig. 14.

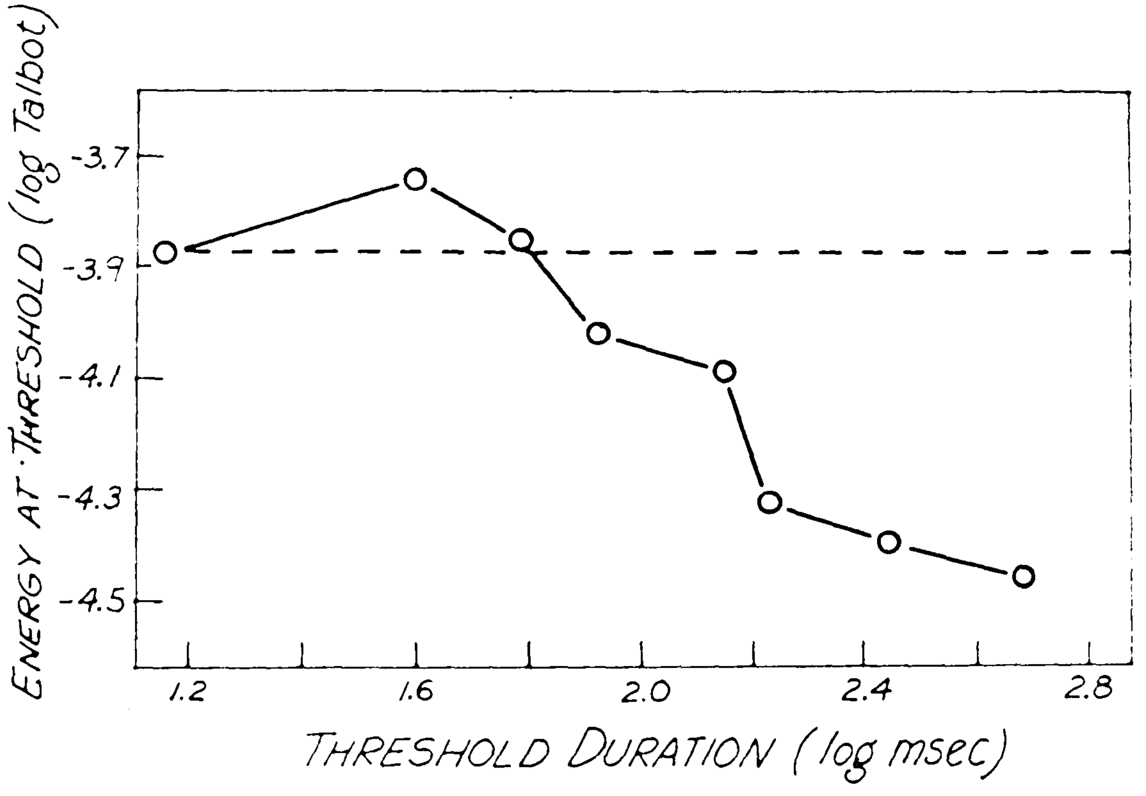

ENERGY AT THRESHOLD (log Talbot)
-3.7
-3.9
-4.1
-4.3
-4.5
1.2
1.6
2.0
2.4
2.8
THRESHOLD DURATION (log msec)

TABLE 5

Experiment II. Slopes of Functions for All Subjects

a. Log Luminance vs Log Threshold Duration

Subjects	Full Analysis		Partial Analysis	
			H	L
#883	-1.46	(3/6)	-0.89	-1.64
#886	-1.41	(3/6)	-1.13	-1.43
#894	-1.33	(5/4)	-0.99	-2.04
TG	-1.31	(4/3)	-0.73	-1.47

b. Log Energy vs Log Threshold Duration

	Full Analysis		Partial Analysis	
			H	L
#883	-0.45	(3/6)	0.11	-0.64
#886	-0.41	(3/6)	-0.13	-0.43
#894	-0.33	(5/4)	0.01	-1.04
TG	-0.31	(4/3)	0.27	-0.47

Notes:
H, high luminance levels
L, low luminance levels
(/), number of high / low luminance values

respectively.

c. Analysis of Latency Data. Figure 19 is a scattergram of log latency vs log energy at threshold for all three monkeys. It is apparent that at brief stimulus durations requiring energy levels of about -3.8 log Talbot, latencies were similar and of the order of 2.65 log msec. At longer durations which required relatively lower energies, there was a disproportionately greater and progressive increase in the latency.

2. Human Observer

a. General data analyses. Table 4 contains also the threshold magnitudes associated with each luminance level for TG. Performance at the highest luminance level was consistently above threshold even with the shortest durations available. The threshold values at 1.461 and 0.023 cd/m2 were 1.11 and 2.53 log msec, respectively. In this case attenuating the luminance by 1.8 log units resulted in a 1.42 log msec increase in threshold. The E values for the highest and lowest luminance used were -4.25 and -4.61 log Talbots. In general less energy was required at the lower levels, the difference being approximately 0.40 log Talbots.

b. Analyses of Log Luminance and Log Energy vs Log Threshold Duration Functions. Figures 20 and 21 show the log L vs log T, and log E vs log T functions respectively, for the human. A GLM analysis was also used on these data. Table 5 shows the slope value arising from full as well as partial analyses. The full analyses yielded a slope steeper than -1.0 for the log L vs log T plot and approximately -0.3 for the log E vs log T plot. Both of these results suggested supersummation. Partial analyses of the data obtained at the higher and lower luminance values indicated that, as in the monkeys, some degree of

Figure 19.

Log latency vs log energy at threshold for the three animals: 0—0, 883; ●—●, 886; +---+, 894. Note the clustering at the high energy levels which suggest a reciprocity function, i.e., for similar energy requirements at threshold, the latencies are also similar. At lower values, however, there is a disproportionately greater increase in latency.

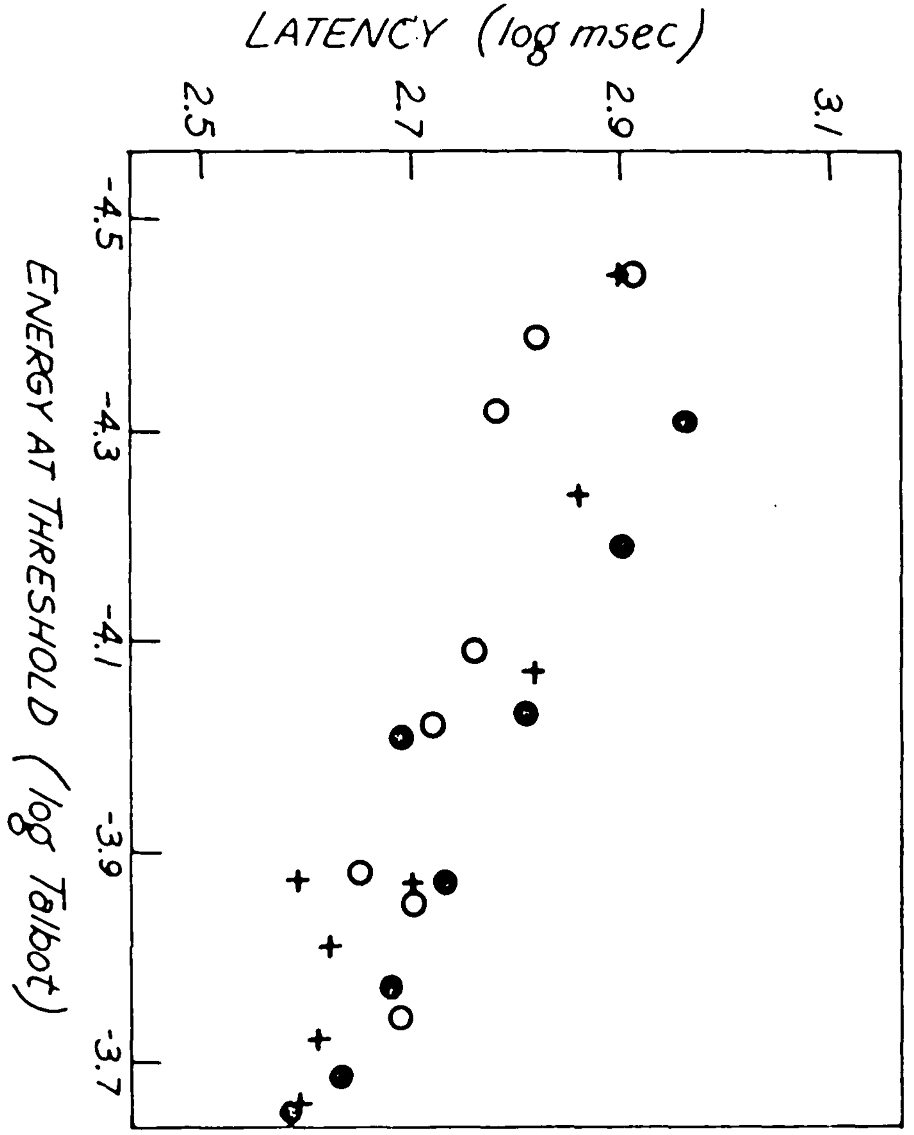

LATENCY (log msec)
2.5
2.7
2.9
3.1
ENERGY AT THRESHOLD (log Talbot)
-4.5
-4.3
-4.1
-3.9
-3.7

Figure 20.

Log luminance vs log threshold duration for the human subject (TG). Notes as in Fig. 13 except that each point represents the mean of three determinations.

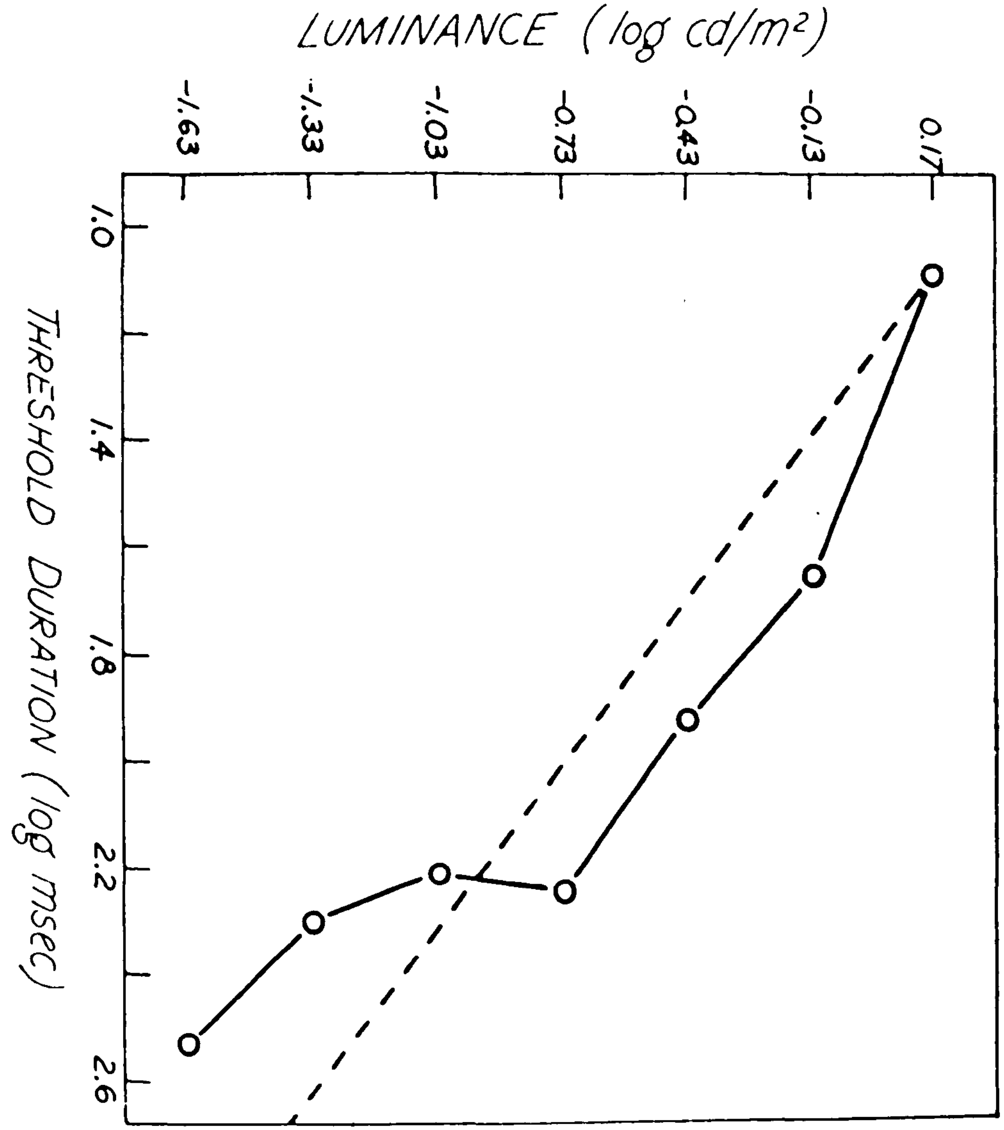
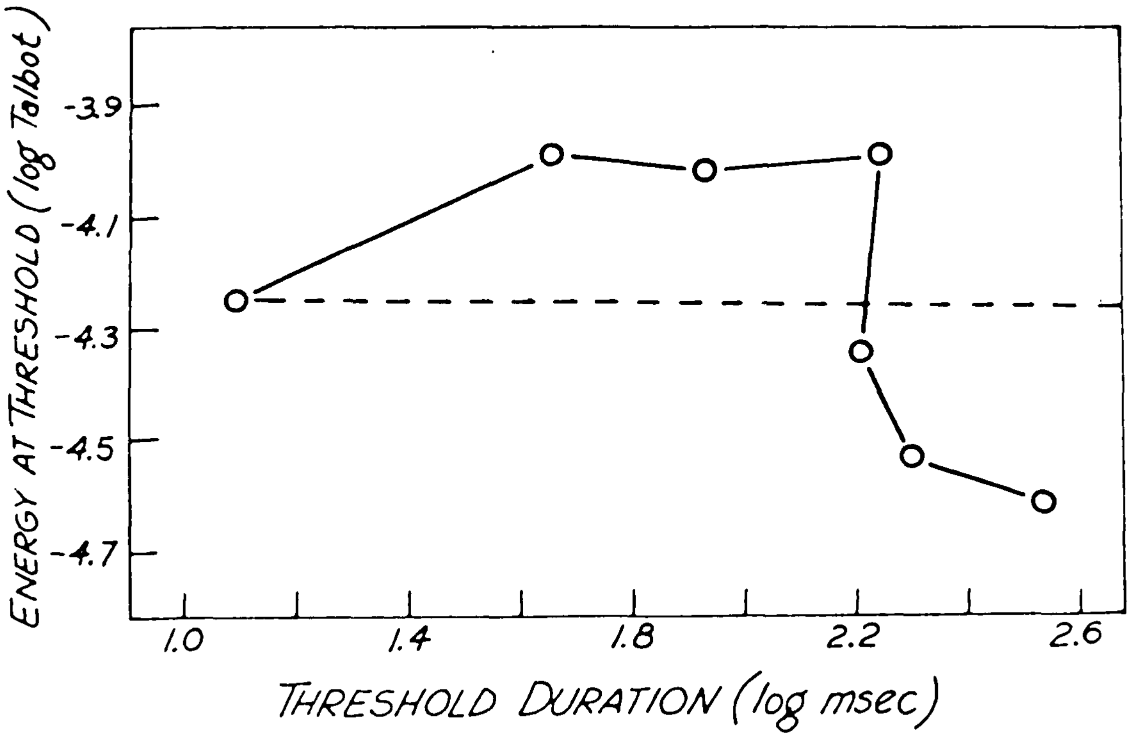

LUMINANCE (log cd/m²)
-1.63
-1.33
-1.03
-0.73
-0.43
-0.13
0.17
THRESHOLD DURATION (log msec)
1.0
1.4
1.8
2.2
2.6

Figure 21.

Log energy vs log threshold duration for the human subject (TG). Notes as in Fig. 14, except that points represent the mean of three determinations.


ENERGY AT THRESHOLD (log Talbot)
-3.9
-4.1
-4.3
-4.5
-4.7
1.0
1.4
1.8
2.2
2.6
THRESHOLD DURATION (log msec)

reciprocity existed at the higher values, whereas the lower points contributed most to supersummation. This was supported by the slope data, which approached -1.0 for the log L vs log T plot and 0.0 for the log E vs log T graph at the higher levels. Similarly, at the low levels, the slope was steeper than -1.0 and approximately -0.5, respectively. The inflexion point of the functions corresponded to a threshold of 157 msec.

c. Analysis of Latency Data. The latency data for the human did not show any clear relationship to log energy at threshold. Like the monkeys, the human subject had no constraints to respond as quickly as possible to the stimuli. In addition, and more important, motivation was not manipulated by food deprivation or positive reinforcement. For the latter two reasons, the data were not thought to merit further consideration.

In summary, for both monkeys and the human, analysis of entire functions showed that decreases in luminance were associated with increases in threshold duration. However, magnitude of threshold increments did not correspond to decrements in luminance, with the threshold durations increasing less than the corresponding decreases in luminance. The slope of the line of best fit for log luminance-log threshold duration, for each subject, was greater than unit negative slope.

Partial analysis of the functions indicated that reciprocity occurred at the higher luminance levels, while supersummation was present at the lower levels. In addition, these lower values contributed most to steeper than unit negative slope. No asymptote was found at the lowest level of luminance explored.

C. Comparison Across Experiments I and II

Experiments I and II contained some common features that allowed for a comparison of the influences of the state of light adaptation on the results. These features included: 1) the same two subjects (numbers 883 and 886); 2) the adaptive procedure; 3) two level of luminance (highest and 1.2 log attenuation). In Experiment I, the stimulus and adapting fields were flux equated at each luminance value used. Therefore, the level of light adaptation was not constant. In Experiment II, however, light adaptation was fixed, and equated with the highest luminance stimulus. As Table 6 demonstrates, a 1.2 log attenuation in luminance resulted in about a 0.4 log unit increase in threshold in Experiment I, and approximately a 1.0 log unit increment in Experiment II. The energy required at threshold decreased by 0.8 log units in the first study, and by only about 0.3 log units in the second study. In Experiment II, when adapting field was at a higher luminance than the stimuli, i.e., in the low luminance condition, the increment in threshold was greater whereas the decrement in energy at threshold was lesser than the respective magnitudes in Experiment I. These data indicate that although duration was more effective than luminance in determining the criterion response in both experiments, the level of light adaptation had a significant effect on tachistoscopic pattern discrimination thresholds.

TABLE 6

Differences Elicited by 1.2 log Attenuation in Luminance Across Experiments

	#883		#886	
	log θ	log E	log θ	log E
Exp. I	0.41	0.79	0.40	0.81
Exp. II	0.99	0.21	0.85	0.36

Chapter V

DISCUSSION

Since the publication of Bloch's paper in 1885 on intensity-time reciprocity, most studies using light flashes have supported his findings. This relationship has also proven to be robust for more complex situations, i.e., acuity tasks, digit identification, shape discrimination, motion detection, and numerosity, and with stroboscopically presented stimuli (Allport, 1970; Brown, 1955; Hunter & Sigler, 1940; Kahneman & Norman, 1964; Kahneman, Norman & Kubovy, 1967; Leibowitz, Toffey & Searle, 1966). Parameters other than intensity and time have been manipulated to ascertain their effect on the temporal summation function in the attempt to understand visual processing.

Unlike other tachistoscopic studies in monkeys which involved discrimination masking (Adkins, Fehmi & Lindsley, 1969), the consequence of brain lesions on pattern recognition (Chow & Orbach, 1958), and changes in latency and accuracy in identifying stereometric objects (Fuster, 1958), and the effects of amphetamine on brightness discrimination (Thurmond, 1965), the present investigation determined thresholds for pattern discrimination, as well as trade-off functions of time and intensity.

Experiment I contrasted two psychophysical methods: descending staircase method and constant stimulus procedure. Two levels of luminance were used, adapting and stimulus fields were flux-equated, and subjects were required to initiate trials to minimize attention and motivational variables. The psychophysical data suggested that duration may be more effective than luminance for pattern discrimination threshold. When luminance was attenuated by 1.2 log units, threshold duration increased by approximately 0.4 log units regardless of which method was used. In addition, less energy was required for the longer duration stimuli. The energy difference was approximately 0.8 log Talbots. These results obtained with the two different psychophysical methods are indeed in striking agreement, both with respect to thresholds as well as energy required at threshold, and give confidence to investigators who choose to use the adaptive procedure.

To obtain intensity-duration functions and to examine the findings of the first study more fully, Experiment II was conducted using the descending staircase procedure with light adaptation held constant. The stimuli were the same luminance level as the adapting field or seven other lower values. In general, for all subjects, analyses of entire functions showed that decrements in luminance were associated with increments in stimulus duration threshold. This increment was of a lower magnitude than the corresponding attenuation in luminance. The slope of line of best fit for log luminance-log threshold duration, for each subject, was steeper than unit negative slope. For all subjects, as luminance was halved, threshold duration did not double. Slopes of the log luminance vs log threshold duration variables ranged from approximately -1.3 to -1.46. Partial analyses of the individual segments of the functions indicated that reciprocity occurred for brief stimuli, while supersummation was present at the longer durations. In addition, these longer durations contributed most to the steeper than unit negative slope obtained. Furthermore, measures of response latency also suggested a reciprocity function at high energy values followed by a failure at lower levels. No region of total failure of summation was ever attained and, therefore, no value of critical duration became available. These failures could be due to a too limited sampling of the scotopic range. However, another feature of the functions, which thus far has received no attention, is the inflexion point between reciprocity and supersummation. This characteristic may serve as a reference point like critical duration and utilization time to further understand visual processes.

Threshold data obtained in Experiment I and II were in accord, but the magnitudes were not of the same degree, i.e., when the adapting and stimulus fields were flux-equated, a 1.2 log attenuation of luminance resulted in approximately a 0.40 increase in threshold duration; when the fields were not equated and light adaptation was held constant, this value was approximately 1.00 log unit. Attenuating the luminance by 1.20 log unit in Experiment I resulted in an energy difference of approximately 0.8 log Talbots; in Experiment II this value was approximately 0.3 log Talbots. These findings indicated that the level of light adaptation had a significant effect on pattern discrimination thresholds.

It should be noted that other factors may contribute to the different magnitudes of supersummation across studies. For instance, pupillary size must have remained relatively constant in Experiment I, and varied during the trial at all but one level in Experiment II, since the adapting fields were always of higher luminoux flux than the stimulus fields at those levels. The fact that supersummation was found in Experiment I indicated that pupillary size was not an important determinant of the phenomenon. Moreover, the influence of pupillary changes can be safely ruled out even in Experiment II, because pupillary area increases by only 15% during the initial 600 msec on changing from bright illumination to total darkness (LeGrand, 1968), which represents a change of several log units above the maximal attenuation used in Experiment II. It should be recalled that only one out of 31 thresholds was above 600 msec (see Table 4). Finally, even if such minute amount of dilation were influencial, the expected results would be in the opposite direction to those of the present study, namely that less energy would be required at threshold in Experiment II than in Experiment I (see Table 6).

The possible influence of eye movements on the results must also be considered but only in Experiment II since thresholds values in Experiment I were always shorter than the reported latency for visually elicited saccades, which according to Kling & Riggs (1972) is 180-250 msec. In Experiment II, the inflexion point between full reciprocity and supersummation was close to that latency and, therefore, it was possible for the subject to execute saccades within the time domain of the supersummation effect. Although the role of eye movements have been minimized in temporal integration studies (Kahneman, 1964; Sperling, 1979) the question must await further experimentation.

The most significant result of the present investigation is the occurence of supersummation for the range of luminance explored, from low photopic to scotopic levels. This finding is not in agreement with many other studies of temporal integration involving either light flashes or more complex stimuli; typically these investigations demonstrate complete reciprocity followed sometimes by partial integration and then a region of no summation. The supersummation phenomenon does, however, appear, albeit rarely, in the literature for a variety of tasks, such as visual acuity and numerosity (Hunter & Sigler, 1940; Kaswan & Young, 1963). Studies on Limulus demonstrates this phenomenon behaviorally as well (Kong and Wasserman, 1978). Supersummation has been defined in terms of log I vs log T functions which have a slope steeper than -1.0 at longer durations and is considered to be indicative of a facilitatory effect (Kong & Wasserman, 1978). This increased efficiency is opposite of what is demonstrated in typical IT investigations, since longer pulses generally require more energy at threshold.

Another important feature of the present study is the use of pattern stimuli to explore temporal integration functions. This approach has been employed rarely. One such investigation involves identification of triads made of zeroes and ones (Kahneman, 1964). The results demonstrate a region of reciprocity followed by failure of summation. Another experiment shows similar functions, but in this case the task was to report the position of the gap in a Landolt C (Eriksen, Hamlin & Breitmeyer, 1970). In both studies, stimuli of high luminance and contrast were used and the subjects were dark adapted. These parameters clearly differ with those used in the present study, and may be related to the different shapes of the obtained integration functions.

The advantage of using pattern stimuli in animal experiments is the possibility of clarifying the nature of visual deficits created by brain lesions. It is well known, for instance, that bilateral resections of temporal neocortex interferes with pattern discrimination (for review see Dean, 1976). Although most studies interpret these results as indicative of a disturbance in higher visual functions, there is some evidence that they can be attributed at least in part to alterations in the functional visual fields (Pasik, Pasik, Battersby & Bender, 1960). Moreover, an increase in differential thresholds for pattern discrimination were found only at low luminance levels after the lesions (Valciukas & Pasik, 1965). It is possible that combining spatial and temporal characteristics of the stimuli, as in the present study, may help elucidate further the nature of these disturbances.

The results of the present investigation are unexpected to some extent because response requirements as well as the intensity and time of the stimulus values selected appear to overlap with those used by other investigators. Methodological issues, integration models, and implications of the data for future research will, therefore, be considered.

Methodological Issues. Both psychophysical procedures used in this investigation belong to the equal-performance category and both methods yield similar threshold duration and threshold energy data, which indicates that the method of constant stimuli could have been used instead of the descending staircase procedure, and that similar functions would have been obtained. The adaptive method seems more convenient, however, than the method of constant stimuli for the following reasons: 1) it is efficient because data values are concentrated about threshold; 2) the subject is more often and more reliably reminded of the task requirements because the independent variable is affected by responses; and 3) a continuous behavioral assay is available to the experimenter. Additionally, psychometric functions can be derived from this method by using stepping rules which converge on different levels of correct responding, e.g. the 70.7% and 29.3%. Since the psychometric function is roughly linear in the midrange, the two points can be used to approximate this relationship.

Disorganization of behavior occurred with both psychophysical methods when luminance was attenuated. Although this was more marked in the second experiment, it resulted more from holding light adaptation constant and using lower levels of luminance than from the adaptive procedure per se. To minimize deterioration in performance, a stepping rule could be chosen which converges on a higher threshold level, i.e. making the task easier. This change would be particularly beneficial in experiments expected to produce a deficit such as brain lesion or certain pharmacologic mainpulations.

Integration Models. In general, studies which interpret temporal integration in terms of peripheral *or* central processes address the issues of complete summation, critical duration, partial summation, and no summation, and ignore supersummation altogether. Contrariwise, the model proposed by Wasserman and Kong (1979) takes into account both peripheral *and* central factors, with particular emphasis on central nervous system analysis of peripheral signals. "Event" analysis and "process" analyses produce different sorts of "signatures" (see Figure 3): the former elicits the usual temporal integration function, the latter a function in which a region of complete summation is followed by supersummation. Analysis of physiological as well as behavioral data in Limulus appear to support their position that the non-linearity of receptors as well as more central nervous system analysis account for supersummation. Reported central non-linearity seems to depend on the receptor response (Wasserman & Kong, 1979). Compression or a process which is time limited might account for supersummation in a linear system, which is characterized by its response to brief pulses of light. To obtain the prepotent time effect, the system's dynamic range in response to intensity would be limited, i.e., above a certain value intensities are treated as equivalent. In this case duration becomes more important (Sperling, 1979).

Bloch's law is ubiquitous in visual research, as attested to by the number of measures encompassed. But are there tasks whose solution require a contribution of time independent of intensity, i.e., where T = K. Examples are provided by Kaswan and Young (1963) and Leibowitz, Toffev and Searle (1966). In the first case, subjects in a forced choice situation, were required to discriminate between linear displays of dots, which were paired or evenly spaced. The paradigm used was one of equal energy. They found that intensity had little effect on accuracy, but changes in exposure time, especially influenced the discrimination of the dot pairs. Additionally, the relative spatial distance of between to within pairs of dots also influenced accuracy. Detection of stimuli per se, however, was a function of intensity and duration; relative spatial distance was unimportant. The general conclusion was that duration was more important for accuracy of discrimination than intensity. The findings suggest that perception becomes differentiated over time. A two-stage model of perception was suggested. Initially, the visual system deals with the presence or absence of stimuli, but with increased exposure time, it becomes concerned with the detail of the stimulus. In this case, duration becomes more important than intensity.

In the Leibowitz et al. (1966) study, a matching to sample paradigm was also presented tachistoscopically and intensity and time were varied to produce equal energy packages. The test object was a circular disc oriented at constant angle which produced an eliptical retinal image with an axis ratio of 0.5. Subjects were required to select a stimulus which appeared similar to the sample. In terms of shape perception per se, the data demonstrated that at brief durations (0.1-1 msec), the mean matched axis ratios were similar for equal-energy stimuli, i.e., observers selected comparison stimuli on the basis of retinal image. For the brief durations mentioned, there was little tendency toward shape constancy. The latter phenomenon only occurr at durations beyond critical duration. The authors conclude that time makes a critical contribution, independent of intensity, for shape constancy.

Sperling (1979) offered examples in which time would also have a prepotent effect. One case involved exposure of text and the criterion response was percentage correct recall. Given enough luminance to detect the stimuli, further increments would only improve performance slightly but increases in duration would be highly facilitatory. Hunter and Sigler's (1940) numerosity data may be thought of in terms of a processing which requires time. At longer durations, small increments were associated with dramatic increases in the efficiency of the visual system. Sperling (1979) suggested that processing, which requires time but is relatively unaffected by intensity, would be suggested by the above examples.

The results of the present investigation appear to parallel those of Kong and Wasserman (1978) in that a region of reciprocity was followed by a region of supersummation. The use of a form discrimination task might have tapped into a time-limited process which would become evident at durations beyond tc. In the present study, subjects were required not only to detect the presence of a stimulus, but also had to determine its location and pattern. Therefore, exposure time may have had a more important effect on the criterion response than luminance.

Our findings on response latency may be related to those of studies on intensity-time reciprocity in reaction time (RT) measurements. It should be noted however, that the constraint of responding as quickly as possible after stimulus detection was not used in the present investigation. Another methodological difference was the use of stimuli which were not of identical energy. In any event, it was found that when stimuli were of brief duration and high luminance, the energy required at theshold were comprable (within 0.2 log units) and that under these circumstances the latencies were also of similar values (within 0.1 log unit). These results suggest that response latency shows some IT reciprocity at brief stimulus durations which agrees with previous investigations using RT (Kietzman, Shapiro & Bienstock, 1975) but not with others (Grossberg, 1968).

Future Research. In summary this investigation has established a data base for the normal monkey which includes threshold determinations using two psychophysical methods. Additionally, intensity-time functions were obtained. Further, a time-limited process, i.e. supersummation has been demonstrated. Since the animal model has few experimental restrictions, the phenomenon might be explored further using adjuct techniques, e.g. recording cellular responses at different levels, ablations, and neuropharmacological manipulations. For example, the visual system is dichotomous in function, i.e. a transient system indicates that something is there, and a sustained system performs a high level resolution. In animals, these systems consist of Y and X cells respectively. The X cells respond to high spatial frequencies, have relatively high thresholds, and are involved in form resolution; Y cells are sensitive to lower frequencies, have a lower threshold, and are tuned to movement (for review see Breitmayer & Ganz, 1976). At lower energy levels, the sustained system would have a longer latency than at higher levels. If the response of such a system increases exponentially, small increments in time at longer durations may result in a disproportionate increment efficiency of the system. This possibility could be investigated using electrophysiological techniques in addition to the type of stimuli and procedures outlined in this study.

Recently, some authors (Sperling, 1979; Wasserman & Kong, 1979) have stressed the importance of using complex stimuli, more diverse tasks, as well as non-conventional data analysis in studies of temporal summation. The visual environment can be thought of in terms of continuous signals varying in amplitude over time. Considering the presence of frequency selective channels, the use of stimuli more complex than single flashes may be appropriate to understand the non-linear nature of the visual system. Sperling (1979) has proposed the use of at least sinewave or multiple pulse stimuli. In conjunction with a more complex display, a number of different responses can be measured, e.g. detection, localization, discrimination, recognition, and meaningfulness (Wasserman & Kong, 1979). Data might be analyzed in terms of "event/process", signal detection, spatial frequency (Fourier analysis), as well as with traditional psychophysical methods.

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