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Visual Recovery from Brief Exposures to Very High Luminance Levels,

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USAF School of Aerospace Medicine
Aerospace Medical Division (AFSC)
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Prepared under Contract No. AF 33(657)-9229,
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FOREWORD

This study was initiated by the USAF School of Aerospace Medicine, Aerospace Medical Division, Brooks Air Force Base, Texas. The research was conducted by The Ohio State University Research Foundation, Columbus, Ohio, under Contract No. AF 33(657)-9229, with Dr. Glenn A. Fry of the School of Optometry, as supervisor and Norma D. Miller of the School of Optometry, as principal investigator.

This report is cataloged by The Ohio State University Research Foundation as Technical Documentary Report No. 1.

ABSTRACT *legible*

The design and calibration of the apparatus for delivering brief, high intensity flashes from a xenon-filled flash tube are described. A maximum field luminance of 4.6×10^5 lamberts was provided by the flash tube seen by Maxwellian view. A rotating mirror was synchronized with the flash tube discharge to produce exposure durations from 42 μ sec to 1.4 msec. Field sizes could be varied from a point source to 10° , and an adapting field optical system allowed the subject to be preadapted to various luminance levels before the flash was received.

The criterion measure for recovery times following the flash was the correct identification of Sloan-Snellen test letters. Five different letter sizes were provided subtending visual angles from 41.9 to 10.2 minutes of arc.

Some data are reported for five exposure durations of the flash and for five field sizes for the 20.3 minutes of arc test letter at a luminance of 0.066 mL.

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VISUAL RECOVERY FROM BRIEF EXPOSURES TO VERY HIGH LUMINANCE LEVELS

I. INTRODUCTION

The problem of visual recovery following exposures to higher luminance levels is essentially a problem of readaptation to the original scene illuminance, or to the conditions that had been provided for the performance of a given task. In the present study, the task of interest was that of detecting the critical information from airplane instrument panels under normal conditions of illumination for such instruments. Several previous studies pertinent to this problem have dealt with various types of temporary high luminance fields and their effect on the subsequent period of readaptation. Russell¹ used a black silhouette of an airplane against various background luminances to determine recovery times following a flash of 2° visual angle. Both the duration and luminance of the flash were varied and he concluded that the time of recovery depends approximately on the product of flash duration and flash luminance. He also found that the time of recovery reaches a maximum when this product is about 3.4×10^2 Lambert seconds. His highest field luminance was 1.7×10^3 L and his shortest exposure was 5 msec with the longest 10 sec.

Fry and Alpern² tested the effect of flashes varying from 1 msec to 3 sec on the periphery, 5° from the fovea. They also found that the recovery time to a given level of peripheral acuity depended on the product of flash luminance and duration within the range tested. The maximum luminance was 14.7 L.

Metcalf and Horn³ performed an exhaustive study of the effect of varying the luminance of a 3.8° flash, presented for 0.1 sec, on the recovery time necessary to detect a 17-min-of-arc test stimulus, presented at several luminance levels comparable to those found in instrument panels. They found a linear relationship between the log flash luminance and the recovery time. Their maximum flash luminance was 8×10^3 L.

The present study was undertaken to determine the effect on recovery times of varying the duration of the exposure of a high luminance field. The maximum flash luminance was 4.6×10^5 L and the maximum duration 1.4 msec. The effect of duration is a matter of interest in the design of protective devices, for pilots subjected to high luminance exposures, to determine if there is a point of diminishing return in shortening the interval between the onset of the flash and the operation of the protective devices. If there is a perfect reciprocity relationship between the duration of a flash and the luminance, that is, if the total energy received in a brief flash is the sole determining factor in the effect of that flash on recovery time, then the higher the luminance anticipated, the shorter must be the time required for the protective device to become fully effective. If, however, the reciprocity relationship breaks down and there is a reduced

effectiveness of the flash energy at short exposures, then the requirements for the protective devices would be less stringent.

Subjectively, the effect of a high luminance flash is to produce an afterimage the size and shape of the flash field, which is perceived as a bright area if the observer looks at a normally illuminated or dark surface. Any detail that could be detected prior to the flash is usually lost against this bright area for a short period following the exposure. The elapsed time between the flash exposure and the observer's ability to again distinguish the pertinent detail is a measure of the recovery time or readaptation time resulting from the disturbance. This is not the same as the time required to completely lose the afterimage and regain the former level of adaptation but is related to it and is shorter. The observer feels that he is "looking through" the afterimage to distinguish the required detail. The reason for this effect is that under normal conditions of illumination we are operating at suprathreshold values of detection and recognition and the criterion measure in this and in the previous studies used threshold values. In the practical application of a study such as this, the threshold value is the important one because it is necessary to know how quickly a pilot can glean the essential information from his instruments following a flash, even though he may still be experiencing the veiling effect of the bright afterimage.

One complication, arising from this experimental procedure of using a detection or recognition threshold for determining recovery time, could lead to errors in the application of the data. The afterimage following a very high luminance flash goes through positive and negative phases in which the afterimage is seen alternately brighter than and darker than a uniform background of low luminance. It is sometimes possible to detect the test stimulus, even with intermittent presentation, during one of the negative phases and then lose it again for some time during the subsequent positive phase. It is hoped that some additional work can be performed during the course of this study to determine the magnitude of this possible error in the analysis and application of the results.

II. SCOPE OF THE PRESENT STUDY

The present study was designed to investigate a number of variables of flash presentation that might affect the recovery time. The flash exposure times were varied from 42 μ sec to 1,400 μ sec. Provision was made to present the flashes in five field sizes from a point source (approximately 20 min of arc) to 10° . The intermediate steps were 7.5° , 5.0° , and 2.5° . Four levels of adaptation prior to the flash were tested, ranging from three minutes in a dark room to adaptation to a 10° field of 1.83 L. Five letter sizes were used for the targets for measuring recovery times covering the range of numerals and letters used in instrument panels. The apparatus for

presenting the test letters was designed to vary the letter luminances from values comparable to those found in present instrument panels up to values that could be obtained by floodlighting the instruments.

The experimental plan of the study was developed so that a statistical analysis of the data could be performed to indicate any interactions between the variables. Either five or six subjects performed each of the experiments as an aid in making the results more generally applicable. The group of subjects consisted of five men and one woman all in their early twenties.

A recording infrared pupillograph was constructed to measure the pupil diameters following the brief flashes. There are good data available on the pupil reflex following flashes of one msec or longer but the range of exposure times needed to be extended toward shorter durations.

III. APPARATUS

The individual components will be described in detail in the following subsections, but the arrangement of the various elements is shown in the schematic drawing in Fig. 1. The optical system consisted of four main elements: (1) the flash source exposure branch, (2) the optical train containing the field stop for the flash exposure and providing the Maxwellian view of the flash, (3) the adapting field system, and (4) the optics for viewing the stimulus letters.

A uniformly bright segment of the xenon flash tube, S_1 , was focused on the entrance aperture, A_1 , by a short focal length lens at sufficient magnification to fill the aperture. The light was collimated by a large lens, L_1 , then reflected from the rotating mirror, M_1 , through the lens, L_2 , mounted in a panel set in a door frame between two rooms. This arrangement prevented the ambient light from the source room from reaching the subject's area, and passed only that portion of the flash occurring when the mirror had rotated into the correct position relative to the second lens. The combination of L_1 and L_2 formed an image of the entrance slit at a 2.4:1 reduction in the plane of the aperture, A_2 . The rotating mirror swept the image across this aperture so that the length of the aperture and the speed of rotation of the mirror controlled the pulse shape and duration of the flash.

The mirror, M_2 , reflected the light from A_2 through the achromat, L_3 , which again collimated the beam for passage through the field stop, A_3 , which was at the focal point of the second achromat, L_4 . This arrangement permitted the subject to view the field stop with relaxed accommodation and focused the aperture, A_2 , at a 1:1 magnification in the plane of his pupil, providing a Maxwellian view system. The subject's head was held in position by a forehead rest and a bite plate which could be adjusted to align the head relative to the optical axis of the system.

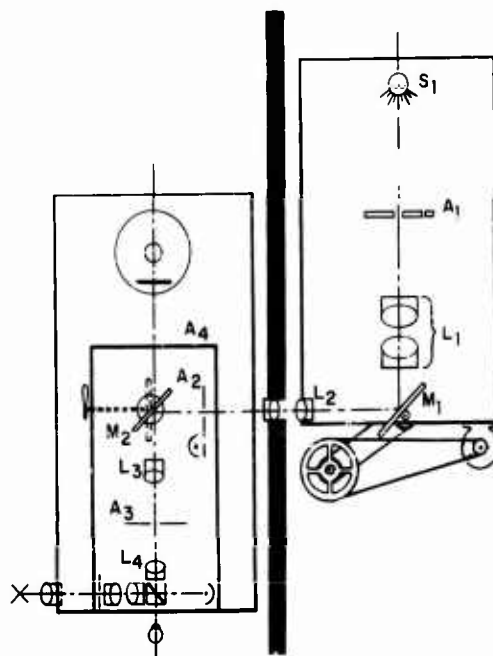


FIG. 1. SCHEMATIC OF OPTICAL SYSTEM

A beam splitter was mounted between the last achromat and the subject so a portion of the beam was diverted to be reflected by mirror, M_3 , into a phototube for monitoring each flash. The same beam splitter was used to reflect light from a controlled ribbon filament lamp, after passage through an auxiliary optical system, to provide a 10° adapting field of variable luminance.

The mirror, M_2 , was pivoted so it could be swung out of the beam immediately after the flash for the presentation of the stimulus letters through the lenses, L_3 and L_4 . A magnified image of a ribbon filament lamp was focused in the plane of the letter which was the transparent portion of a high density film. The achromat, L_3 , focused the letter at a 2:1 reduction in the plane of the field stop, A_3 , to be seen by the subject at infinity as a bright letter on a dark surround. An aperture, A_4 , 9 mm in diameter, was filled with light from the ribbon filament and was conjugate to the subject's pupil so the natural pupil operated to control the retinal illuminance of the letters.

A. FLASH SOURCE

A xenon flash tube was chosen for the source for the high luminance exposures because of the high intrinsic brightness and relative stability of such sources. With suitable condenser banks the peak luminance of the tubes can be extended to several milliseconds before decaying exponentially. The particular model chosen for this study was an EGG Sun-Flash unit rated at 10,000 watt-seconds. The time characteristics of the flash are shown in Fig. 2 which is a reproduction of an oscilloscope trace of a phototube signal. It indicates that the peak luminance remains reasonably constant for a period of more than a millisecond. The flash tube used in the unit is a coiled glass tube filled with the gas. The brightest areas of the tube occur at the points where the observer looks into a column of the gas, as indicated in the photograph in Fig. 3 taken at unit magnification. It seemed desirable to use only one of the bright segments for the flash source due to the nonuniformity of the entire tube surface. An enlarged image of the segment was focused on the entrance aperture, 10.5 x 20.0 mm, and this then became the effective source for the system. Figure 4 shows the arrangement of the tube and aperture.

By maintaining an interval of at least one minute between successive flashes, the peak luminance varied less than 5%. There was an increased variation of the order of 10% when the line voltage varied with additional drains on the line. This was carefully controlled during any one experimental session. The power pack furnished with the unit contains a voltmeter in the control panel and it was adequate for monitoring the line drop. The flash can be triggered by a manual switch on the control panel or by an external flash activating a phototube trigger. The spectral characteristics of the discharge and the values of peak luminance will be covered fully in a later section on the calibration of the apparatus.

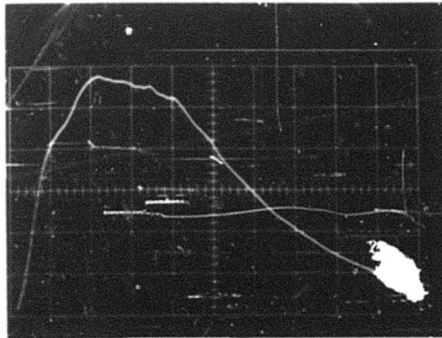


Fig. 2. Oscilloscope trace of total flash, (0.5 msec/cm)



Fig. 3. Flash tube during discharge showing unevenness of luminance

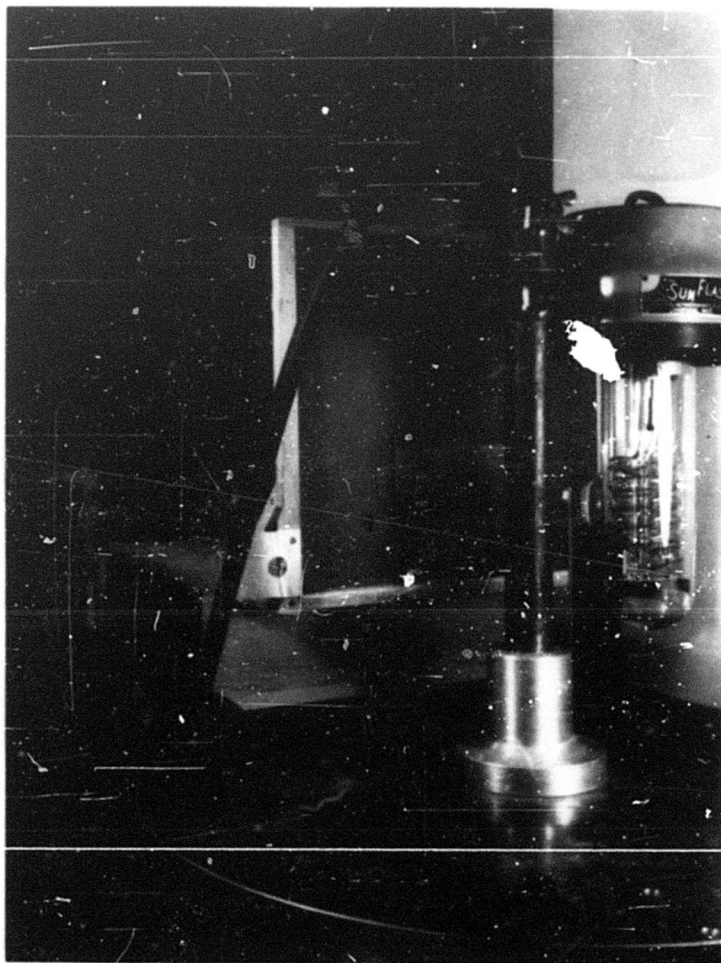


Fig. 4. The arrangement for imaging the bright segment of the flash tube on the entrance aperture

B. CONTROL OF EXPOSURE DURATIONS

Originally, it was proposed to use a rotating sector for a shutter mechanism to control the exposures, but the hazards involved in driving a 30-inch sector disc at 1800 rpm seemed to be too great. It was impractical to reduce either the size or speed of rotation because of the difficulties in filling a 10^9 flash field for exposure times as low as 50 μ sec. A system utilizing a rotating mirror in a collimated beam was finally decided upon. Figure 5 shows the arrangement of the elements. The collimating lens was a Bausch and Lomb 48 in., f/6.3 telephoto. The 4 x 6 inch first surface mirror was mounted on a cast aluminum frame, seen in the center of the photograph. The speed of rotation of the mirror was controlled by a series of pulleys to reduce the speed of the mirror mount shaft from that of the motor shaft which turned at 1725 rpm. The mirror speeds used in the various exposures are listed in Table II of the section on calibration, together with the resulting exposure durations. The speed of rotation of the mirror could be checked with each pulley change by means of the General Radio Strobotac at the left of the photograph. When the mirror was at the 45° position relative to the axis of the collimating lens, the beam filled the Bausch and Lomb 20-in. f/5.6 telephoto anastigmat lens mounted in the door panel. It is visible just above the Strobotac in Fig. 5. The 20-in. lens focused the parallel light reflected from the mirror in the plane of the aperture, A_2 , on the other side of the pannel, and as the mirror rotated, the image was swept across the aperture.

The image of the entrance aperture was reduced by the ratio of the focal lengths of the collimating and the focusing lenses, or by a factor of 2.4. The aperture, A_2 , was 4.5 mm high to accept the total height of the image, but was one-half as wide as the image. The ratio of the widths of the entrance and limiting apertures determined the pulse shape for the exposures. The 2:1 ratio theoretically produces a pulse in which the rise time is equal to the constant luminance portion and to the decay time, because one-half of the image will have swept the leading edge of the limiting aperture before the aperture is filled with light; and then it will remain filled with light for the second half of the image, producing a constant luminance. The equivalent square wave for such a pulse is equal to the half-width, or to twice the constant portion. Our oscilloscope traces indicated a close approximation to the theoretical pulse shape but with some rounding through the constant portion.

The durations of the exposures were given by a simple arithmetical calculation. For any given rotational speed of the mirror the time for one complete rotation can be determined, and from this the time necessary for any given angular displacement. Remembering that the beam reflected from the mirror has twice the angular displacement as the mirror, the same angular displacement of the image will take half as long. A ray entering the lens at an angle to the axis and pointed toward the nodal point leaves the lens at the same angle to the axis, so the nodal point is the pivot about which the image swings with the rotation of the mirror, but with twice the speed of the mirror rotation. The image is formed 20 inches or 508 mm from the nodal point. The linear velocity of the image can be calculated



Fig. 5. The rotating mirror mount with the 48" collimating lens and the 20" lens

from the formula for the circumference of the circular path of the image and from the speed of rotation of the mirror:

$$\text{velocity of image (mm/sec)} = \frac{2\pi \times 508 \times 2 \text{ rpm}}{60}.$$

Since the equivalent square wave duration for the pulse is equal to twice the time required to sweep the limiting aperture width, and the width was 4.1 mm, the duration of the equivalent square wave is given by:

$$t = \frac{2 \times 4.1 \times 60}{2\pi \times 508 \times 2 \text{ rpm}} = \frac{.07712}{\text{rpm}}.$$

The maximum and minimum speeds available with our pulleys were 1820 and 55 rpm, yielding maximum and minimum pulse duration of 1.4 msec and 42 μ sec.

The decision to substitute the rotating mirror unit for the sector disc shutter introduced a few problems which were time-consuming to solve, but which were eventually overcome. The mirror mount shown in Fig. 5 was modified by the addition of counterbalancing yokes attached to the upper portion of the casting and to the under portion around the shaft collar. A fairly heavy set screw was mounted in the center of the upper yoke to allow the entire assembly to be balanced for dynamic stability for each speed of rotation. Before this modification was introduced, it was found that the mount deformed at the higher speeds sufficiently to throw the image of the source aperture below the optical axis of the 20-in. lens so it missed the lower edge of the limiting aperture. With the counterbalancing yokes and set screw installed, the position of the set screw could be adjusted to yield a maximum oscilloscope trace for each rotational speed. A slight deformation of the mount continued due to uneven tension of the belt and pulley system, but the error introduced was less than 10% of variation in the trace height for constant luminance of the source aperture.

C. TRIGGERING THE FLASH

One of the most exacting problems in the design of the apparatus was that of synchronizing the flash with the rotation of the mirror. There is roughly a millisecond delay between the start of the flash discharge and the point at which it reaches peak luminance. It was necessary, therefore, to initiate the flash at such a time as to have the mirror reach the correct orientation to throw the image of the source on the leading edge of the limiting aperture at the instant the flash reached peak luminance. This was particularly critical in the case of the longest exposure (slowest mirror rotation) since the time of travel across the limiting aperture was slightly longer than the duration of the peak luminance. Inasmuch as the lengths of the exposures were controlled by changing the mirror speed, the millisecond delay represented a different angular displacement for starting the flash for each of the five exposures. It seemed impractical to attempt to

construct a mechanical triggering device on the mirror shaft because of the small changes in phase angle required. It was decided that an optical means of triggering would be preferable because it would be positively coupled with the reflecting surface of the mirror, and by using a long optical lever the necessary precision in angular displacement could be provided. At the slowest mirror speed, the angular displacement between the initiation of the flash and the correct orientation was only 0.33° , and at the highest speed it was 11° .

It was found that the external triggering phototube supplied with the unit would not respond to tungsten light but only to an auxiliary xenon flash. The phototube was replaced with one having a phosphor sensitive to the near infrared to increase the effectiveness of the tungsten light, but it did not produce an adequate signal. Several transistor circuits were built to amplify the phototube signal in an effort to reach the necessary triggering level but they were not successful.

The General Radio Strobotac is an adequate source to operate the external phototube, so several attempts were made to trigger it and let it trigger the Sun-Flash. The strobotac can be fired by an external triggering line by simply shorting the line across the chassis. This feature was used in a rather complex arrangement whereby light from a tungsten lamp was reflected from the rotating mirror onto a sensitive photocell which could be positioned accurately on an arc about the center of rotation of the mirror. The signal from the photocell operated a transistor circuit closing a relay which acted as a simple switch to short the triggering line of the Strobotac. The system had the advantage that a long optical lever was utilized to provide a fine adjustment on positioning the photocell. The system failed because the lag in response of the photocell varied with previous light exposure and temperature and was as high as 20 milliseconds.

The final arrangement was even more complex but had the advantage of great stability and quite adequate precision. The apparatus is shown in Fig. 6, with additional detail in Fig. 7. The Strobotac was fired by the external contactor manufactured by General Radio to synchronize the flash in phase with some point on the mirror shaft. The phase angle can be controlled by a remote control cable while the shaft is running, but there is some slippage of the magnetic coupling and the dial furnished with the instrument for measuring the phase angle is not sufficiently finely divided for the precision required. An optical vernier was developed to increase the precision of setting by focusing a pointer attached to the Strobotac reflector on a scale after reflection from the rotating mirror. A lens and beam splitter (shown in Fig. 6) were used to reflect the light from the Strobotac onto the rotating mirror, where it was again reflected and brought to a focus on the scale shown just above the beam-splitter. The position of the pointer when the rotating mirror was at the 45° position was marked on the scale and the required displacements for triggering at the different mirror speeds were calculated and marked. The remote control cable could then be adjusted by the experimenter until the pointer image fell on the suitable mark. When this was accomplished, the Strobotac was firing one millisecond before the correct mirror orientation

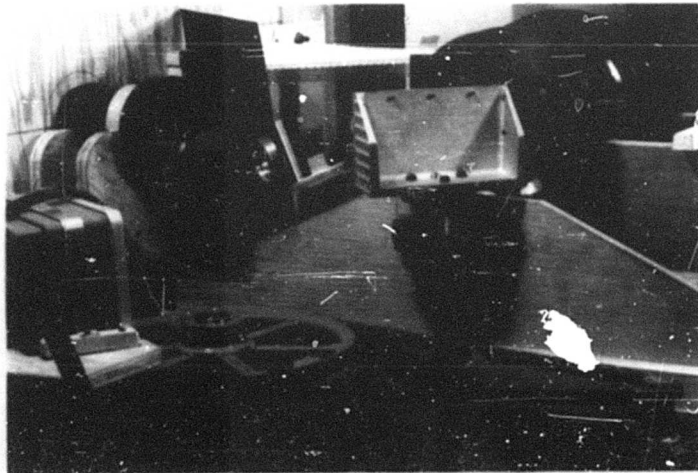


Fig. 6. Lens and beamsplitter for triggering flash in phase with mirror rotation

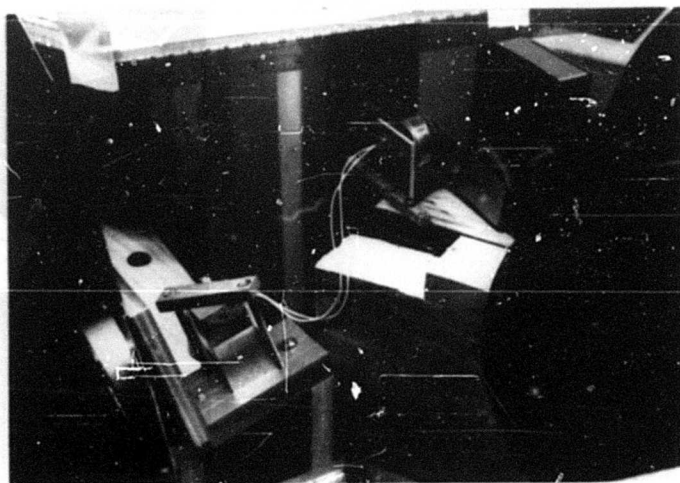


Fig. 7. Detail of beamsplitter showing rotary solenoid shutter over phototube

on each revolution of the mirror. The experimenter then closed a push button switch which activated a rotary solenoid shutter (shown in Fig. 7), and exposed the triggering phototube to the next Strobotac flash. The delay between the Strobotac flash and the start of the Sun Flash discharge was of the order of a few microseconds. The displacement of the pointer image for the different mirror speeds ranged from 3.5 mm to several centimeters relative to the position for the 45° mark, which was ample for precise settings. There was some instability in the system because of slippage of the contactor coupling, but with careful adjustment of the contactor on the mirror shaft it could be kept within acceptable tolerance.

D. MAXWELLIAN VIEW SYSTEM

Figure 8 shows the optical system in the subject's room for presenting the flash by Maxwellian view to the subject. The exposure limiting aperture, A_2 , is shown just below the 20-in. lens in the cor panel. During a flash it became the effective source which, when focused in the plane of the subject's pupil by the two achromatic lenses, allowed the field to be seen filled with light of the same luminance. The movable mirror is in front of the aperture in the photograph. The table for pivoting it out of the stimulus beam could be adjusted by means of the knob on the long screw to align the mirror relative to the optical axis of the lenses in a horizontal plane. The base of the mirror mount was pivoted on the rod fastened to the circular table by means of the two screws in the base so the mirror could be adjusted to align the beam in a vertical plane. The lever for swinging the mirror out of the stimulus letter beam is shown at the edge of the wooden base. The two achromats were mounted in eccentric mounts to aid in aligning the system. The field stop mount is shown between the two achromats with one of the aperture plates in place; the four additional apertures are shown on the base. The five different sizes provided the flash fields of required angular subtense. The aperture plates were carefully machined so they could slip into the mount and be concentric with the optical axis. The exposure-limiting aperture was at the focal point of the first achromat to provide collimated light, and the field stop was in the collimated beam at the focus of the second achromat so the subject saw it sharply defined with relaxed accommodation. The subject's eye was positioned with the plane of the entrance pupil at the other focal point of the second achromat.

E. MONITORING THE FLASHES

The phototube chassis, shown in the upper right of Fig. 8, received a portion of the light from each flash after reflection from a beam splitter and a first surface mirror. The signal from the phototube was fed into a 533 Tektronix oscilloscope fitted with a Polaroid camera back. Each flash trace was photographed for a permanent record of trace height and pulse duration. It was found that a simple shielded cable was inadequate to feed the signal into the oscilloscope because of capacitance losses at the shorter exposures, so a 10x attenuating probe was used for the coupling resulting in a definite improvement in displayed signal. Some loss was

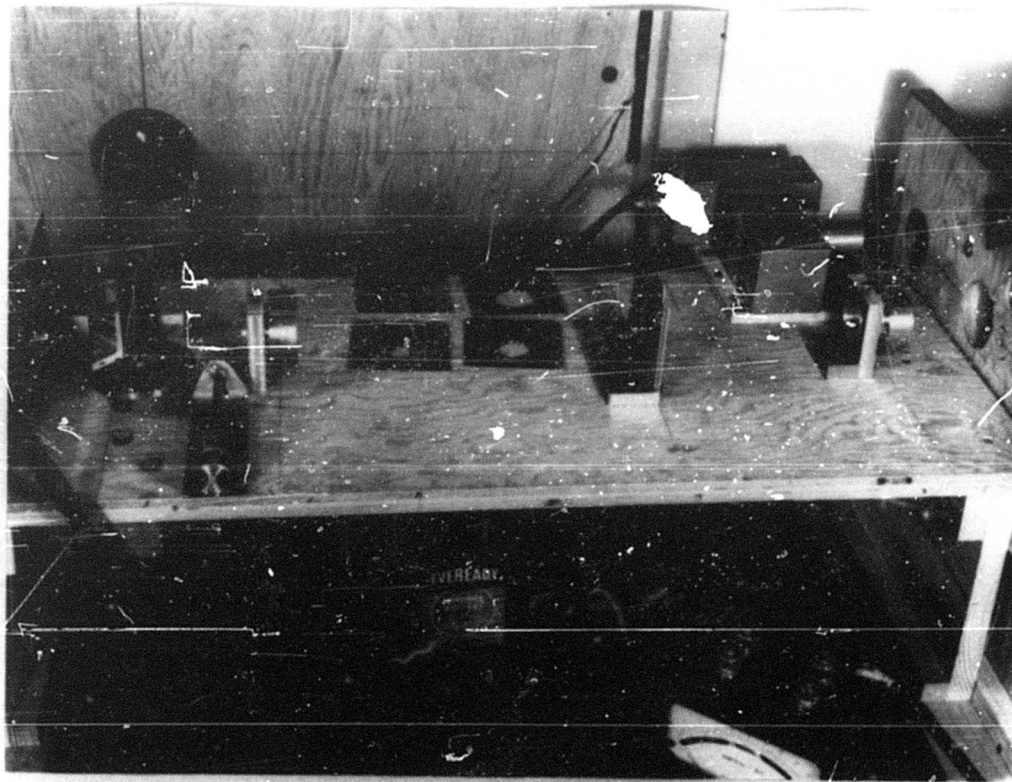


Fig. 8. Maxwellian view system for flash exposures showing exposure limiting aperture

still experienced at the shortest exposure time and the problem has not yet been solved. The arrangement was quite adequate, however, as a check on the variability in flashes of a series and to indicate if any gross errors in alignment or triggering had occurred. Periodically a standardized tungsten lamp was substituted for the flash source to allow a running calibration of the flash tube output.

F. ADAPTING FIELD SYSTEM

The view of the apparatus from the subject's side of the board, seen at the right of Fig. 8, is shown in Fig. 9. At the left of the photograph is the lamp house for the adapting field, with the optical system extending into the center of the picture. A ribbon filament lamp in the lamp house was focused on an aperture 2 mm in diameter, which in turn was focused at a 1:1 magnification in the plane of the subject's pupil for a Maxwellian view. The luminance of the ribbon filament was controlled by a Variac between the AC line and the 0 v transformer. The field luminance was adjusted by neutral density filters placed in the parallel light beam between the two achromats. The 2-mm aperture was mounted with horizontal and vertical adjustments so its image could be centered in the the image of the exposure-limiting aperture after reflection from the beam splitter. It was placed at the focus of the first achromat to collimate the light.

The field stop also has horizontal and vertical adjustments to bring its virtual image into coincidence with that of the field stop of the flash system. It was placed at the focal point of the combination of the two achromats to be seen at infinity by the subject. It subtended a 10° visual angle equal to the largest flash field used.

For those experiments performed against a dark field, the adapting system was modified to provide fixation markers. They consisted of clear lines in a dense film in the form of an interrupted cross and were trans-illuminated by the lamp through a red filter. The subject controlled the luminance of the markers with the Variac so they were visible just a few seconds before the test letters which were seen in the center of the dark area of the interrupted cross.

During the portion of the experimental sessions involving the adapting field, an additional lamp housing holding a 100-watt frosted lamp was added above the adapting field optics. It is shown in the upper left of Fig. 9. It provided the source for projecting an image of the fixation cross through an auxilliary lens into the plane of the field stop. A lantern slide cover glass was used to reflect the light into the optical system of the adapting field with a minimum loss of luminance of the adapting field. The adapting field was turned off immediately after the flash so the test letters were again seen against the dark background in the center of the interrupted cross pattern. The subject adjusted the luminance of the pattern to a value just higher than that of the test letters before each run was started.

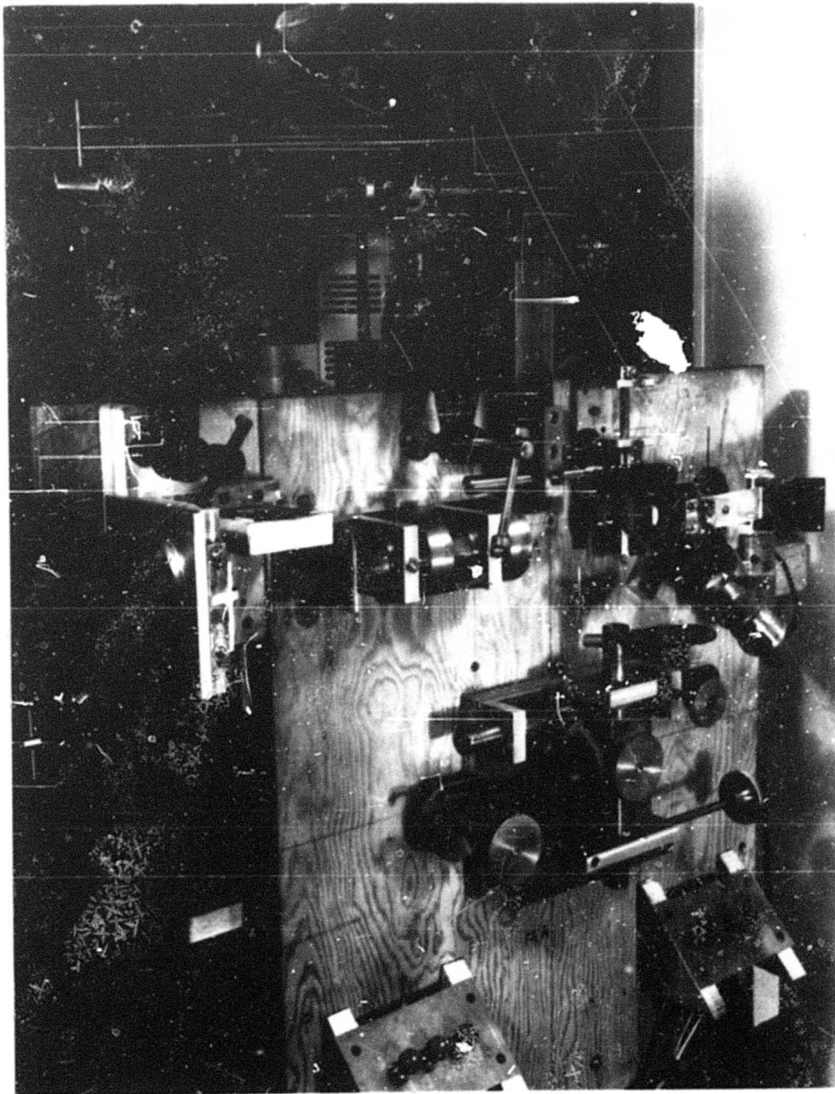


Fig. 9. Adapting field system and bite plate mounting

The beam splitter cube in the center of Fig. 9 was mounted to pivot about a horizontal and vertical axis to make the optical axis of the adapting field optics perpendicular to the axis of the flash system. The same beam splitter was utilized in reflecting a portion of the flash into the monitoring phototube.

G. ALIGNMENT OF THE SUBJECT

A plate was attached to the beam splitter mount near the rear face of the cube to accept interchangeable devices for aligning the optical systems and for aligning the subject's eye relative to the light beams. The first consisted of a ground glass disc scribed with a small circle which was positioned at the focus of the last achromat in the flash system. When the flash optics were properly aligned, the image of the exposure-limiting aperture was sharply focused and centered on the scribed circle. The adapting field optics could then be adjusted to produce a sharp image of the lamp house aperture in the center of the circle. The position of the ground glass plate coincided with the proper position of the subject's pupil, 3 mm behind the vertex of the cornea.

The second device was a small artificial pupil centered with respect to the circle on the ground glass but mounted several mm in front of it, i.e., closer to the beam splitter. This provided a peep hole for the subject to view a ground glass target in the field stop mount. The ground glass was scribed with a cross centered in the field stop. When the subject's head was properly positioned to center his eye on the optical axis, the cross hairs were symmetrically oriented in the center of the shadow formed by the peep hole on the retina. The positioning was done by the subject by means of the adjustments provided on the bite plate mounting. The mechanism for holding the bite plate can be seen in the lower portion of Fig. 9. It allowed fine control of the bite plate position in three mutually perpendicular directions. The subject adjusted the position from side to side and up and down with the peep hole sight and the experimenter adjusted the bite plate in the fore and aft direction to bring the vertex of the cornea into the proper position. This was accomplished by means of the sighting device seen in Fig. 9 at the right of the beam splitter. It consisted of a scribed vertical line on a glass plate in front of an aperture in a metal plate also carrying a vertical line. By looking into the mirror set at 45° to the board the experimenter could sight through the aperture and bring the two vertical lines into coincidence and then adjust the bite plate until the vertex of the cornea was coincident with them. When the subject was in the correct position, the Maxwellian beams from the flash system and adapting system entered the center of the pupil and the two fields were concentric with the beams. Then by fixating the center of the interrupted cross pattern, the flash field was concentric with the fovea.

H. STIMULUS LETTERS

Recognition of Sloan-Snellen letters was chosen as the criterion measure of recovery time following the brief flashes. The population of 10 Sloan-Snellen letters was originally selected because they have nearly equal thresholds of visibility but for this study the original population was reduced to six letters that had proven in the past to be more nearly equal for low contrast thresholds. They were: H, K, O, N, R, and Z. They were drawn as block letters with the width of the strokes $1/5$ of the total height. The five sizes to be used in the study were photographed on kodalith film as clear areas in the high density background. Transilluminated, they were seen as bright letters on dark surround. The sizes were chosen to be comparable with the numerals and letters used on airplane instruments. Baker and Grether⁴ cite the height of numerals and letters on instrument panels of 0.15 to 0.30 inch for a viewing distance of 28 inches for low luminance viewing, and 0.10 to 0.20 inch for higher luminances down to 1.0 ft-L. These figures represent visual angles of 18.4 to 36.8 min of arc for the low brightness, and 12.25 to 24.5 minutes for the higher values of luminance. The largest letters prepared for this study subtended 42 min of arc viewed at infinity through the 180-mm achromat of the flash optics. The smaller sizes were in steps reduced by a factor of $\sqrt{2}$.

The letters were randomly arranged around the circumference of a drum which held 30 letters in all. Since the drum could be started from any position, there was little possibility of the subject memorizing the order of the letters. The position of the drum relative to the rest of the apparatus is shown at the top left of Fig. 9. The driving mechanism and illuminator are shown in greater detail in Fig. 10. Two drums were machined so that the different size letters could be alternated easily and usually two different size letters were mounted on one drum so the recovery times for two sizes could be determined with one flash. The drums were mounted on a shaft driven by a 1725 rpm motor through a gear train containing a geneva gear. The letters were advanced at the rate of one per second by this mechanism. A rotary solenoid shutter was activated by a pin on one of the gears so its action could be synchronized with the drum rotation and the shutter opened for 40 msec during the time the letter was stationary. This arrangement allowed a different letter to be flashed briefly every second.

The lamp house at the right of Fig. 10 housed a ribbon filament lamp that was run by a 6 v power pack with less than 1% ripple. The power pack was connected to the line through a constant voltage regulator and a Variac, and was monitored and controlled throughout an experimental session by means of a sensitive ammeter in the circuit. The ribbon filament was focused in the plane of the letters after reflection from the two mirrors seen in the center of the photograph. Neutral density Inconel filters were placed in the beam before the mirrors to reduce the luminance to a value comparable with the highest instrument panel illumination. Lenses in the optical train focused a uniform field of light in the plane of an aperture plate seen in front of the drum in Fig. 9. The opening in this plate was 9 mm in diameter and it was conjugate to the subject's pupil through the

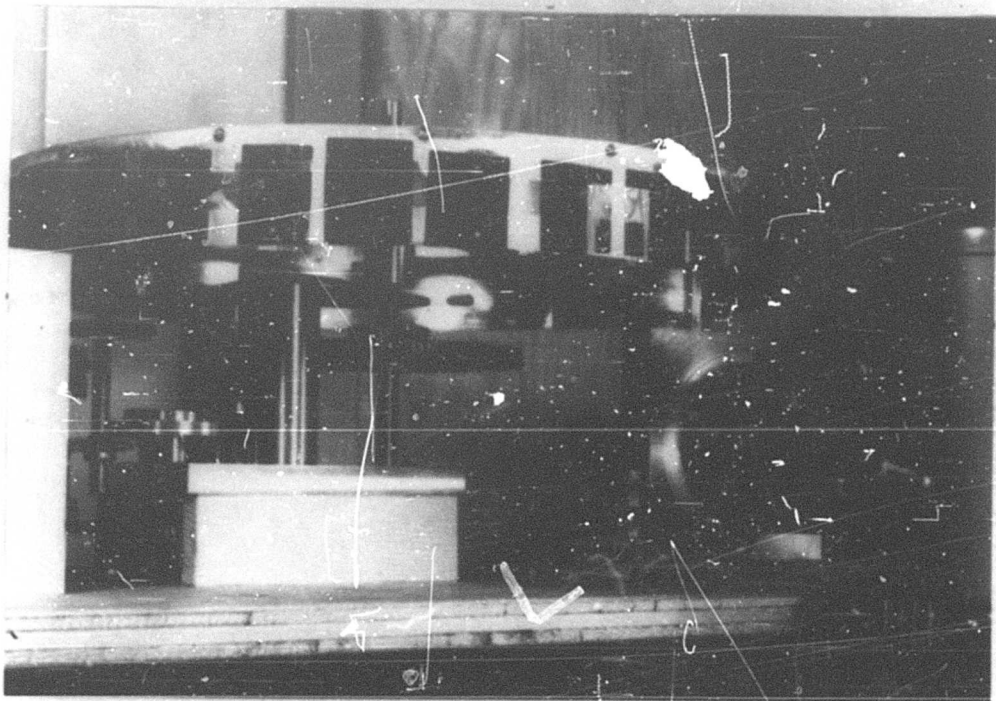


Fig. 10. The stimulus drum for presenting the test letters

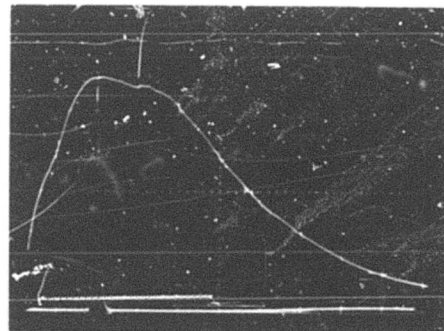
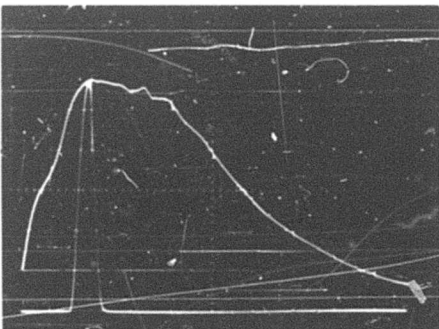
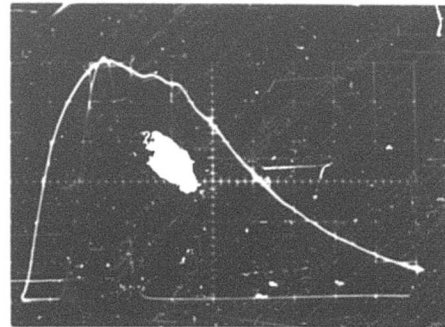
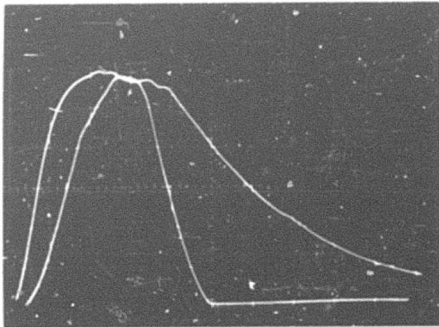


Fig. 15. Oscilloscope traces of the different pulse durations showing the portion of the total flash used with the different mirror speeds

two achromats of the flash system. This made the subject's natural pupil the limiting stop for the light beam. The first achromat of the flash system focused the letters at a 2:1 reduction in the center of the flash field stop, where they were seen by the subject with relaxed accommodation through the second achromat. Additional neutral filters were placed over the 9-mm aperture to adjust the luminances to the values used in the study.

The criterion of recovery time was two successive correct responses in identifying the letters. Six push button switches were installed below the bite plate for the subject to use in responding to the letter flashes. The subjects quickly learned to depress the appropriate button when a letter was recognized. The switches activated six neon glow lamps arranged near the back of the stimulus drum so the experimenter could compare the subject's responses with the letter just exposed.

I. MEASURING THE RECOVERY TIMES

An electric clock with a 110 v DC starting mechanism was used to time the interval between the flash and the two correct letter responses. The power for the starting mechanism was provided by a rectifier connected to the AC line with a relay in the circuit, acting as a simple switch. The relay was closed by means of a transistor circuit and a photocell mounted near the flash tube. This arrangement started the clock automatically at the instant of the flash and the experimenter had only to record the elapsed time when two successive correct responses were signalled by the subject.

Each drum carried 15 letters of each size in two groups, with the order of the letters randomized within the groups. Before the flash the drum was rotated to bring one of the letters of the larger group into position. When the subject first perceived the red fixation pattern after the flash, he depressed a switch which activated a holding relay closing the line to the drum motor, and the letters were then presented at one second intervals. When he scored two correct responses, the experimenter recorded the time and then when one of the smaller group of letters was in position, he stopped the drum with a microswitch which interrupted the holding relay. The subject started the drum again when he saw a faint blur of light from the stimulus letters and again signalled the responses so the experimenter could record the time when the criterion was reached.

J. THE PUPILLOGRAPH

An infrared pupillograph for automatically recording the changes in the pupil diameter was built, with slight modifications, from the description by King.⁵ It was modified to record from one eye only, but the electric circuitry is essentially the same as that developed by King. The arrangement of the optical parts is shown in Fig. 11. Light from a tungsten projection lamp is focused on the holes in the scanning disc and the scanning spots are focused on the subject's iris. A mirror below the axis of the lens reflects

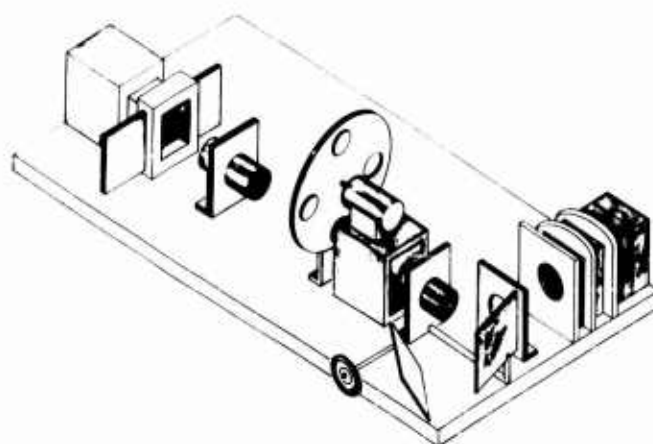


FIG. 11. SCHEMATIC OF OPTICAL SYSTEM OF THE PUPILLOGRAPH

the light from the iris through another lens onto the receiving surface of an infrared photomultiplier. The tungsten light is filtered through an infrared filter before passing through the scanning disc, so the pupillary reflex is not disturbed by the measuring light. The phototube signal is amplified and then clipped to remove the portion of the signal caused by reflection from the sclera. The remaining signal is amplified once more and fed into a sawtooth generator. The voltage of the sawtooth generator is proportional to the time taken for the scanning spot to move across the pupil of the eye. The voltages of the generator are measured by a peak detector whose output is fed into a recorder for automatically tracing the changes in pupil response.

The unit developed by King for Lowenstein and Lowenfeld is commercially available, but in a form for clinical use and embodying a number of refinements that were not considered necessary for laboratory investigations. The task of building a somewhat simplified model was undertaken for reasons of economy. In the laboratory, it is possible to position the subject's head by means of a bite plate so a horizontal scan will cross the diameter of the pupil. This makes it possible to use a simple linear scan instead of the 20-line area scan in the commercial instrument.

IV. CALIBRATION

A. FLASH SOURCE COMPARED WITH TUNGSTEN RIBBON

The spectral distribution and luminance of the Sun Flash tube were determined by comparison with a standard ribbon filament lamp through a number of narrow pass interference filters. The comparison was accomplished by measuring the responses of two phototubes, a 919 and a 929, with a fast-rise-time Tektronix oscilloscope. The two phototubes have different phosphors, one having a maximum sensitivity at 800 m μ and the other at 400 m μ . The ribbon filament lamp was chosen as the standard source because of its stability and its rather large uniformly bright surface. Precise measurements of the characteristics of tungsten ribbon have been made in the past by Forsythe and others so its spectral distribution and luminance are well established as a function of the current. Figure 12 is a curve redrawn from the data of Forsythe and Worthing⁶ relating the color temperature to the current. A family of curves was drawn from the data of Barnes and Forsythe,⁷ with wavelength as a parameter, showing the relationship between the energy in a 10 m μ band and the color temperature. These two sets of data allow us to plot the spectral steradiancy of tungsten ribbon filament lamp for constant current value.

The ribbon filament, after a short aging period, was run at 18.0 amps throughout the calibration. The current and voltage were held constant by using a power supply with less than 1% ripple connected to the AC line through a voltage regulator. A sensitive ammeter was monitored continuously during the exposures. The spectral steradiancy for the ribbon filament

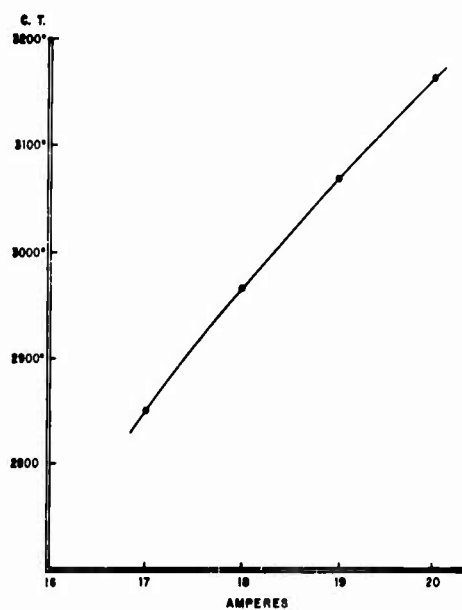


Fig. 12. Color Temperature of Ribbon Filament as a Function of Current.

under these conditions of operation is shown in the curve of Fig. 13 interpolated from the data described above. From Fig. 12, the color temperature of the filament at 18.0 amps would be 2965°. As a check on the values interpolated from energy curves and plotted in Fig. 13, the luminance of the filament was calculated using the standard photopic luminosity factors. This calculation indicated a filament luminance of 867.16 c/cm².

The lamp was substituted for the flash tube and focused on the entrance aperture which was masked down to an 8.2 mm square. The image of the filament was larger than the aperture so it acted as a uniformly bright source, the luminance of which was measured with a MacBeth illuminometer by placing the reference plate 20 inches from the aperture and measuring the illumination of the plate. This gave a value of 938 c/cm² for the filament luminance. The experimentally determined value was 8.2% higher than the calculated value, which is well within an acceptable tolerance.

Fourteen interference filters were available, most of them with multiple transmission peaks. The wavelengths of the transmission peaks between 400 and 1100 mμ were measured on a spectroradiometer. There were 24 bands in that region which could be used in the comparison with suitable blocking filters. The flash source luminance was so much greater than that of the tungsten lamp that the relative spectral distribution had to be measured with two different optical systems. The relative values were then converted to an absolute scale by the direct comparison of the two sources through identical optics for two bands, at 555 and 570 mμ, with both phototubes. The chief difficulty encountered in making the comparison was the tendency to overload the phototube-oscilloscope system with the flash, resulting in capacitance coupling and a reduced signal trace. This was overcome by using a 10X attenuating probe to connect the phototube to the oscilloscope, and by introducing calibrated neutral density filters in the beam to prevent overloading the probe.

The two optical arrangements used for determining the relative distribution of the source energy were the regular flash optics through the 20-inch lens for the flash source and for the direct comparison, and an auxiliary optical system for the tungsten source. The auxiliary system consisted of a 6-inch, large-diameter lens which focused the filament on the phototube surfaces at such a magnification as to cover the entire surface. A rotating sector was placed in front of the lamp so the same time scale could be used on the measuring oscilloscope as was used with the flash source. With one megohm load resistors in the phototubes, this arrangement yielded signals of from 0.1 to 5 volts with the 919 tube, and 0.6 to 20 volts with 929. The signals from the flash source were several times larger than this through the flash optics.

Table I shows a summary of the comparison of the sources with the two phototubes. Column 1 lists the transmission peaks. The ratio of the luminance of the flash source and the tungsten ribbon filament is shown in column 2 as measured with the 919 tube, and column 3 with 929. Column 4 gives the average ratio of the two sources, and column 5 the energy in w/cm²/sr/10mμ band for tungsten at each of the transmission peaks (the values were

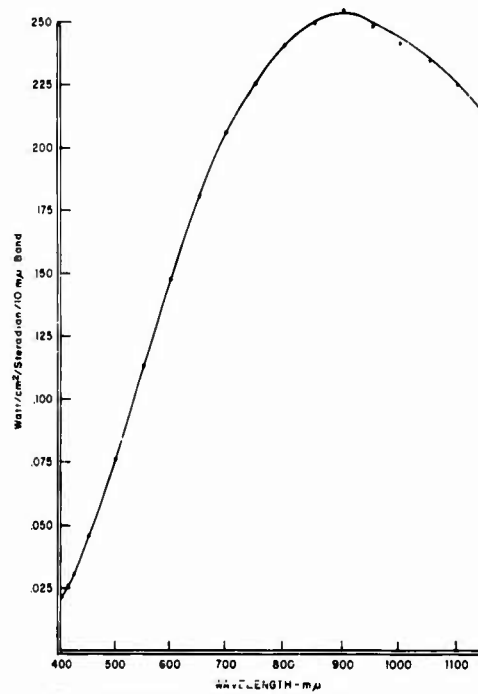


Fig 13. Spectral Stereadiance of Tungsten Ribbon Filament at 2965° Color Temperature.

Table I. Spectral Stereadiance of Sun Flash Tube

λ (m μ)	Flash Tung. (919)	Flash Tung. (929)	Flash Tung. ev.	w_λ Tung. (w/cm ² /10m μ)	w_λ Flash (w/cm ² /10m μ)
423		1318	1318	.0322	42.4
434		1330	1330	.0380	50.6
435		1800	1800	.0381	68.6
443.5		1750	1750	.0421	73.9
457.5		1850	1850	.0498	92.2
464.8		1200	1200	.0540	64.9
477	2020	1675	1998	.0615	122.8
503.4	944	1165	1054	.0790	83.4
510	901	1065	983	.0836	82.2
532.6	939	902	920	.0996	91.7
554.2	685	714	700	.1162	81.4
555	701	702	701	.1165	81.7
570	554	628	591	.1278	75.5
580	498	472	485	.1345	65.3
621.9		344	344	.1626	55.9
640.4	344	301	323	.1748	56.4
657.8	314	311	313	.1853	58.1
685.9		352	352	.1998	70.3
701.3	262		262	.2065	54.2
828	239		239	.2476	59.1
867	342		342	.2530	86.5
1005	716		716	.2420	173.2
1015	686		686	.2404	165.1
1050	665		665	.2342	156.0

interpolated from Fig. 13). The last column shows the products of the values in columns 4 and 5 and is the energy distribution of the flash source in absolute units. The estimated accuracy of the values in the last column is $\pm 20\%$. The energy distribution of the flash source is shown in Fig. 14. When the energy of the flash is multiplied by the standard photopic luminosity factors, and the sum multiplied by 680 lu/w, the luminance of the brightest portion of the Sun Flash tube is found to be 5.45×10^5 c/cm². Six weeks later, at the end of the experimental sessions, during which time the tube was in use six to eight hours a day, this value had dropped by 10%.

B. TRANSMISSION OF THE OPTICAL SYSTEM

When a source is presented by Maxwellian view, the subject sees the field of the optical system filled with light of the same luminance as the source but reduced by the loss through the optics. Having determined the luminance of the flash source, it was necessary to measure the transmission of the total optical system to specify the luminance of the flash field used in the brief exposures.

The standard tungsten lamp was substituted for the flash tube and focused on the entrance aperture of the system by the short focal length lens. The aperture was masked to a rectangle the size of the filament image. The optical system then formed an image of the filament at the plane of the subject's pupil. The rotating mirror was kept stationary at the 45° position. A MacBeth illuminometer was fitted with a short focal length lens and a small exit pupil, and then aligned so the exit pupil, illuminated by a bright source directly behind it, was focused in the plane of the filament image and fell within it. Under these conditions the MacBeth measures the luminance of the image of the source, and it can be shown that this is the luminance of the field viewed by the subject with the eye properly positioned for a Maxwellian view. The luminance measured was 230 c/cm² at the beginning of the experimental sessions; this gives a value of 26.6% for the transmission of the total optical system. Six weeks later, when a considerable amount of dust and dirt had accumulated on the optical surfaces, this value was reduced to 161 c/cm², or 18.6% transmission.

The measurement of the field luminance by the above method involved the use of six Inconel filters to reduce the field brightness to a level comparable with the working standard lamp of the MacBeth. The filters had a total nominal density (the manufacturers rating) of 5.1. Each had been previously calibrated with the MacBeth in parallel light; the sum of the experimentally determined densities of the filter pack was 5.358. As a check on the accuracy of the calibration, the field luminance was measured in a different way for comparison. The reference plate of the MacBeth was placed 20 inches behind the filament image and the illumination measured; no filters were needed. It was 1.43 ft-c and a simple calculation involving the field angle and image area gave a value of 227 c/cm² for the field luminance.

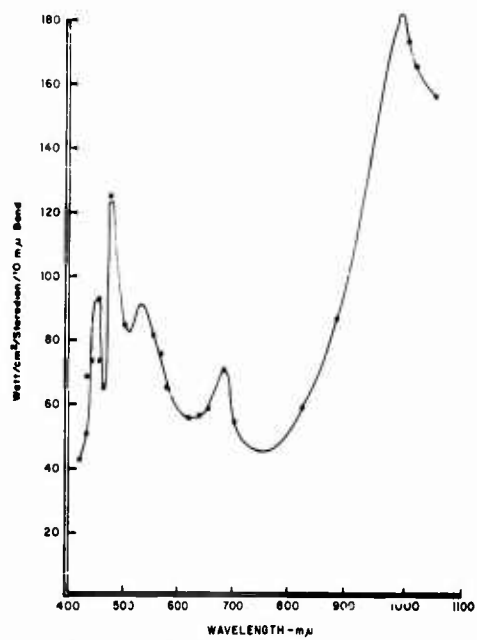


Fig 14 Spectral Stereometry of Sun Flash Tube

C. FLASH DURATIONS

The Tektronix oscilloscope was calibrated with a time mark generator to insure that the time scale of the horizontal sweep was correct. For each of the mirror speeds used in the experimental sessions, a careful measurement of exposure duration was made using the 929 phototube and the oscilloscope coupled with the attenuating probe. The horizontal sweep of the oscilloscope was triggered by an external signal from an auxiliary phototube, placed to receive light from the rotating mirror a short period before the source image entered the exposure-limiting aperture. In the calibration and the monitoring, the horizontal sweep was triggered internally, i.e., by the signal fed into the amplifier. This method had the disadvantage that the triggering level of the scope determined the start of the horizontal trace. For the measurements of exposure durations, it was necessary to have the traces start before the signal to the amplifier was applied so the entire shape of the pulse could be displayed.

Figure 15 shows the pulse traces for all but the shortest exposure duration. A trace of the time course of the total flash discharge is displayed on each of the pictures, along with the pulse, to show the triggering interval for each speed. The trace of the total flash was photographed by setting the rotating mirror at the 45° position. In each case, the time scale of the oscilloscope was 0.5 msec/cm. It can be seen that the half-width for the longest exposure is slightly less than the 1.4 msec calculated from the velocity of the image sweeping the aperture. This is due to the fact that the total time of passage of the rectangular image across the exposure-limiting aperture was slightly longer than the peak luminance duration. As a result, the pulse rise and decay portion is steepened, with a somewhat shortened pulse as a result. The error is less than 10% of the calculated duration. The calibration of the triggering system is demonstrated in that each pulse peaks within the constant luminance portion of the total flash.

Table II shows the rotational speeds used for the flash exposures with the calculated and measured pulse durations. The last column gives the log of the total energy in the pulse, based on the average field luminance and transmission during the experimental period, the area of the Maxwellian beam, and the pulse durations.

Table II. Exposure Durations and the Product of Retinal Illuminance and Exposure for the Different Mirror Speeds

Rotational Speed (rpm)	Exposure Calculated (msec)	Exposure Measured (msec)	Log Energy (td·sec)
55	1.401	1.28	7.43
138	0.559	0.54	7.05
345	0.223	0.22	6.66
750	0.103	0.10	6.32
1820	0.042		5.94

D. ADAPTING FIELD LUMINANCES

The adapting field luminances were measured with a MacBeth illuminometer in the same manner as for the flash field luminance described previously. The ribbon filament lamp illuminating the adapting field was controlled with a Variac between the line and the 6 v transformer. Walsh⁸ gives as the luminance of clear blue sky 1.25 L, so the Variac was adjusted to produce a luminance close to this value for the brightest field used. The actual value was 1.83 L and with the 2-mm-diameter lamp house aperture focused on the subject's eye, this was equivalent to 1.83×10^{14} td. According to Rushton's data on the bleaching of foveal pigments,⁹ this corresponds to a 35% bleach. The other two field luminances were adjusted by inserting neutral density filters in the light beam; their values were 0.137 and 0.010 L. In addition to these values of adaptation luminance, the subject was preadapted to a dark field for three minutes prior to the flash.

The procedure for preadaptation to the higher luminances consisted of exposing the subject to a field luminance 1.1 log units higher than the desired value for 10 sec, and then reducing the luminance by the addition of neutral filters to the values given above. This method is described by Rushton in the above cited reference. He shows that the original 10-sec exposure produces the desired bleach of the foveal pigments, and this level is then maintained indefinitely by the lower luminance. By using this technique, the time required for steady state adaptation was shortened, and the desired state could be accurately maintained while the mirror speed was adjusted for the flash. The adapting field was extinguished immediately after the flash so the test letters were seen against a dark field for all conditions.

E. TEST LETTER LUMINANCES

The short-focal-length lens on the MacBeth, which had been used in the measurement of the flash and adapting fields, was replaced by a lens of somewhat longer focal length. It was chosen to image the illuminated exit pupil of the MacBeth on the plane of the field stop of the flash system, after passage through the beam splitter and the last achromat. The letter was removed from the stimulus drum so the image of the ribbon filament lamp could be seen in the center of the field stop. The MacBeth was then aligned to bring the image of the exit pupil into place inside the ribbon filament image. The MacBeth reading could then be used to calculate the luminance of the filament image, and this, in turn, gave the luminance of the test letter after multiplying by the transmission of the clear Kodalith film. The letter luminance was 0.066 mL or 0.0615 ft-L. This is slightly higher than that found in red lighted instruments panels which range from 0.02 to 0.05 ft-L. Provision was made to increase the luminance by steps of 1.0 log unit to determine the change in recovery times as a function of instrument illumination.

The sizes of the test letters were measured on a traveling microscope, and after the 2:1 reduction by the achromat in the flash system, they subtended visual angles of 41.9, 28.6, 20.3, 16.3, and 10.25 min of arc as viewed by the subject.

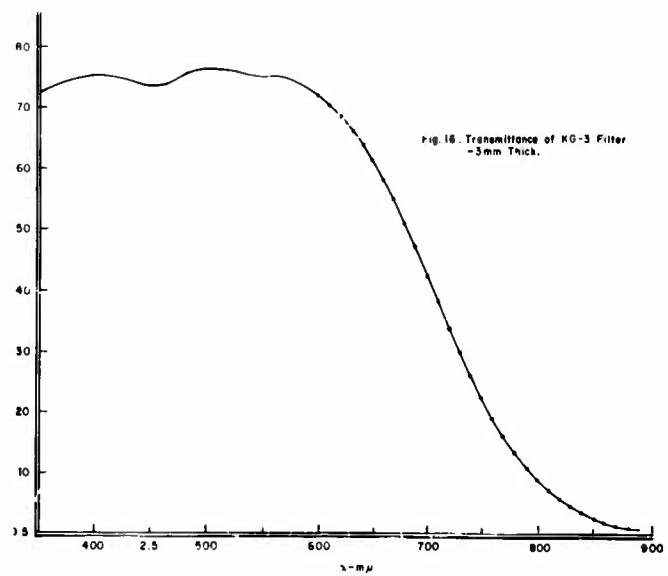
V. EXPERIMENTAL RESULTS

The various experimental conditions to be tested were arranged for presentation in separate experiments and will be described in that manner in this section. Six subjects took part in some of the experiments and only five in others. They were all students in, or recent graduates of, the School of Optometry, except for one psychology student. They had all taken part in the final assembly and in the calibration of the apparatus so they had a continuing interest in the results and correspondingly high motivation. All subjects served as experimenters during the runs when they were not making the observations.

The experimental procedure for testing the different conditions was developed with the help of the Statistical Laboratory to insure the validity of the subsequent statistical analysis.

A. EFFECT OF REMOVING THE INFRARED ON THE RECOVERY TIMES

A KG-3 filter was used to absorb all radiation past 850 m μ to find if the large energy band at around 1000 m μ in the flash contributed significantly to the length of recovery. The transmission curve of the 3-mm-thick KG-3 filter is shown in Fig. 16. Exposure durations of 0.56 msec were used and each subject received four flashes through the KG-3 filter, four through a



0.13 neutral density, and four unfiltered flashes. The order of the conditions was different for each subject. The flashes were presented three minutes apart so there was some possibility of a cumulative effect, but ordering the conditions would cancel the effect on the means for the different conditions. The means of the four flashes for each condition are shown in Table III, by subject for each of the two letter sizes tested. The visual density of the KG-3 filter was 0.12. The subject L. L. had unusually long recovery times on some days, and in this experiment the recovery times are almost twice as long as those of any of the other subjects.

B. THE EFFECT OF EXPOSURE DURATIONS ON RECOVERY TIMES

The recovery times for the identification of a 0.066 mV test letter subtending 20.3 min of arc were measured following flash exposures of five different durations, ranging from 0.42 msec to 1.40 msec. Each of the six subjects received four flashes of each duration. The flashes were presented three minutes apart, except when the recovery time exceeded the interflash interval; the subject was given 30 seconds between the recovery and the next flash. The flash durations were varied in order from the longest to the shortest in one session, and then from the shortest to the longest in the next session on the next day.

This procedure was followed in order to test the effect of the prior exposures on the measured recovery times. The data are recorded in Table IV where the mean recovery time for the four flashes of each duration are listed by subject for the two orders of conditions.

The mean of all of the data for each exposure duration is shown in Fig. 17 plotted against the log of retinal illuminance times exposure time. On the same curve is the data of Metcalf and Horm with the ordinates in units of log td·sec. No correction for the Stiles-Crawford effect has been made in calculating the retinal illuminance for their 6-mm-diameter pupil or our 4-mm-square Maxwellian beam. The two sets of data agree well except at the higher energy levels. There is a possibility of a cumulative effect in our data at the higher energies because flashes were presented too close together.

From the agreement in the two sets of data, it would appear that there is complete reciprocity between change in luminance and change in exposure time, at least to 42 μ sec, our shortest exposure time. As an additional check on this relationship, six subjects tested the recovery times following 42- μ sec flashes, and following 559- μ sec flashes filtered through a 1.2 neutral density. The log of the ratio of the exposure times was 1.12. Each subject received four flashes of each condition. The mean of all data for each condition was 17.74 sec for 559 μ sec, and 17.54 sec for 42 μ sec.

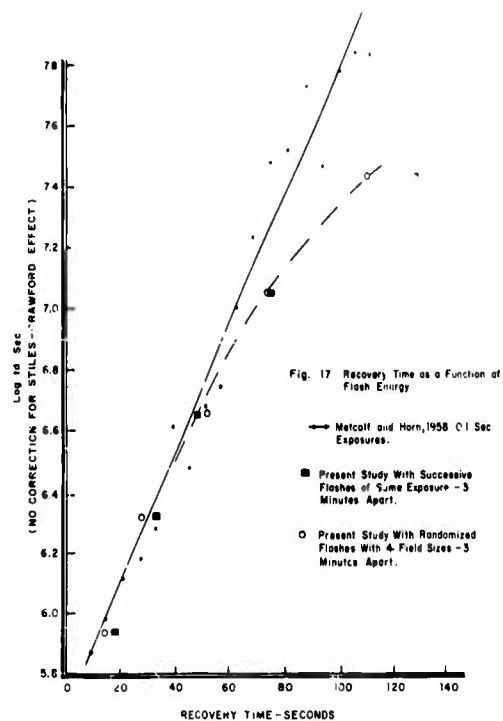
Table 111. Effect of Removing the Infrared on the Recovery Times for a 0.066 mμ Test Letter

<u>28.6' visual angle</u>			
Subject	KG-3	0.13 Neutral	Unfiltered
J. C.	60.92	51.08	57.32
L. L.	115.35	94.95	147.57
D. H.	38.15	41.47	55.60
E. H.	49.42	50.12	70.71
W. K.	62.85	55.00	67.80
Means	65.34	60.52	79.80

<u>20.3' visual angle</u>			
Subject	KG-3	0.13 Neutral	Unfiltered
J. C.	79.87	70.08	75.04
L. L.	130.3	112.32	161.00
D. H.	46.75	54.97	67.85
E. H.	68.27	68.37	87.42
W. K.	84.20	84.01	80.64
Means	81.88	77.95	94.42

Table IV. The Effect of Exposure Durations on Recovery Times
for a 0.066-ml. Test Letter, 20.3' Visual Angle

Order of flashes from shortest to longest duration					
Subject	.042 msec	.103 msec	.223 msec	.558 msec	1.401 msec
V. K.	14.55	85.48	70.42	167.76	213.88
J. C.	6.95	14.47	16.75	53.86	116.30
D. H.	29.50	44.15	48.25	102.95	145.72
D. M.	9.57	16.60	22.41	35.65	81.42
L. L.	14.95	12.97	22.45	39.55	120.82
E. H.	25.52	23.02	29.37	62.02	51.00
Means	17.22	33.12	34.95	76.97	121.52
Order of flashes from longest to shortest duration					
Subject	.42 msec	.103 msec	.223 msec	.558 msec	1.401 msec
V. K.	31.75	40.40	76.75	48.85	170.22
J. C.	20.50	38.75	55.10	100.22	162.95
D. H.	34.40	59.07	40.57	63.10	101.90
D. M.	9.50	16.90	28.10	46.93	93.22
L. L.	11.62	17.25	61.58	115.10	177.92
E. H.	13.95	20.75	40.72	59.85	105.42
Means	20.30	32.19	50.47	72.34	134.94



C. THE EFFECT OF FIELD SIZE

To test the effect of field size, an experimental design was developed using a 5 x 5 x 5 Latin Square that would allow statistical analysis of the effect of the field subtense, and of the exposure duration and any interaction between them. Five subjects were used and they tested the 25 combinations of the five fields and the five exposure durations in random order. In randomizing the flash conditions, the cumulative effects of the higher energy flashes could be cancelled out. The test letter for measuring the recovery times subtended 20.3 min of arc and had a luminance of 0.066 mL.

The data, listed by subject and by field size for each of the exposure durations, are shown in Table V. Each value in the table is based on just one flash of the given conditions. Table VI gives the mean recovery times for all five subjects for each of the fields and exposures. The analysis of variance has not been completed as yet but the recovery for the four larger fields, subtending angles of 10° , 7.5° , 5° , and 2.5° , do not appear to be significantly different by inspection. The mean for these four fields for the different exposures is shown at the bottom of the table compared with the values for the $20'$ field.

The data for the four larger fields are plotted in Fig. 17 as open circles. It is probably more valid than the data taken with successive flashes at the different durations. At least in the case of the longest exposure, the recovery time is shortened in the randomized design.

The similarity of results with the four fields subtending visual angles larger than that subtended by the fovea, indicates that once the total fovea is exposed, the luminance of the flash and its duration are the only factors contributing to recovery time. This is the same result that was obtained by Russell with 2° and 20° fields.

Table V. Recovery Times for the Different Combinations of Field Size and Exposure

Field Size	.042 msec	.103 msec	.223 msec	.558 msec	1.401 msec
<u>L.L.</u>					
10°	13.7	18.8	55.0	73.2	119.2
7.5°	19.8	15.0	60.2	102.8	118.7
5.0°	12.5	10.3	48.5	87.0	120.0
2.5°	12.9	35.5	103.8	86.0	103.4
20'	6.5	5.3	7.3	10.5	123.0
<u>V.K.</u>					
10.0°	14.2	37.5	23.0	65.6	149.8
7.5°	8.0	41.5	79.1	75.5	164.4
5.0°	8.4	35.7	28.5	145.4	115.5
2.5°	8.0	24.3	59.2	41.8	107.0
20'	7.5	15.0	5.7	15.5	38.4
<u>D.H.</u>					
10.0°	17.0	40.62	22.33	39.35	84.8
7.5°	13.0	24.17	23.7	64.9	66.3
5.0°	12.4	11.8	48.22	46.4	85.6
2.5°	5.5	32.3	38.1	61.2	68.5
20'	3.6	12.4	5.1	16.8	37.0
<u>E.H.</u>					
10.0°	15.0	38.3	90.0	76.5	133.0
7.5°	28.5	27.0	37.2	36.0	115.5
5.0°	27.5	35.0	89.5	101.0	92.5
2.5°	26.1	39.4	101.2	83.7	180.7
20'	17.5	10.0	5.3	30.0	14.9
<u>J.C.</u>					
10.0°	12.6	25.2	24.4	72.5	63.3
7.5°	12.8	19.4	46.3	47.1	104.3
5.0°	9.4	29.5	24.8	99.2	84.2
2.5°	7.3	16.6	36.6	76.8	118.7
20'	5.1	8.1	5.0	7.4	5.6

Table VI. Summary of Recovery Times for Different Field Sizes and Exposure Durations (Means of the Data for the Five Subjects)

Field Size	0.42 msec	.103 msec	.223 msec	.556 msec	1.401 msec
10.0°	14.49	32.07	42.94	65.42	110.02
7.5°	16.41	25.40	49.28	65.26	113.61
5.0°	14.02	24.46	47.89	95.79	99.56
2.5°	11.96	29.62	67.77	70.31	115.66
20'	8.05	10.15	5.67	16.02	45.77
Mean of the four larger fields	14.22	27.89	51.97	74.19	109.71

D. THE EFFECT OF PREADAPTATION LEVEL PRIOR TO THE FLASH

Five subjects tested the effect of preadaptation prior to receiving 0.56-msec flashes with a test letter subtending 20.3' and a luminance of 0.006 mL. Three adaptation levels were used with the luminance of the 10° adaptation field at 1.83, 0.137, and 0.010 L. Each subject received four flashes for each of the conditions. Prior to each flash, the subject was given a 10-sec exposure to a field 1.1 log units higher than the adaptation field luminance used. The light was reduced at the end of the 10 sec by the addition of a neutral density filter in the beam. The 10° flash field was superimposed on the adapting field and then the adapting field was extinguished immediately after the flash. The data for the individual subjects shows a slight tendency for a cumulative effect of the successive flashes, especially for the lower field luminances. The data have not yet been analyzed to test the significance of the trend. If the analysis confirms the cumulative effect, the experiment will be repeated with longer inter-trial intervals.

Table VII. The Effect of Preadaptation Prior to the Flash Recovery Times from a 0.56-msec Flash to a 0.066 mL Letter Subtending 20.3'

Subject	Preadaptation Luminance		
	1.83 L	0.137 L	0.010 L
J. C.	118.5	67.7	65.5
L. L.	178.7	138.0	111.4
E. H.	96.1	42.3	43.5
D. H.	94.4	73.2	66.1
V. K.	53.8	57.7	60.9
Means	108.30	75.78	69.47

E. THE EFFECT OF TEST LETTER SIZE AND LUMINANCE

The experimental result for the effect of changing the test letter size and luminance are not yet completed.

VI. INTERPRETATION OF RESULTS AND CONCLUSIONS

Even though the statistical analysis of the data is not complete, certain conclusions can be drawn from the results with reasonable confidence. The similarity between our data for constant luminance flashes and varying exposure durations, and the data of Metcalf and Horn for constant duration and varying luminance, suggest that the reciprocity relationship between time and intensity holds, at least within the range of 100 msec of their flash to 0.042 msec of our shortest flash.

The effect of preadaptation seems to be the same as increasing the energy in the flash by an amount necessary to produce the same degree of foveal pigment bleach as is produced by the preadaptation field. Fairly large amounts of infrared radiation in the flash apparently have no effect on recovery times.

Some additional work needs to be done before the standard statistical tests of significance of the various trends can be applied. The form of the

distribution of the data for one condition must be found by compiling a large body of data for the one condition to determine if the standard tests of significance are valid in this type of data.

The effect of field size on recovery time appears to be negligible once the field is large enough to expose the entire fovea. This indicates that the luminance of the flash, and hence the retinal illuminance of the image, is the determining factor, and not the illumination at the eye. It would appear to be desirable, therefore, to express the energy in terms of troland-sec for any flash subtending an angle greater than 2.5° and for any duration down to 40 μ sec.

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