

THE THRESHOLD DETECTABILITY OF SLOWLY
FLASHING LIGHTS

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ABSTRACT

THE THRESHOLD DETECTABILITY OF SLOWLY FLASHING LIGHTS

by Douglas Hall Williams

Literature regarding the calculation of the effective intensity and conspicuity of flashing lights below CFF is reviewed, and problems with present attempts at measurement and prediction are discussed. A study is done to provide a first step toward a more useful way of measuring these phenomena. Equipment is described which provides square light pulses of different rates, luminances, and PCF. Group thresholds were obtained from 20 naive subjects using the method of constant stimuli, for 20 combinations of rates from 1 to 4 flashes per second, and PCF from 15% to 85%. These results were compared with those from one trained subject which were obtained using the method of limits. Results are found to be substantially the same. The implications of the findings for future research are discussed, and some of the methodological precautions necessary in these future studies are mentioned.

Approved Terrence J. H. Allen
Date 5/20/66

THE THRESHOLD DETECTABILITY
OF SLOWLY FLASHING LIGHTS

By

Douglas Hall Williams

A THESIS

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Douglas Hall Williams

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Chapter I

BACKGROUND OF THE STUDY

Introduction

The problem of the effectiveness of flashing lights has been studied for as long as there have been lighthouses. With the advent of high-speed vehicles, the problems have become more critical. The use of flashing obstruction indicators on highways, and flashing airway beacons and clearance lights has caused this problem to become of concern to designers and manufacturers. The purpose of these devices is to attract the operator's attention, communicate to him the fact that he is approaching a hazard, and give him information as to the location and size of the hazard. All this must be accomplished when he is far enough away so that he has time to slow down or take evasive action. Signal lights now employed in these applications typically flash one to two times per second, with pulse-to-cycle fractions (PCF) of 5% to 50%.

Relevant Literature

Several different methods of measuring the effectiveness of flashing lights have been used. These methods

range from pure perceptual studies, carried out in a laboratory under controlled conditions, to informal observations under field conditions. Several of these different approaches will be reviewed in turn, in an attempt to show what the state of the art is at present. Methodological problems encountered by these investigators will also be noted.

Effective Intensity

One way to approach the problem is to determine the brightness of a flashing light necessary for it to appear as bright as a steady light. The work of Blondel and Rey (1912) was the first analytical work in this area, and took this approach. Since the basic equations they derived are still in use after 50 years, it is worthwhile to review their study, with special attention to their assumptions and experimental method.

Reviewing Broca and Sulzer's work of 1902, Blondel and Rey (1912) noted that their curves showed that the apparent intensity of a short flash of light varied according to the length of the flash. They set out to study this relationship. Using two different types of apparatuses, one checking the results of the other, they presented 25 series of flashes to 17 heterogeneous subjects. The subjects adjusted the test flash to apparent equality

with a long control flash of known candlepower (psychophysical method of adjustment). Only relative, not absolute, brightnesses of the stimuli are reported. Three seconds were left between presentations of test flashes, as Blondel and Rey assumed that this would allow any effects of one flash to die out before the next was presented. The authors noted that the results, in terms of intensity for subjective equality, were so heterogenous that taking arithmetic means would be suspect, so they used geometric means. They hypothesized that some of this variance was due to the fact that they did not use an artificial pupil, and that variations in the state of dark adaption of the observers were not controlled. Despite these problems, they arrived at a set of data points which was described by the equation:

$$E_t = A + Bt \quad (I)$$

where

E = intensity of illumination on
the pupil (i.e., Lumens/m²)

t = duration of the flash

A and B = constants.

This form of the equation had been inferred by Blondel and Rey from rational considerations and the results of previous research. When the data had been collected and plotted, they found that $A = aE_0$ where E_0 is the intensity of a threshold light and "a" a constant equal to .21. When the flash was infinitely long, the effective intensity

would have to be the steady light threshold, E_0 . Therefore, Blondel and Rey concluded that $B=E_0$. Finally then, they had

$$Et = .21E_0 + E_0t \quad (II)$$

They also wrote the equation in the equivalent forms

$$t(E-E_0) = .21E_0 \quad (III)$$

and

$$\frac{E}{E_0} = \frac{.21+t}{t} \quad (IV)$$

The assumptions on which these equations were based would limit their usefulness to square pulses. This condition is sometimes ignored (Neelans, Laufer, and Schaub, 1938); the equations have been found useful for other wave shapes.

In summing up their paper, Blondel and Rey state the practical implications of their work for cases when only a given amount of energy is to be used in the flash: "...it is always advantageous to reduce the duration of the flashes without the necessity of fixing a limit of minimum duration. The limit is in reality fixed by the conditions for producing the source of light at the apparatus..." (Blondel and Rey, 1912, p. 652).

Recommendations were also made for flashing sources used in communications, designing a source for maximum efficiency, and setting existing apparatus for maximum effectiveness: "...it is therefore of interest to reduce

if possible the dimensions of the light source producing a given flux, by increasing the intrinsic brilliancy "i" at the expense of the diameter..." (Blondel and Rey, 1912, p. 650).

The method and results of this pioneering study have stood the test of time. However, one would wish that the subjects had been a little more carefully described, better dark adapted (or that the artificial pupil had been used), that some statistical analyses had been carried out, or at least variances given for the values which were "too heterogeneous" to use means. However, we should not expect a 1912 study to meet today's standards of analysis. One might, however, question the use that has been made of the Blondel-Rey equations without checking them or the methods by which they were derived.

Studies have been done more recently to check the Blondel-Rey equations, and one of the most often quoted is the one by Neelans, Laufer, and Schaub (1938). Briefly, their method was to set up several airway beacons on buildings 8.3 and 2.9 miles from the observers. Next to the beacons was a projector which could be varied in intensity to match the apparent brightness of the beacon flash. They obtained fair agreement with the Blondel-Rey equation

$$\frac{E}{E_0} = \frac{.21+t}{t}$$

Unfortunately, there are several things wrong with their method. Instructions to the subjects were apparently ambiguous, as "...some O's...stated that they used the apparent size of the source as a measure of its visibility; ...other O's undertook to match the fixed light with the most visible portion of the flash." (Neelans, Laufer, and Schaub, 1938, p. 281). The effect of the atmosphere of course could not be held constant, and the authors noted at times a variation in the measured threshold of the subject as large as a factor of nine in the candlepower of the steady source necessary for subjective equality. The color temperature of the comparison projector was also noted to vary with intensity, and this had unknown effects on the observer's judgments. The investigators for no stated reason inserted a red filter in one of the beacons for some measurements and not for others, doubled the flash rate on some runs for some beacons, and then averaged all these data in with the rest for the final curves. Most importantly, they indicate that the flash probably did not have a square shape, as it properly should to satisfy the Blondel-Rey equation. They did not indicate what the shapes might be, and used the square-pulse equation anyway.

Toulmin-Smith and Green (1933) measured the fixed-light equivalent of suprathreshold flashing lights, using equipment similar to that of Blondel and Rey. They wanted

to use a suprathreshold value brighter than that used by the 1912 investigators, in order to conform more closely to the bright signals used by ship's navigators, which must be considerably above threshold to be useful. The method of adjustment was used, with the brightness of a steady pinhole source being adjusted to match the brightness of a flashing source. Flashes of different pulse-to-cycle fraction, of a rate about one per second, were used. It is unclear from the experimental report how the subjects were selected. It reads as though two or three subjects were used. It was found that the data were described by the formula

$$\frac{I_0}{I} = \frac{1.1 t}{.15+t} \quad (v)$$

This equation is put in terms of I (illumination per unit solid angle) instead of E (illumination per square meter) as Blondel and Rey wrote it. There are also slight differences in the coefficients (the .15 corresponds to "a" (= .21) in the Blondel and Rey version.)

In 1934, Hampton made an important modification of this. He observed that using this equation, one would predict that for a long flash, the apparent intensity would exceed that of a steady light. Of course this is not reasonable, so Hampton derived an expression from Toulmin-Smith and Green's data which is more satisfactory in this regard. It is:

$$\frac{I_0}{I} = \frac{t}{\left(\frac{.0255}{E_c}\right)^{.81} + t} \quad (VI)$$

where

E_c = minimum useful illumination in
candles per mile at the observer's
eye.

This expression matches Toulmin-Smith and Green's data as well as their formula, but does not make unreasonable predictions about long flash durations.

The Constant "a"

One of the most abused and debated features of Blondel and Rey's formulas is the constant "a". This number is simply the point where the straight line plot of Blondel and Rey's results crosses the abscissa. It enters their equations as a constant added to the time, t . In their original article, Blondel and Rey admitted that this constant, which they found equal to .21, might need to be adjusted somewhat in the future.

There has been no universal agreement on the value for "a". Different investigators seem to pick a convenient value, or derive one for their purposes which hardly ever matches anyone else's value. Projector (1960) in a review, found values for this "constant" as different as .055 to .35. He suggests a standardization on a value of about .1 to .2, but offers no rationalization for

this except that most of the data falls somewhere near these values.

In the face of all this debate and disagreement, one begins to wonder if "a" actually is a constant. If this parameter varied with variations in some other factor, such as flash rate, one would expect each investigator to get a different "a" value, for each rate he used. The results of Neelans, Laufer and Schaub (1938) are typical here. When "a" was calculated to produce the best fit to their data, it was found to vary from .46 to .1 over the whole study. Their final graph can be seen to be a close approximation for all the airway beacons used, if "a" is varied for them; but no single value of "a" fits the data for any two beacons adequately. Perhaps what is needed here is an investigation which does not start with the assumption that "a" is a constant. If "a" could be found to vary systematically with changes in some other variable, this could be incorporated in equations easily. But this relation must be discovered first.

Hampton (1934) seems to have tried this, plotting "a" against different assumed values of E_c . (see Equation VI). This improved prediction, but still assumes the quantity corresponding to "a" in his equation stays constant over all variations in pulse length, frequency,

waveshape, and color.

Waveshape

Blondel and Rey realized that all light pulses were not square. They conjectured that for a non-rectangular pulse, since "...we have shown that the useful excitation is at each moment proportional to the difference $E-E_0$ between the real illumination E and the limiting illumination E_0 of the threshold..." the equation would take the form (Blondel and Rey, 1912, p. 654):

$$I_e = \frac{\int_{t_1}^{t_2} i dt}{a+(t_2-t_1)} \quad (VII)$$

where:

I_e = the "effective intensity" of a pulse

i = the actual intensity at time t

a = .21

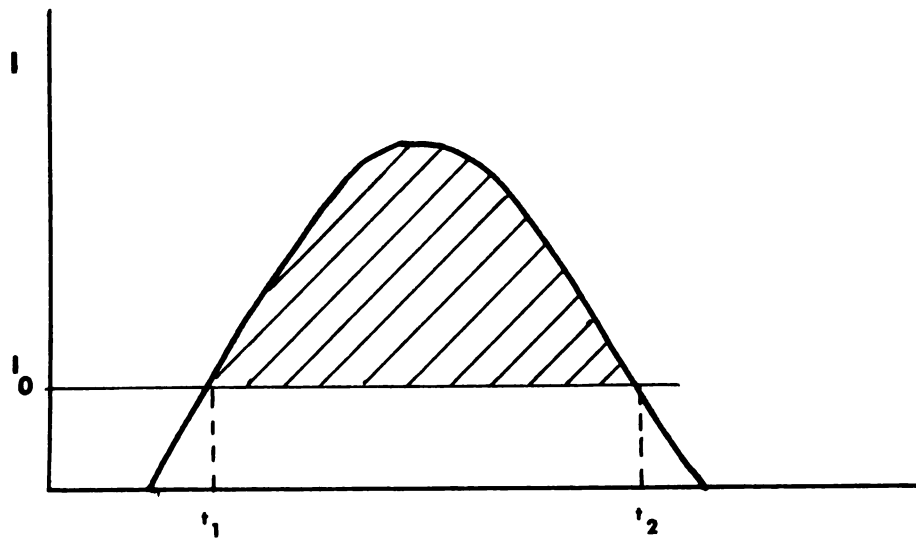
They asserted that "...the integral of excitation can be obtained by the simple quadrature of the curve representing E by measuring with the planimeter the area of the curve which is placed above the straight line E_0 " (Blondel and Rey, 1912, p. 654).

Note that this is the part of the curve above the threshold E_0 , representing total flux above threshold (see Figure 1a).

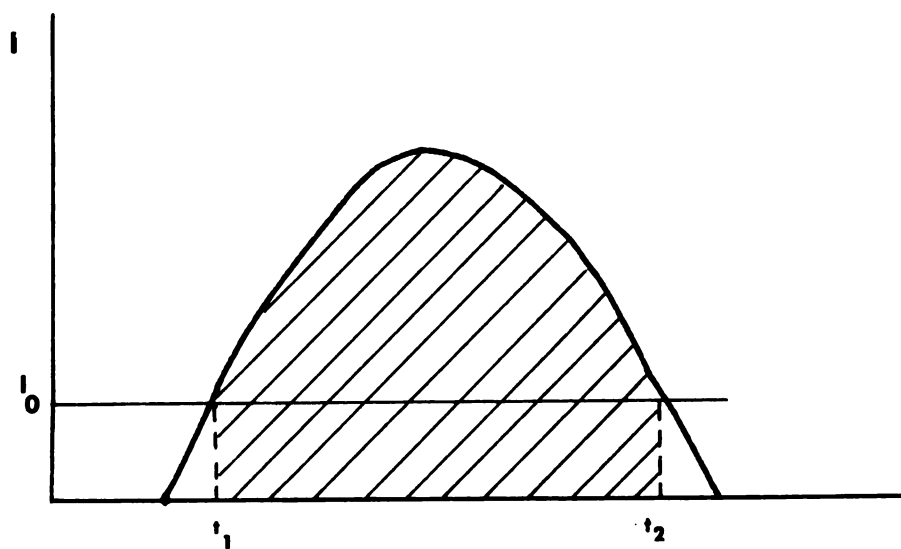
Some investigators have attempted to fit their data with the integral form of the Blondel-Rey equations (Projector, 1957; Wesler, 1960) but a dispute has arisen as to what limits ought to be used for the integral. The curves of Figure 2 will help clarify this dispute. Equation II applies to the square wave case, Figure 2a. Here the time (t) is simply the total time the pulse is on, and the equation considers the total flux emitted. In practice, only flashed acetylene flames, lights with rotating shutters, or laboratory sources give this shape of wave. For some non-square wave, such as Figure 2b, where equation VII applies, it is clear that choice of the limits of integration will make some difference, often large, in the answer obtained for the equivalent intensity. The rationale for Blondel and Rey's choice of t_1 and t_2 (where I equals the threshold value) is not obvious. For example, in the case of an incandescent lamp flashed by a relay, (light pulse curve in Figure 2c) one could use the whole emitted flux (t_0-t_6), the time when the lamp's intensity passes some arbitrary value such as 10% of its total intensity (t_1-t_5), the values Blondel and Rey suggested (t_2-t_4) or the relay contact closure time (t_0-t_3). Each of these will yield a different result, and there are arguments for, and against, each.

Douglas (1957) using Blondel and Rey's work as a

Figure 1. Suggested integrations
of a hypothetical I-t curve of light output

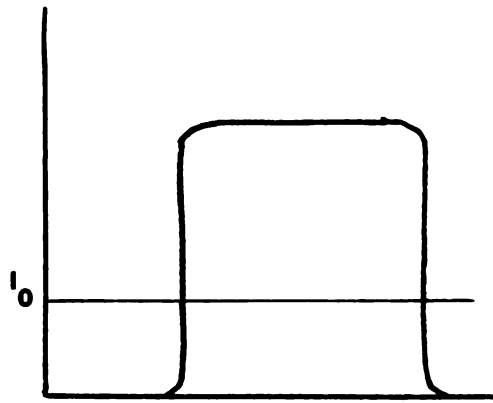


1a

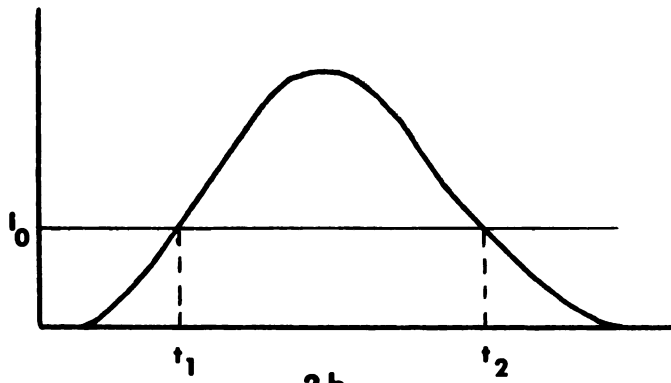


1b

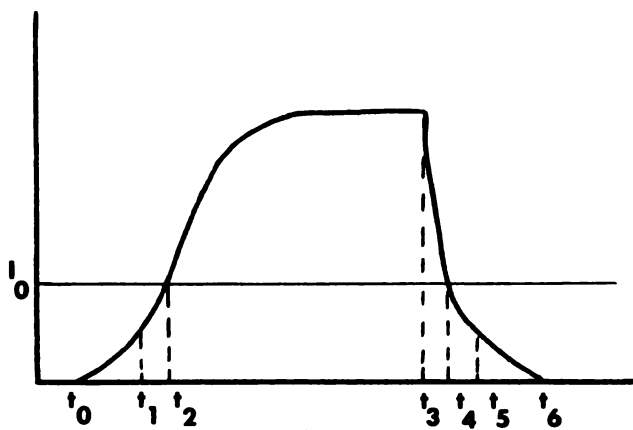
Figure 2. Various theoretical
and real I-t curves



2a



2b



2c

base, derived a method of choosing "t" values so that I_e was a maximum. The Douglas derivation is based upon a somewhat different integration of the light-pulse curve than that suggested by Blondel and Rey. They had conjectured that the area above the threshold line should be integrated, i.e., the total light flux above threshold should be taken (see Figure 1a). Douglas' method yields a value corresponding to total light flux in the pulse, from the zero-light condition to the peak of the pulse (see Figure 1b). Douglas does not offer any explanation for this difference.

Using the integral form of Blondel and Rey's work, Douglas shows that I_e will be a maximum when the integration limits t_1 and t_2 are the times when the instantaneous intensity, I , is equal to I_e . In actually calculating I_e , then, an investigator has to successively approximate the correct value. Douglas claims this in practice is not too difficult. He demonstrates the usefulness of the method in several practical problems. An advantage is that this method clears up any ambiguity about the integration limits.

Douglas and others caution the user of these equations that they apply only at threshold, and are only approximations at greater intensities. The usefulness of the equations is consequently limited. One must check

any results for supra-threshold ranges, or conditions varying from the dark background, dark-adapted subject conditions from which the original data were obtained. It is attempts to extend the equations to other cases which have caused most of the difficulty with the constants and integration limits. There would seem to be no objection to altering the constants and limits to fit a particular situation, if there were an adequate reason to do so, and the values were checked by experiments.

Conspicuity

To evaluate supra-threshold intensity, quite a different method was used by Gerathewohl (1951a). He used a reaction time measure to find what he terms conspicuity. This is defined in terms of a complex reaction time to flashing light signals. His method consists of placing a subject in front of a screen (of luminance 2.7 millilamberts) on which are displayed complex signals of luminance 3.6 to 5.7 millilamberts. These signals flash on at random intervals, and differ in color, flash rate, brightness, and position. The subject also has to respond to an auditory task. He utilizes foot-pedals and levers to signal his reactions to the various tasks. With this apparatus Gerathewohl measured reaction time to flashing stimuli and steady stimuli at different contrast levels.

He found:

...The response time decreases with increasing contrast, decreases with increasing flash frequency, and decreases with increasing flash duration. This effect is most pronounced with low-contrast, low-frequency signals; but it is not very consistent. (Gerathewohl, 1953, p. 27)

His fastest flash rate was four flashes per second, and his slowest was one in three seconds. In a later study, he recommended to the Air Force that the most conspicuous signal would be three flashes per second when the signal was at least twice as bright as the background. (Gerathewohl, 1954). However, in a similar study, and then a later replication of it, Dean (1962) was unable to duplicate these results, failing to reach the .05 significance level with similar reaction time data. He hypothesized that flash rate might not be a determinant of signal conspicuity when apparent brightness had been controlled by the Blondel-Rey formula.

Gerathewohl's results were not very clear-cut, which may be in part due to artifacts in his method. Gerathewohl stated that the timing circuits were such that if a subject missed a signal (did not respond) the time until the next signal was automatically added to his reaction time score. (Gerathewohl, 1951a and 1951b).

Depending on the situation for which one is using the data, this way of measuring time makes the time scores

too short or too long, or meaningless. If one is extrapolating to a situation where a flashing light, if not detected, simply goes out again, the times given by Gerathewohl are not meaningful. If one is interested in a situation where if there is no response to the flashing light, something drastic happens to get the operator's attention (for example, ignoring the "wheels up" light when landing an aircraft; if appropriate action is not taken, a horn sounds) then the time scores are too long. It would seem that a record of "misses" would be more useful than having the misses buried in the data by being recorded on a cumulative clock. The reaction time data may or may not have a practical significance. In a situation only slightly different from the one in which these times were derived, it is almost certain that they would change. In an instance in which a panel has more lights, or more compelling distracting stimuli, the reaction times would certainly differ. Whether or not the rank order of the different rates would be preserved is not known.

Erdmann (1962) has used a slightly different measure which raised the same questions as Gerathewohl's studies, but without involving the problem of reaction time. He set up a device which presented a one-second train of flashes of known waveshape (square) and frequency (1,

2, 3, 4, 5, 10, 15, and 20 flashes per second) against a background of known, controlled brightness. The dependent variable was the percentage of positive responses to the flashes. The subjects were warned that a series of flashes was about to be presented by a buzzer sounding before each flash train. There were only two subjects. He found that increasing flash luminance increased the probability of detection, as one would expect. He also found that for low background illuminances, probability of detection increased as flash frequency increased, up to about 20 flashes per second. For higher background luminance, 10 flashes per second was found to be the most detectable. Erdmann interpreted this in terms of the number of opportunities to make the detection, since the flashes were all the same, and explained a puzzling drop-off in detection at the higher frequencies as an effect of a period of diminishing sensitivity of the receptors due to the effect of the preceding flash train (see Figure 3).

Erdmann's experiment was better controlled, and used a more reasonable measure of the effectiveness of the lights. However, one would wish that Erdmann had used more than two subjects, for the plotted data are not completely regular, and not the same for both subjects.

The finding of a ten per second rate being most detectable meshes well with Bartley's (1935, 1958) findings that at this flash rate, what he calls "brightness enhancement" occurs. This is shown in Figure 4 (from Bartley, 1958) and is explained by Bartley in terms of the alternation of response theory. Note that the maximal brightness enhancement occurs at about ten flashes per second. Erdmann's finding for this frequency could, then, be due entirely to the greater apparent brightness of the stimuli, which made them of relatively higher contrast with the background than other flashes of different frequency.

Context of the Present Study

The above studies fail to give adequate answers to the questions they set out to explore. In addition to the difficulties of maintaining experimental control in situations similar to the practical situations in which flashing lights are used, their task was made more difficult by the need for further research on the basic visual processes involved. Such research requires a laboratory situation where relevant variables can be precisely controlled.

A doctoral thesis by Crumley (1964) satisfied these requirements. He gives a very good summary of the relevant

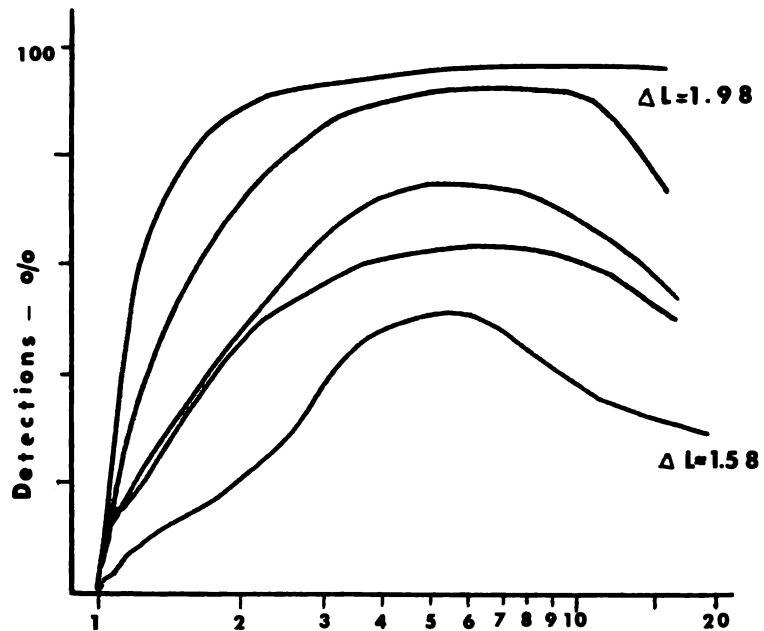


Figure 3. Sample plot of data from Landmann (1962)

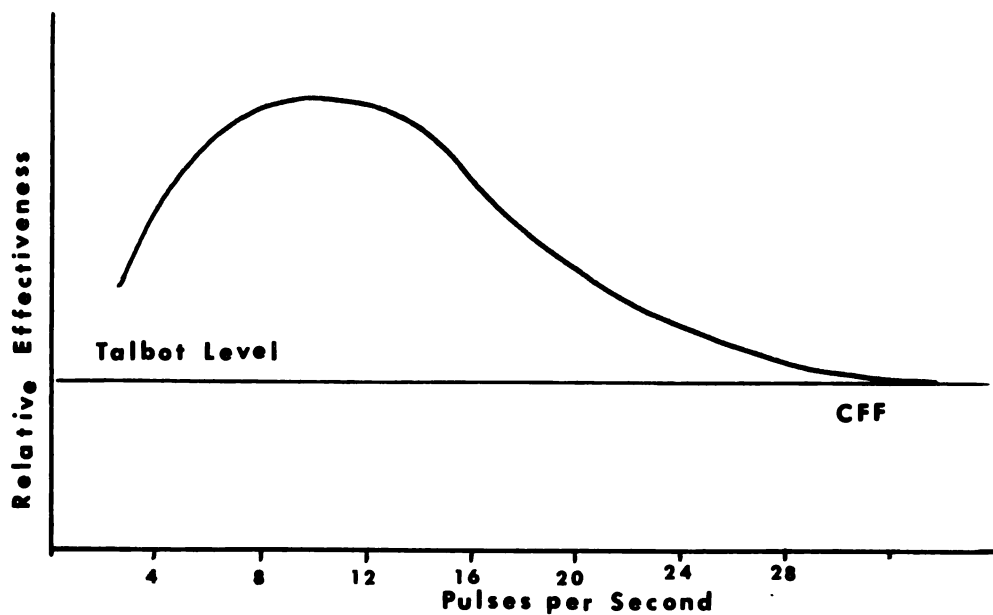


Figure 4. Curve showing brightness enhancement (the Bartley Effect)

literature on flashing lights, and outlines an area of research using the literature review as a base. His thesis research is a study of threshold under different conditions of flash rate and pulse cycle fraction. This study deserves to be examined in some detail. Crumley used small neon bulbs which gave an orange glow, and flashed them electronically at 4, 8, 12, and 16 flashes per second. A board holding the four lamps was placed about 45 feet from the subjects. Four different pulse-to-cycle fractions (Crumley calls them "duty cycles"; the meaning is the same) were used (20, 33, 66, and 90 percent) with each of the flash rates. Thresholds were measured for five subjects. Crumley showed significant (at the .01 level) effects due to flash rate, duration, subjects, practice, rate x PCF interaction, rate x subjects interaction, and one three-way interaction.

Many transformations and re-plottings of these data are done to make it more understandable and the main conclusions reached are: "Detection with the least light energy or maximum probability of detection for a given amount of light occurs when the energy is used to create a train of short, slow flashes." (Crumley, 1964, p. 134). In his summary, Crumley states: "The most effective use of light flux is to increase pulse brightness, next most effective is to increase pulse duration and the least

effective is to increase the number of pulses per unit time." (Crumley, 1964, p. 134)

This experiment was carefully and competently carried out. However, it would have been desirable if the author had offered equations to summarize his findings. Such equations might allow extension of his work in both directions on the flash rate scale. His four-per-second flash rate (the slowest in his experiment) is faster than the fastest flash rate found in conventional signalling applications. His data indicate that this four-per-second rate is the best of the ones tested. However, he makes no statements regarding the extension of his curves downward, in spite of the fact that almost all commercial flashing signals would be in this less-than-four-per-second region.

None of the equations described earlier provides a good fit to all of Crumley's data. The Blondel-Rey curve is shown in one of his figures, along with his data. A consistent difference between each of the flash rates and the predicted curve can be seen. Crumley makes little of this difference, and offers no model to explain the differences.

Further research is needed -- to extend the range of Crumley's data, to develop a more adequate mathematical treatment of the data, and to investigate further important

factors not included in his study. The research reported here takes the first step -- collection of data for flash rates below four cycles per second. Here again, the problems of wave-form, evaluation of supra-threshold intensities, attention value, and peripheral vision are ignored to concentrate on the more basic problem of foveal thresholds of detectability of square-wave pulses. The next phase beyond this study will be concerned with an adequate mathematical characterization of the basic threshold data of this study and others. Subsequent work on the effects of wave-form is planned.

The present study differs from that of Crumley in two respects in addition to the range of frequency investigated. He used neon tubes which gave an orange light discharge; and he used a dim, but not completely dark, room. This latter difference caused two differences in the state of the subjects. His subjects were not as completely dark-adapted, and their attention could wander to features of the room. The writer preferred to leave dark-adaption and color of light as variables to be investigated later, and chose to use white light and completely dark-adapted eyes.

The purpose of the experiment was to investigate the relation between flash rate and pulse-to-cycle fraction for flashes typical of those used in signalling and warning

applications. While the results are not expected to be directly applicable to signalling devices, they are intended as a first step toward providing a sound theoretical basis for application of results obtained in future research.

Two separate experiments were done: one, using a group of readily obtained subjects provided the main results; the other, done on a single trained subject, provided a check on the group experiment.

Chapter II

EXPERIMENTS

Experiment I: Method

Subjects

Twenty volunteer subjects from elementary psychology classes were used. These subjects were males and females, usually 18-19 years old. All had 20/20 vision, or were corrected to 20/20. If they normally wore glasses or contact lenses, they were asked to bring them to the experiment. One subject was replaced because as soon as the room lights were turned off preliminary to the experiment, he hallucinated too much to see the flashes. All other subjects were cooperative and reported little fatigue at the end of an hour of observation. Pilot work had shown, however, that the task became much too fatiguing after two hours.

Apparatus

The stimuli were provided by four Sylvania R1131-C Xenon glow tubes. Operating at the voltages used in the experiment (200 volts D.C.) these tubes give off a white

light, of essentially a square wave shape. Control of brightness was by a set of resistors switched in at the experimenter's control panel. The rate and pulse-to-cycle fraction (PCF) were varied by means of two multivibrator circuits, with switch selected resistors controlling the rate (for flash rate regulation) of one multivibrator and the hold time of the other (for PCF control).

It was decided to select PCF's so that the longer ones (75%, 85%) could be obtained by switching the inverse of the short ones (25%, 15%). The relay which was controlled by the multivibrator timing circuits was a single-pole, double-throw unit, so that the inverse of any on-off ratio could be obtained simply by switching to the other contact of the relay. A switch was provided on the experimenter's control panel to achieve this (see Figure 5).

Wiring the circuit so that each of the durations of pulse (hold times of the relay) for each PCF was given a different switch position on the experimenter's panel would have required 11 positions on the "duration" switch. This is too many to accurately handle rapidly in the dark. It was decided that some "on" times could be made to serve for several PCF and flash rate combinations, without great inaccuracies. By this means, the required

switch positions were cut down to seven. This resulted in some differences between the calculated pulse lengths, and the actual ones, for some flashes; but in all cases these differences were small, and near the limits of accuracy of the equipment. Actual and calculated on-times for pulses of each rate and PCF combination as measured by a Lafayette clock timer are shown in Table 1. See the block diagram, Figure 5, for equipment details.

TABLE 1
ACTUAL AND CALCULATED LENGTHS OF LIGHT PULSE,
AND LENGTH OF DARK PULSE OF FLASHES USED

PCF	Flash Rate, Flashes per Second				
		1	2	3	4
15%	Calculated on-time	.15	.075	.05	.038
	Actual on-time	.15	.075	.05	.05
	Actual off-time	.85	.452	.28	.20
25%	Calc. on-time	.25	.125	.082	.062
	Actl. on-time	.25	.125	.075	.062
	Actl. off-time	.75	.375	.258	.188
50%	Calc. on-time	.50	.250	.165	.125
	Actl. on-time	.50	.250	.150	.125
	Actl. off-time	.50	.250	.180	.125
75%	Calc. on-time	.750	.375	.248	.188
	Actl. on-time	.750	.375	.258	.188
	Actl. off-time	.250	.125	.075	.062
85%	Calc. on-time	.850	.425	.280	.212
	Actl. on-time	.850	.425	.280	.200
	Actl. off-time	.150	.075	.050	.050

The R1131-C glow tubes were mounted on a 1/4" masonite stimulus panel, as shown in Figures 6 and 6a. Neutral density filters were made from photographic film, exposed to give different sheets a uniform gray density.

Each sheet so prepared was cut up to give four identical neutral density filters, one for use in front of each of the four glow tubes (see Figure 6a). The filters were checked by use of a Pritchard photometer, to assure equal light output from each of the four stimuli on the panel, and to measure light output at each switch selected brightness level used. These light output figures for the two different combinations of filters at each of the stimulus levels used in the experiment are shown in Table 2.

TABLE 2

BRIGHTNESSES OF STIMULI, IN FOOTCANDLES,
MEASURED AT THE POSITION OF THE SUBJECT'S EYE

Filter 1 (high brightness)	Filter 2 (low brightness)
2.5×10^{-7}	1.28×10^{-8}
1.6×10^{-7}	7.8×10^{-9}
1.22×10^{-8}	5.6×10^{-9}
$.86 \times 10^{-8}$	4.2×10^{-9}
$.67 \times 10^{-8}$	3.3×10^{-9}

The pulses were directed to one of the R1131-C glow tubes by switches on the experimenter's panel. The intensity of the flash in five steps was also controlled by the experimenter from there, so that the psychophysical method of constant stimuli could be used.

The stimulus panel was placed thirty feet from the subject (see Figure 7). The distance of any stimulus

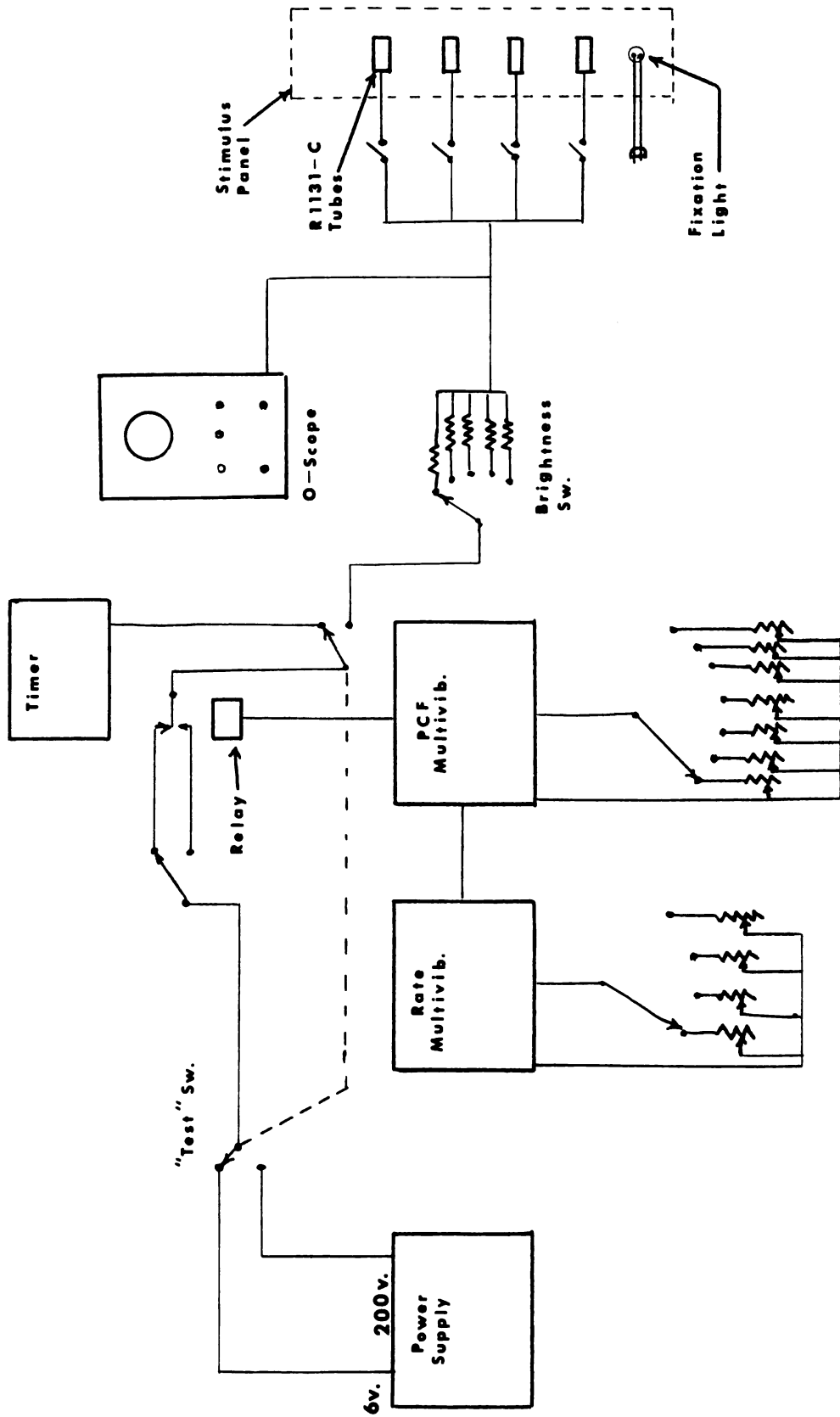
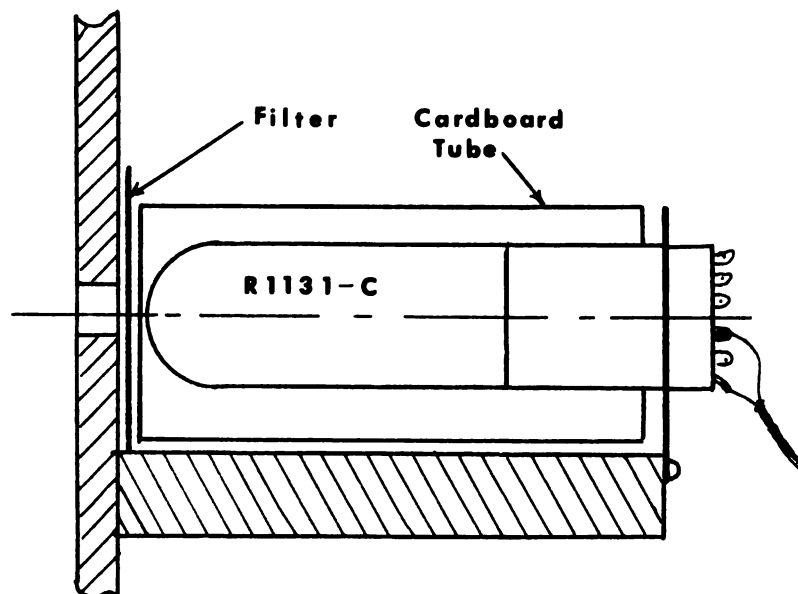
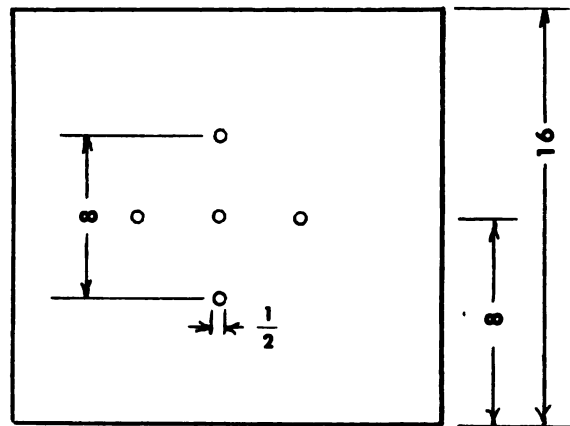


Figure 5. Apparatus block diagram

Figure 6. Stimulus panel



6a
Detail - Side View

tube from the red fixation light was such that foveal vision was used (38 minutes of arc), and the stimuli were point sources (45 minutes of arc).

A Tektronix Model 545 oscilloscope was connected to the leads of a Sylvania B2M sun battery placed in front of one of the stimulus tubes temporarily to verify that the tubes actually produced a square pulse. During the experiment a PACO Model S-50 oscilloscope monitored the pulses going to the tubes to provide a constant check on the duration and shape of the pulses. A Lafayette clock timer was used to provide initial measurement of the length of the time the pulses were on, when originally setting the resistors in the PCF multivibrator. The on-time was periodically checked for accuracy during the experiment by means of a "test" switch and the Lafayette clock on the experimenter's control panel.

The subject indicated which of the four lights he saw and when, by pushing one of four buttons on a control panel that was placed on a lapboard, which he held. This response lighted small neon bulbs on the experimenter's control panel, and the response was recorded. If no response was given to a stimulus, or if the subject indicated a stimulus in the wrong position, a "miss" was scored. Very few guesses (responses when no stimulus was presented) occurred, and so these were not recorded.

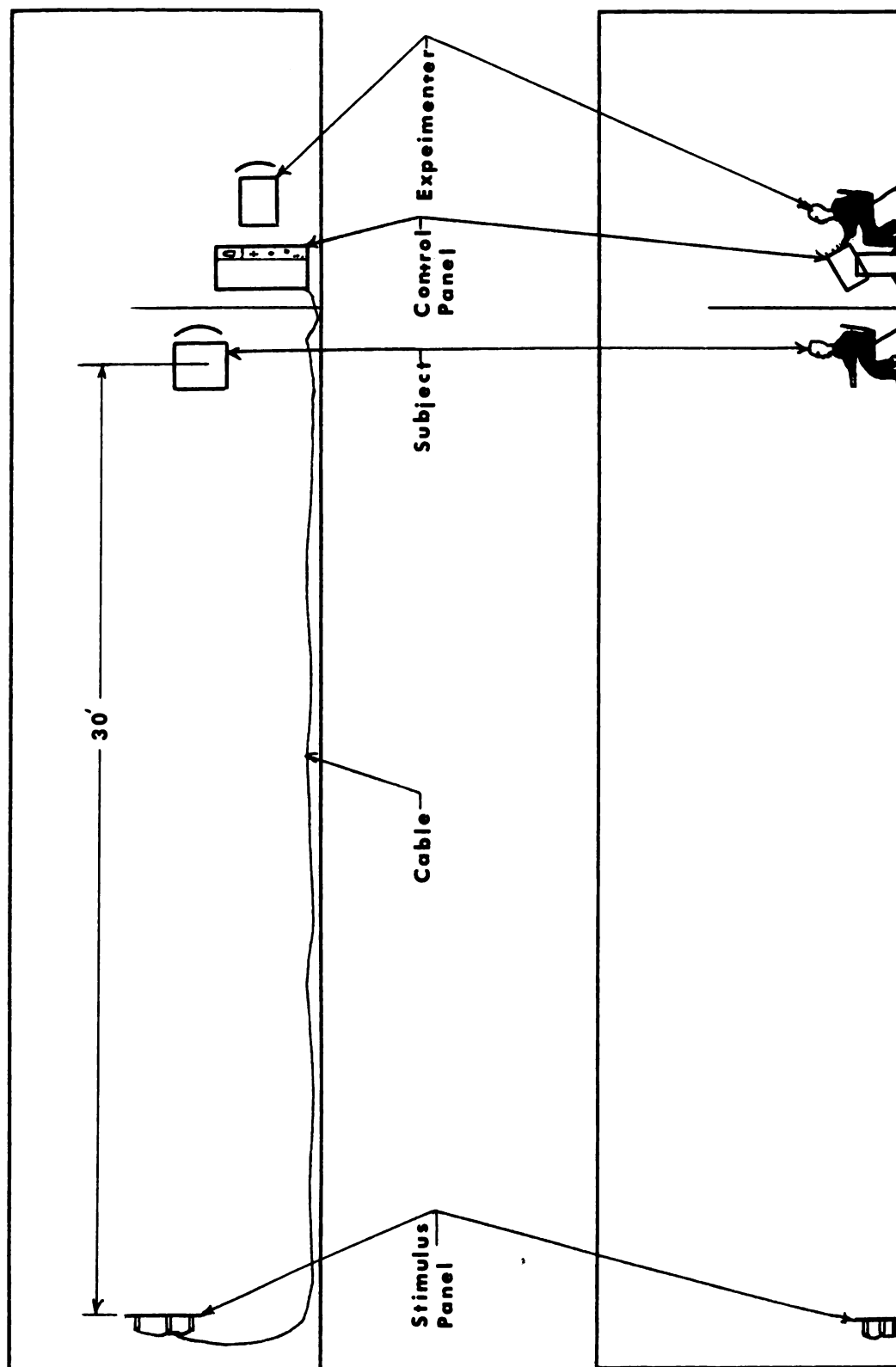


Figure 7.-- Plan of experimental room.

The particular combination of rate, PCF, and brightness was determined randomly for any given trial. A set of IBM cards was prepared with the switch position numbers for each desired combination of rate, brightness, and PCF written on them, along with a table for recording responses of all subjects. These cards, then, had all one hundred possible combinations of the variables (5 PCF's, 4 flash rates, and 5 stimulus levels) on them. After one complete run through all cards, the subject was told to relax for a couple of minutes, and the cards were shuffled. This gave a new random order for the next set of presentations.

Procedure

Subjects were led into the experimental room, seated, and allowed to dark-adapt for about 15 minutes under low illumination while they were given instructions and allowed to practice with their response panel. During this time they were instructed that they would see a dim red light in the middle of the panel visible at the end of the room. They were told to fixate on the red light, and that from time to time a white light would flash a little to the top, bottom, right, or left of the fixation light. When they saw this white light, they were to push the corresponding button on their panel.

Several practice trials were given, in absolute darkness, until it was clear that the subject was dark-adapted and knew what he was supposed to do. Then the experimenter began presenting stimuli, reading switch settings off the previously prepared and shuffled IBM cards. Subjects were given 40 presentations of different combinations of variables, then a short rest, followed by 40 more, until a total of 200 presentations had been given.

In other words, each subject saw two presentations of each combination of rate, PCF, and brightness. Clearly, this was not enough to establish a threshold for each subject. But to do so would have consumed several hours per subject, which was not possible. Instead, the threshold was calculated from the records of several subjects.

Experiment I: Results

The total number of positive responses out of a possible 20 were counted for each of the flash rate by PCF by brightness conditions, and these numbers converted to percentages (see Table 3). These percentage detections were plotted on logarithmic x probability paper, with "footcandles at the subject's eye" on the logarithmic axis, and the percentage detection on the probability axis (see Appendix A). Since no 0% or 100% points appear

TABLE 3
PERCENTAGE DETECTION OF STIMULI

Value of Stimulus	PCF	Flash Rate																				
		One per Second					Two per Second					Three per Second					Four per Second					
		15	25	50	75	85	15	25	50	75	85	15	25	50	75	85	15	25	50	75	85	
Filter 1		100	100	100	100	100	95	100				75	90	100				95	100	100		
2		85	100	95	100	100	75	95				60	70	65				55	60	90		
3		80	85	100	100	100	45	75				35	60	45				40	40	90		
4		45	60	85	95	85	0	70				0	45	20				20	30	35		
5		45	45	85	60	95	20	45				5	5	20				10	10	45		

Value of Stimulus		Flash Rate																			
		One per Second					Two per Second					Three per Second					Four per Second				
PCF		15	25	50	75	85	15	25	50	75	85	15	25	50	75	85	15	25	50	75	85
Filter #2	1	80	100	95	100	100	90	95	100	100	100	100	100	100	100	100	95	100	100	95	100
	2	45	75	80	95	95	55	80	95	100	75	95	90	70	85	95	70	85	95	70	85
	3	20	55	65	70	80	20	45	80	75	55	85	75	65	80	70	65	80	70	65	80
	4	15	10	50	50	65	5	20	50	60	20	50	50	25	55	40	25	55	40	25	55
	5	0	5	15	35	45	10	15	25	35	20	20	15	5	25	40	5	25	40	5	25

on probability paper, 1% and 99% were plotted for these values. Lines were fitted to the data points by eye, and 50% thresholds were found for each flash rate by PCF condition by simply reading off the number of footcandles corresponding to the point where the 50% detection line intersected with the curve fitted to the data points. The standard deviation associated with all thresholds was also gotten in a similar fashion, by reading the footcandle values associated with 16% and 84% detections, and subtracting to give two standard deviations (Guilford, 1954). These thresholds and standard deviations are recorded in Table 4.

TABLE 4
THRESHOLDS AND STANDARD DEVIATIONS
FOR PULSE COMBINATIONS TESTED
(ALL VALUES $\times 10^{-7}$ FOOTCANDLES)

PCF	Flash Rate							
	<u>One/Sec.</u>		<u>Two/Sec.</u>		<u>Three/Sec.</u>		<u>Four/Sec.</u>	
	Thresh- old	s.d.	Thresh- old	s.d.	Thresh- old	s.d.	Thresh- old	s.d.
15%	.080	.04	.14	.056	.17	.088	.15	.096
25%	.058	.019	.08	.036	.12	.055	.12	.051
50%	.051	.024	.57	.027	.054	.023	.061	.030
75%	.040	.021	.044	.016	.047	.020	.042	.021
85%	.032	.017	.042	.015	.038	.018	.042	.017

Several methods of plotting the data were utilized in order to make clear the kinds of effects shown. First, Figure 8 shows the group threshold as a function of flash rate, for each PCF. Major effects in the data are shown clearly. The 50% PCF can be seen to be nearly a straight line, indicating little difference in threshold for this PCF for different flash rates. The 75% and 85% PCF's can be seen to differ very little from each other. Although this graph shows gross effects of both variables, it does not illustrate the nature of these effects very well.

Figure 9 shows threshold as a function of flash duration, which is consistent with the assumption, common to all the mathematical formulations reviewed earlier, that threshold is a simple function of flash duration. Two theoretical curves are also shown in Figure 9. The first, labeled $I_{xt} = \text{Constant}$, appears to fit the main trend of the data for short pulses up to .2 seconds, which is congruent with the Bunsen-Roscoe Law (Bartley, 1958). The second theoretical curve is that of Blondel and Rey, fitted to our data by his method. Examination of the data points suggests that a separate curve should be used for each flash rate. However, this plot of the data does not permit such an effect to be clearly shown.

Figure 10 compares our data to the Blondel and Rey

equations in a more straightforward manner. The abscissa on this graph was derived from the Blondel and Rey equation. In their paper, they calculated a table of the ratios of $\frac{E}{E_0}$ for a range of flash durations from .01 to 3 seconds. The resulting numbers are "effective intensities" of the flashing lights with these pulse lengths. The effective intensity number is the factor by which the brightness must be increased to make the flashing source as bright as a steady one. If these equations hold true regardless of flash rate, all thresholds should fall on the same straight line.

As can be seen, the points seem to fit a straight line for each of the four flash rates. With the exception of the one per second points, these straight lines fit fairly well. This would tend to indicate that the Blondel-Rey equation needs some modification, as changing the value of their constant "a" will not cause these points to fall into a single straight line.

The three-dimensional graph, Figure 11, is another aid to visualizing the results. The light-pulse time forms one axis, and the length of time of the dark pulse forms the other axis, with threshold plotted on the remaining one. This way of treating multiple flash data would seem to be more meaningful than the previous ones. The length of time that the visual system has to recover

between flashes is an integral part of this graph. Note that the one per second flashes provide the points which form the front of the surface, and the four per second ones provide the back. The three per second, 15% flash is the highest in the solid (most difficult to detect) although not significantly different from the four per second, 15% flashes. The flashes rapidly become more easily detected, finally tapering down at the longer (75%) PCF's to approximately the same value for all flash rates.

The most striking effects shown in the data are due to the length of the pulses. This variable clearly has a major effect, across flash rates. The rank-order correlation coefficient between the rank ordering of pulse lengths and thresholds is .9 (smallest threshold goes with longest pulse) for the sixteen different pulse lengths used. However, this way of presenting the data again suggests that the flash rate does affect thresholds. It also makes clear that the present data are inadequate to reveal the nature of the effect of flash rate.

Experiment II: Method

A single subject who had had considerable experience in psychophysical studies was used in order to check the results of the group experiment against thresholds obtained

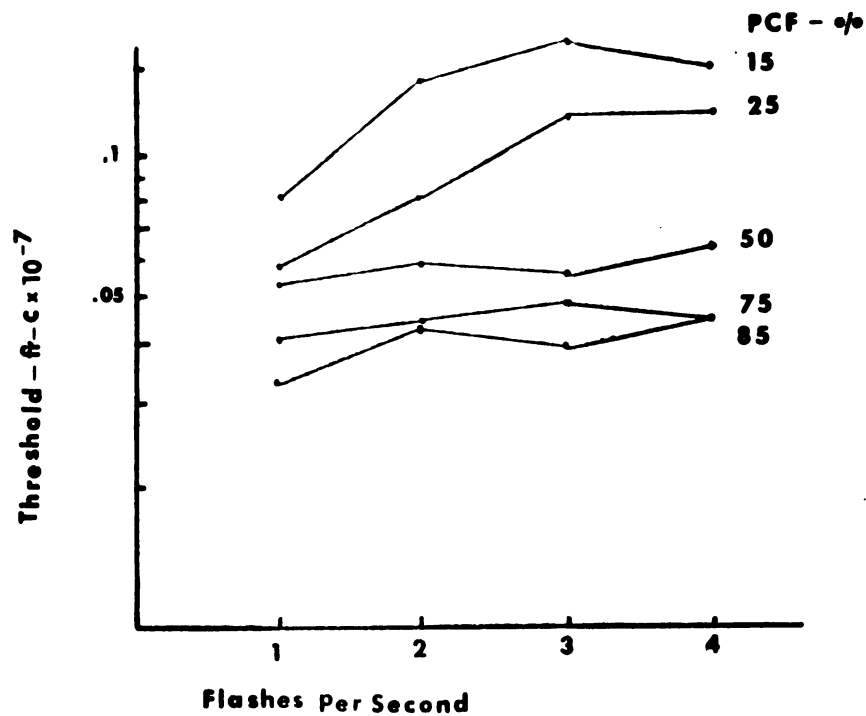


Figure 8.--Thresholds versus flash rate, for different PCFs.

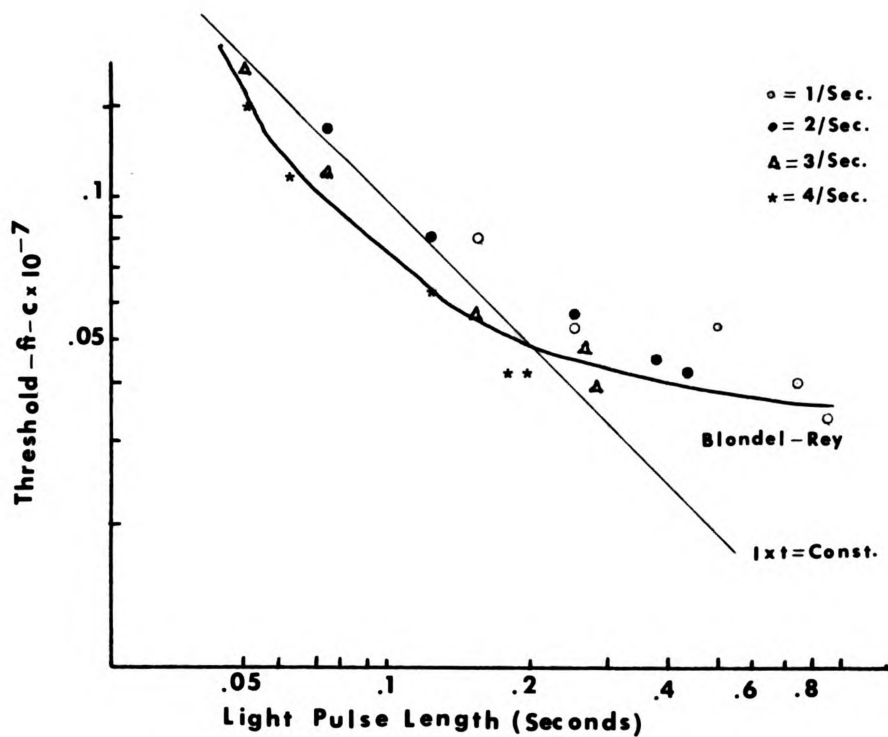


Figure 9.--Thresholds versus length of light pulses, with various theoretical curves.

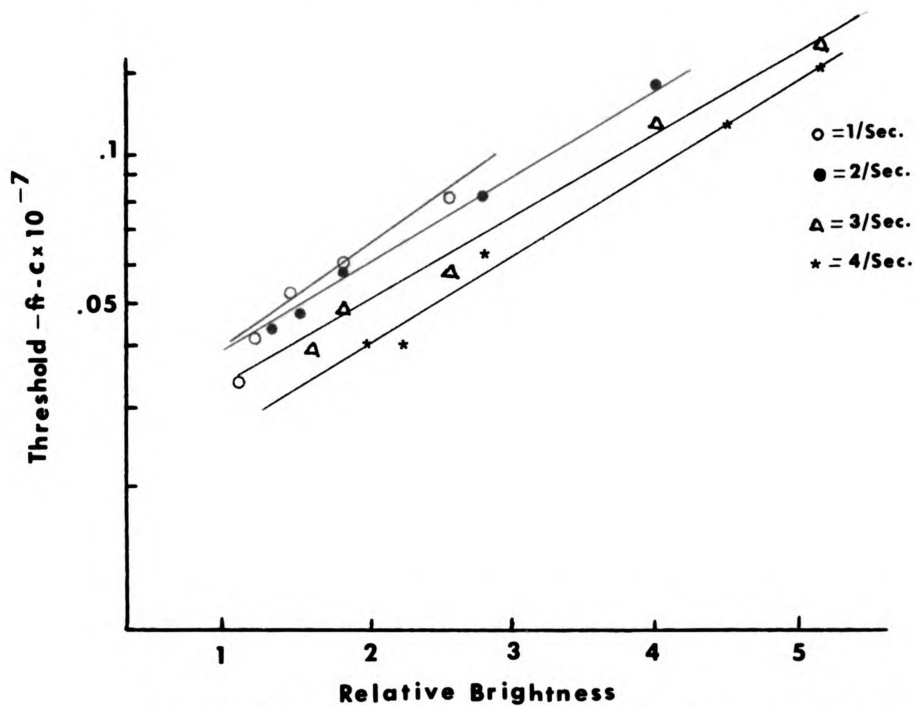


Figure 10-- Blondel-Rey "relative brightness" numbers (derived from light pulse times) against obtained threshold.

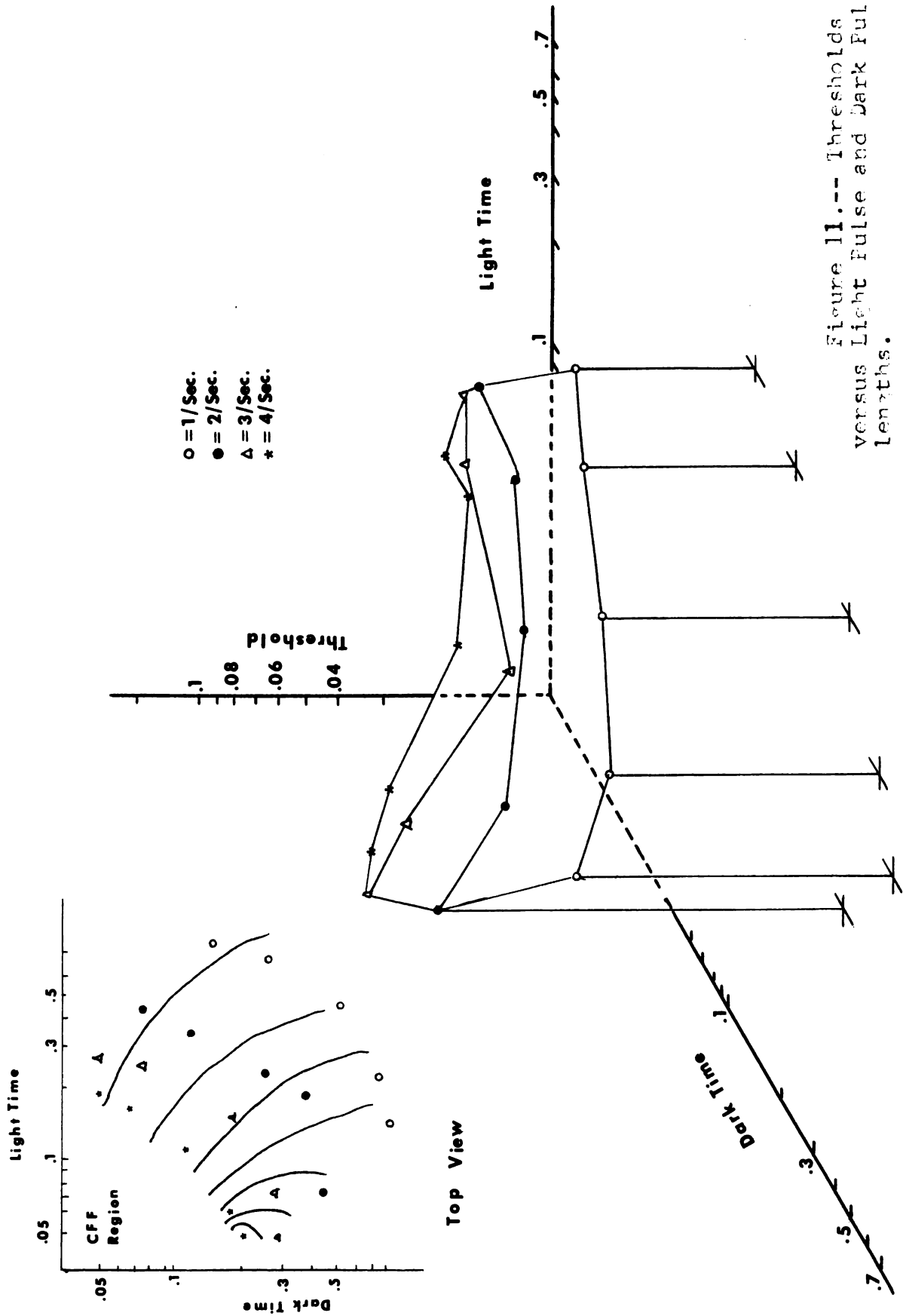


Figure 11.-- Thresholds versus Light Pulse and Dark Pulse lengths.

in the more conventional manner. The same apparatus was used as in Experiment I. However, the Method of Limits was considered to be more appropriate and quicker for use with this trained subject. The procedure was only slightly different from that of Experiment I. After the subject had become dark-adapted, a combination of rate and PCF was picked, and the brightness of one of the four stimulus tubes brought up until the subject reported seeing it. Then the brightness was re-set to a low value, and again increased. The thresholds were recorded each time, and after ten thresholds had been determined, a new combination of rate and PCF was set, and the entire procedure repeated.

Experiment II: Results

The results are shown in Figures 12 and 13. These are comparable to Figures 8 and 10 of Experiment I. The thresholds for this subject are in almost all cases slightly higher than those for the group; but this could be due to some of the differences in the methods, or characteristics of the single subject. Note that the trends for the curves are roughly the same as for the group data.

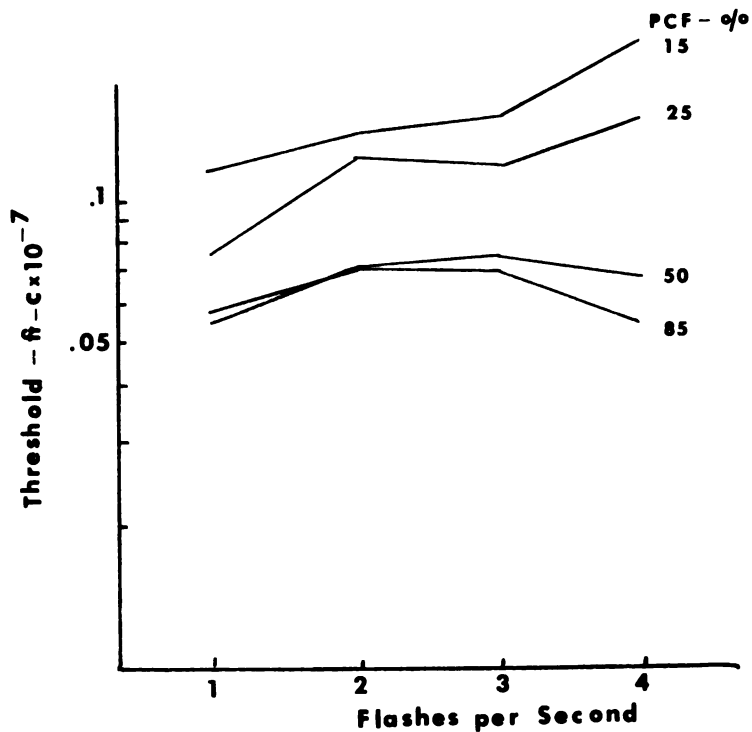


Figure 12.--Thresholds versus flash rate for a single subject (Experiment II).

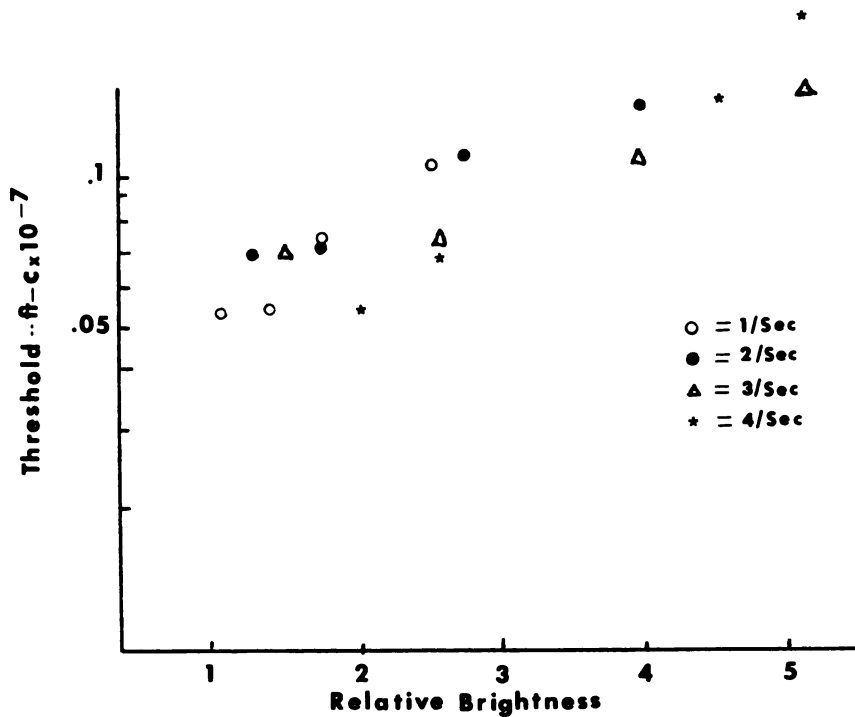


Figure 13.--Blondel-Rey "relative brightness" numbers versus obtained thresholds for a single subject (Experiment II).

Chapter III

DISCUSSION

The data collected here agree with previous findings in the sense that they showed that the thresholds of flashing lights can be predicted with fair accuracy from knowledge of pulse length alone, but that deviations from predictions appear to be related systematically to flash rate. Unfortunately, they are also similar to previous data in that they do not show very clearly the nature of the relation.

The findings shown in Figure 11 appear to be simply downward extensions of the findings of Crumley's study. There, it was clear that the slowest flash rate he used (four per second) had the lowest thresholds, and that in addition the longer PCF's were more visible at any of the flash rates. Here, the same four per second rate was worst, relative to the even slower ones.

The graph of Blondel-Rey values for the flashes used, plotted against the obtained thresholds (Figure 10) most clearly implies that the Blondel-Rey equation does in fact need to be modified. The points do not fall onto a single straight line, nor did they for Crumley, as they properly should if the Blondel-Rey equation held exactly.

Rather, they seem to fall into four lines, one for each flash rate. Simply juggling the value of the constant "a" in the Blondel-Rey equation does not bring these lines together. This would imply that either "a" is a more complex function of flash rate, or that it is a function of some other variable entirely. Again, this is approximately what Crumley found for his faster flashes, and any mathematical model of this relation should handle the data from both experiments.

Two conclusions about the type of research needed can be made. First, threshold determinations of great accuracy are needed. It was noted that the rank-order correlation between threshold and pulse length was .9. The remaining variance is small, and in our data the deviations related to cycle time were not much larger than their error of measurement. Further research will require a large number of experimental sessions with a single observer, followed up by replication on other observers.

Secondly, it seems clear that the manner of data collection should be changed. Rather than using several levels of flash rate combined with several levels of PCF, future work should use levels of flash length combined with levels of time between flashes. In addition to obtaining comparable ranges of each of these variables

with each other, the data will be more readily interpretable in terms of light time and dark time, which appear now to be more relevant variables than flash rate and PCF. This would result in strange flash rates and PCF's; but the results obtained would be much more easily described mathematically.

Another phase of future investigations will be the examination of some of the minor, but suggestive, points revealed in the present study. The lines used to derive the threshold (Appendix A) appear to have different slopes varying with the PCF. This slope is composed of two components: the variance due to individual differences, and the difference due to the differential detection probabilities at the different brightnesses. The problem to be investigated, then, is to determine how much of this variance is due to the contribution of individuals. This can be easily done by obtaining thresholds with the method of constant stimuli in the conventional manner for two or three subjects, and comparing the results with the group data.

Use of the "group threshold" is an unusual procedure. The interpretation of the group threshold is quite simple: the point at which the sum of a group of people's individual detections reaches 50%. In the present instance, it was used because of the kinds of subjects which were available. It was not possible to pay subjects to take

part in the experiment for a long period of time, as the usual methods would require. However, large numbers of elementary psychology students were available, but could not be used more than 1-2 hours each. It was decided to use these subjects, but the second experiment was planned to check the results obtained.

While many observations of one or two subjects has been the usual way of doing threshold studies in the past, there seems to be no necessity for proceeding in this fashion. Blondel and Rey proceeded in a somewhat different manner when they took the relative brightness number they obtained for each of their subjects and averaged it with all other subjects. How many observations were required to get the individual number for each subject is not specified. These numbers are not very stable from observer to observer, so perhaps each number does not have great precision. In any case, Blondel and Rey simply took the geometric mean of all these observations, and used these means in deriving their law. This is very little different from the procedure followed in this study. The individual values of threshold could be estimated, but this would lead to much inaccuracy without at least four times the number of measurements made on each subject. This was impossible with our subjects. The group thresholds, however,

are fairly stable for the smaller number of observations.

Experiment II was planned as a check of the validity of this kind of threshold. The one volunteer subject in Experiment II provided thresholds which by normal standards of psychophysical measurement would be considered fairly accurate. The number of separate thresholds (10), obtained for each combination of PCF and rate would normally be more than sufficient to fit curves to. However, Figure 13 shows that while this subject demonstrates the same general trend as shown in Figure 10, the points are more irregular; straight lines do not fit as well.

A clue to this discrepancy is found in the previously-mentioned rank-order correlation coefficient. With a correlation of .9 between pulse length and threshold, little variance is left to be accounted for by other factors, such as flash rate. This implies that unusual precision will be required in future measurements trying to investigate this question. It appears from Figures 10 and 13 that there is a systematic difference between the Blondel-Rey values and the obtained thresholds; but until measurements with greater precision are obtained, no well-founded hypothesis can be offered as to what this might be due to.

A word of caution is necessary to anyone planning to

use the results of any of these studies of flashing lights: the variable of attention value needs much more careful work before it can be specified with any rigor. It has sometimes appeared in studies in an uncontrolled fashion (Neelans, Laufer and Schaub) or been left out entirely (Blondel and Rey, the present study). Even when the attention value variable has been studied (Gerathewohl) it has not been defined well, nor has it been made clear how one should modify the findings when applying them to different situations.

This accounts for some of the differences between the findings of this study and Gerathewohl's. Our finding that three per second was the least visible should not be compared to his finding it as worst, since for his situation that rate may have been most different from the background. With other distracting stimuli, other results might be obtained.

It was decided that for this study, a condition of "no distracting visual stimuli" would be used to prevent any contamination by this undefined variable of attention value. Hopefully, it will be possible in the future to use the present apparatus and methods to further investigate attention value. The findings of the present study will in that case serve as a base-line condition of zero-distraction, since it was run in an absolutely

dark room, i.e., with no distracting visual stimuli present. Until further work is done, the present study, coupled with the findings of Crumley, could be used as a first approximation to the effectiveness of a flashing light. As the stimulus field becomes more complex, and more flashing or steady distracting stimuli enter the subject's field of view, the results should be applied with more and more reservations about their accuracy.

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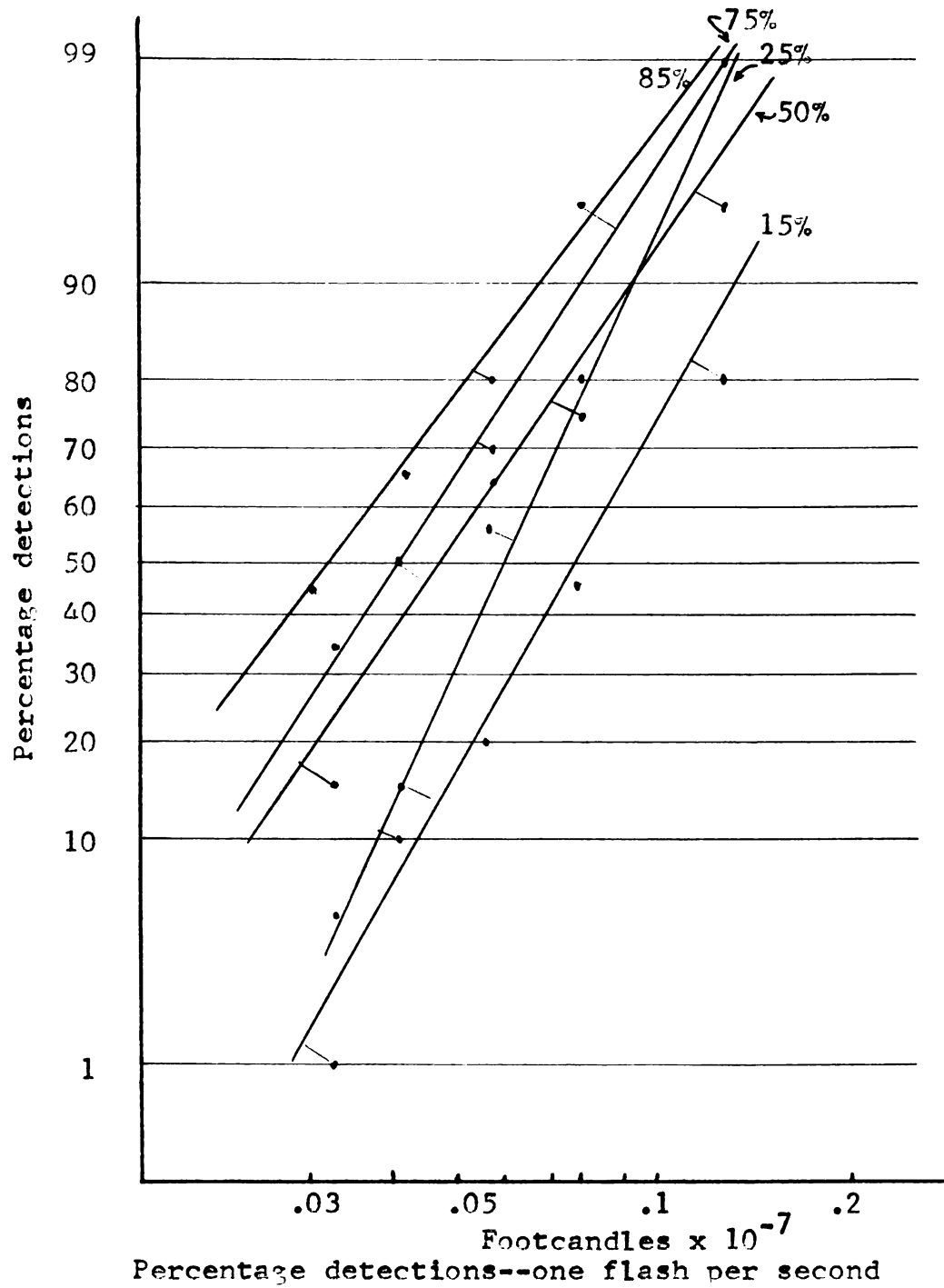
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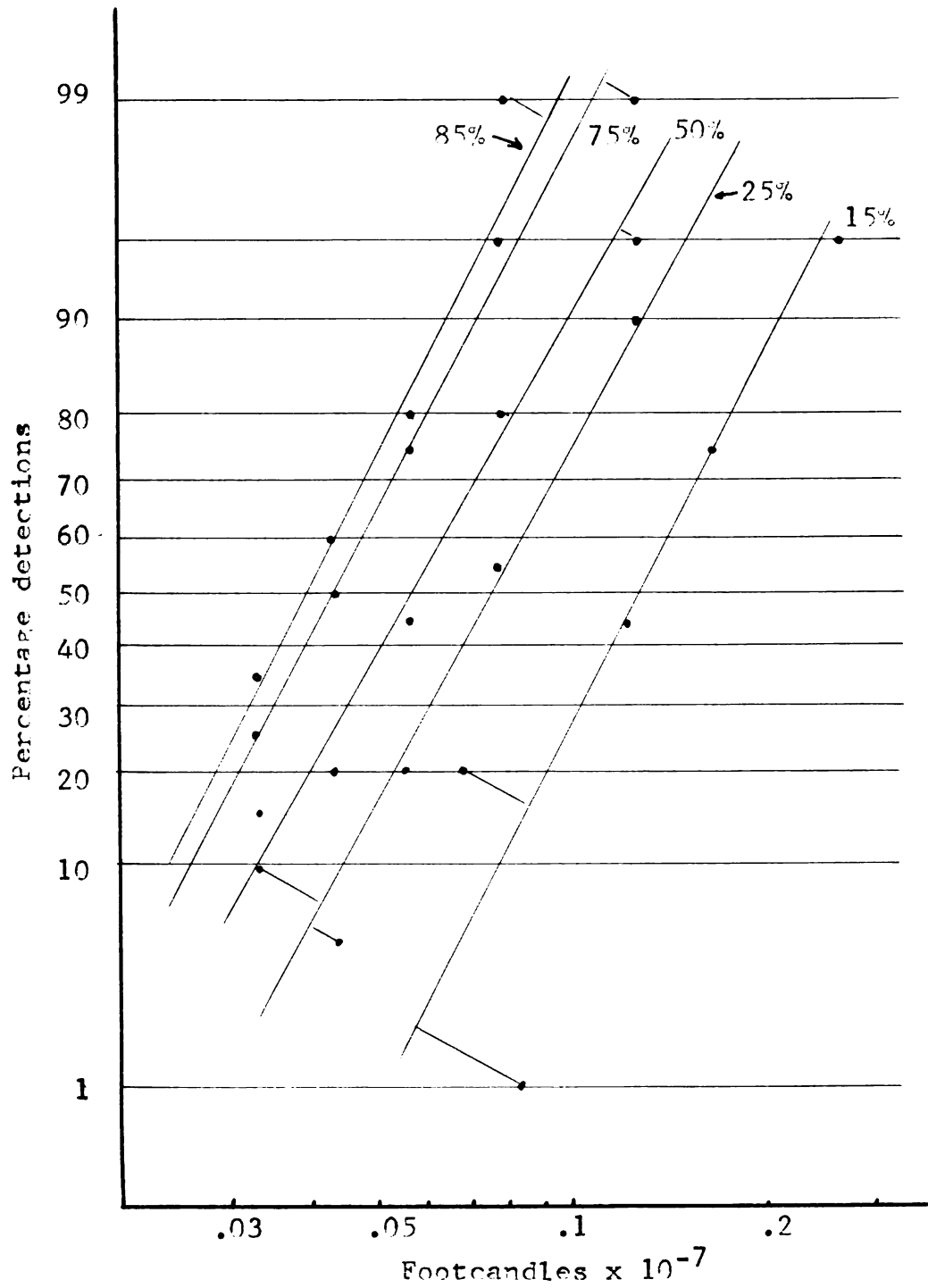
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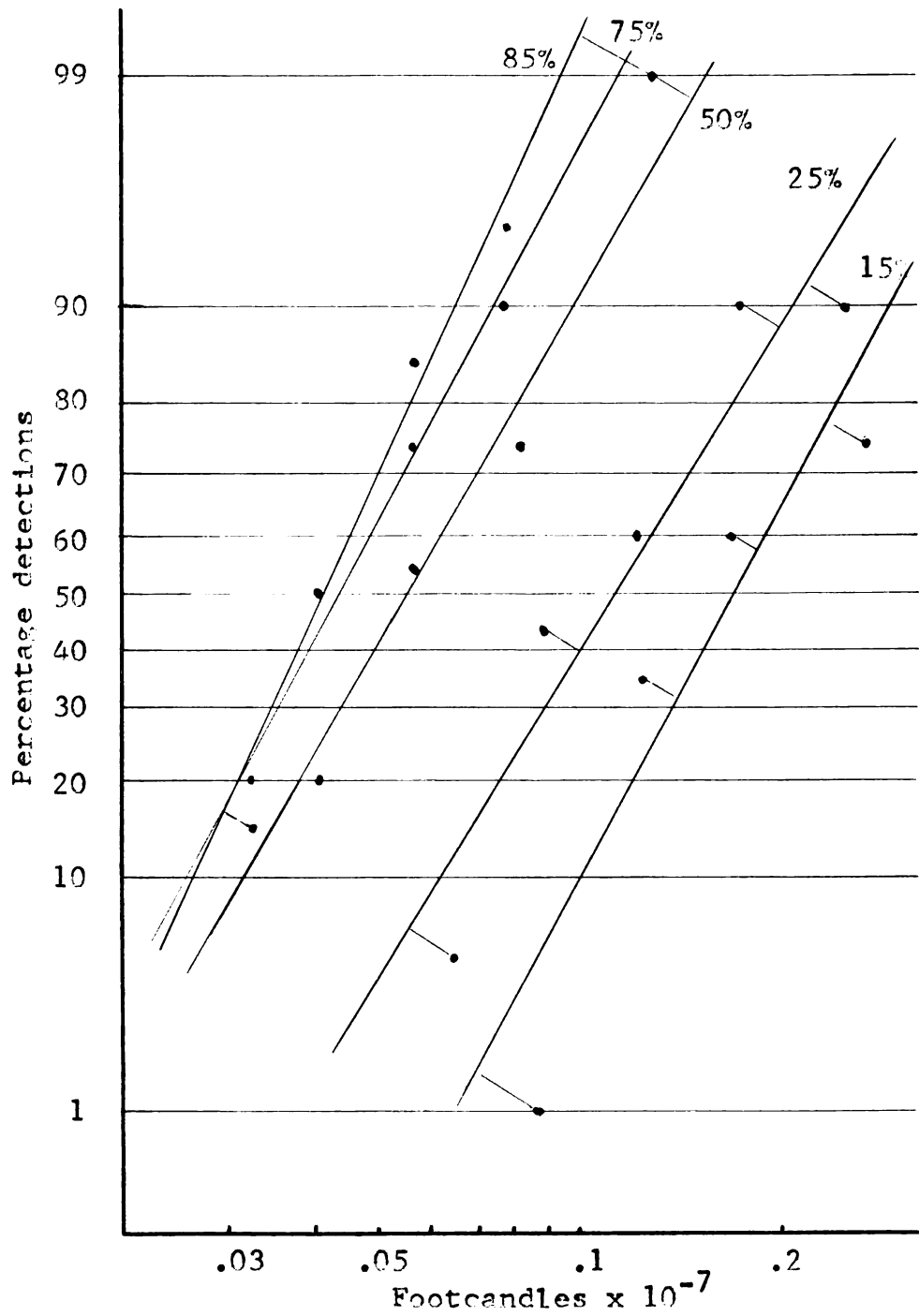
APPENDIX A

PERCENTAGE DETECTION CURVES - EXPERIMENT I

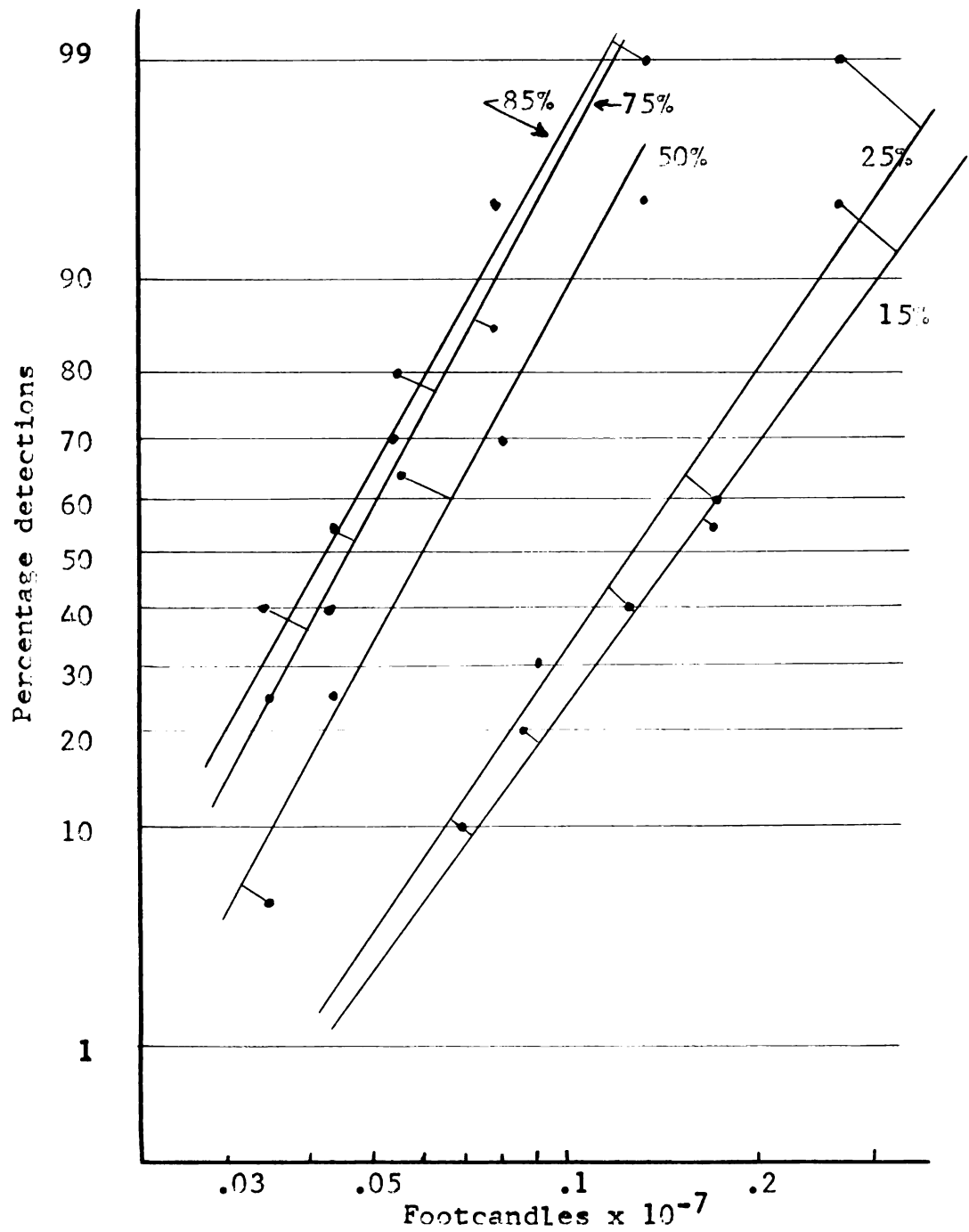




Percentage detections--two flashes per second



Percentage detections--three flashes per second



Percentage detections--four flashes per second

APPENDIX B

SINGLE SUBJECT THRESHOLDS - EXPERIMENT II

APPENDIX B

SINGLE SUBJECT THRESHOLDS -- EXPERIMENT II

PCF	Flash Rate			
	1	2	3	4
15	.116	.143	.153	.23
25	.073	.12	.128	.122
50	.053	.07	.072	.068
85	.054	.07	.069	.052

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