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VISUAL RECOVERY FROM BRIEF EXPOSURES TO VERY HIGH LUMINANCE LEVELS

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FOREWORD

This paper was prepared at the Ohio State University Research Foundation, Columbus, Ohio, by—

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ABSTRACT

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 4.4×10^5 L. 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 μsec. 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 0.0666 mL.

This technical documentary report has been reviewed and is approved.

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VISUAL RECOVERY FROM BRIEF EXPOSURES TO VERY HIGH LUMINANCE LEVELS

1. 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. Russell (1) 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} L.sec. His highest field luminance was 1.7×10^{3} L. and his shortest exposure was 5 msec. with the longest, 10 sec.

Fry and Alpern (2) 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 Horn (3) 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-minute 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, 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

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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 threshold values were the criteria of measure in this and previous studies. In the practical application of a study such as this, 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.

2. SCOPE OF THE PRESENT STUDY

The present study was designed to investigate a number of variables of flash presentation that might affect recovery time. The flash exposure times were varied from 42 to 1,400 μsec. Provision was made to present the flashes in five field sizes from a point source (approximately 20 minutes 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 3 minutes in a dark room to adaptation to a 10° field of 1.83 L. Five letter sizes were used for the targets to measure 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 5 or 6 subjects performed each of the experiments as an aid in making the results more generally applicable. The group of subjects consisted of 5 men and 1 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 1 msec., or longer, but more data are needed for shorter durations.

3. 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 figure 1. The optical system consisted of four main elements: (a) the flash source exposure branch, (b) the optical train containing the field stop for the flash exposure and providing the Maxwellian view of the flash, (c) the adapting field system, and (d) 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.

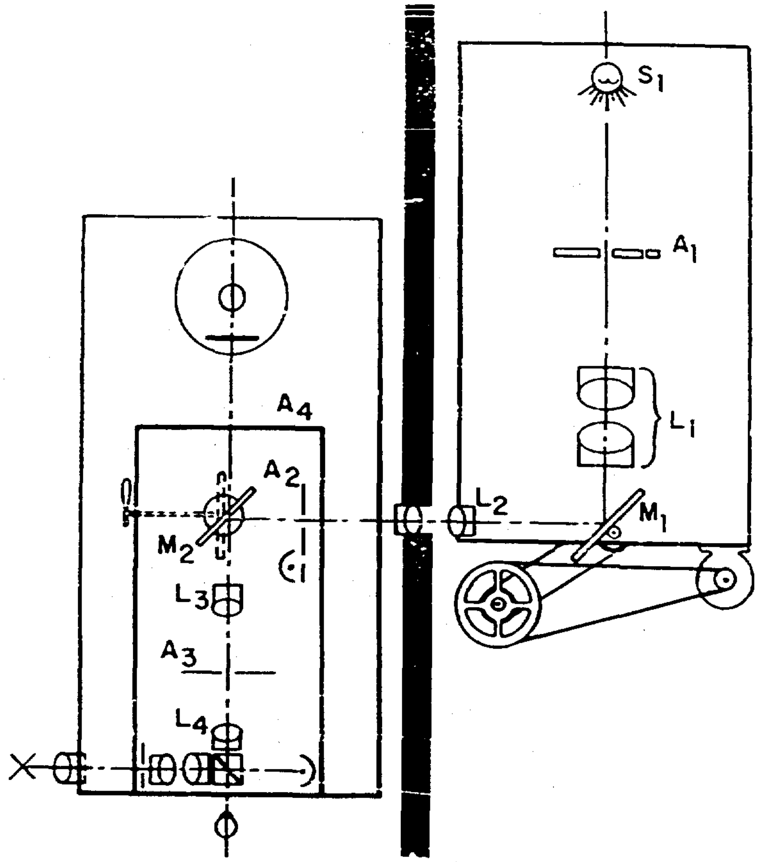

FIGURE 1

Schematic of optical system.

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. It also 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.

A beam splitter was mounted between the last achromat and the subject so that 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 that 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

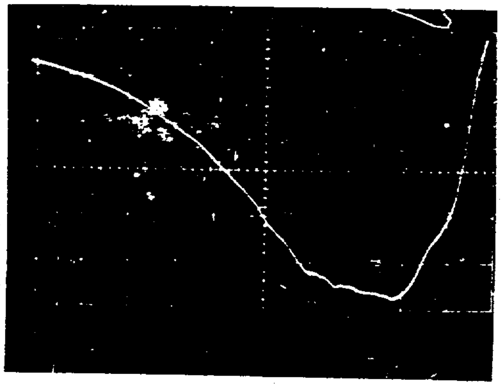

FIGURE 2

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

FIGURE 3

Flash tube during discharge showing unevenness of luminance.

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 that the natural pupil operated to control the retinal illuminance of the letters.

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 w. sec. The time characteristics of the flash are shown in figure 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 figure 3 at unit magnification. It seemed desirable to use only one of the bright segments for the flash source because of 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 1 minute between successive flashes, the peak luminance varied less than 5%. There was an increased variation of about 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 contained a voltmeter in the control panel that 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 discussed fully in a later section on the calibration of the apparatus.

Control of exposure durations

Originally, it was proposed to use a rotating sector for a shutter mechanism to control the

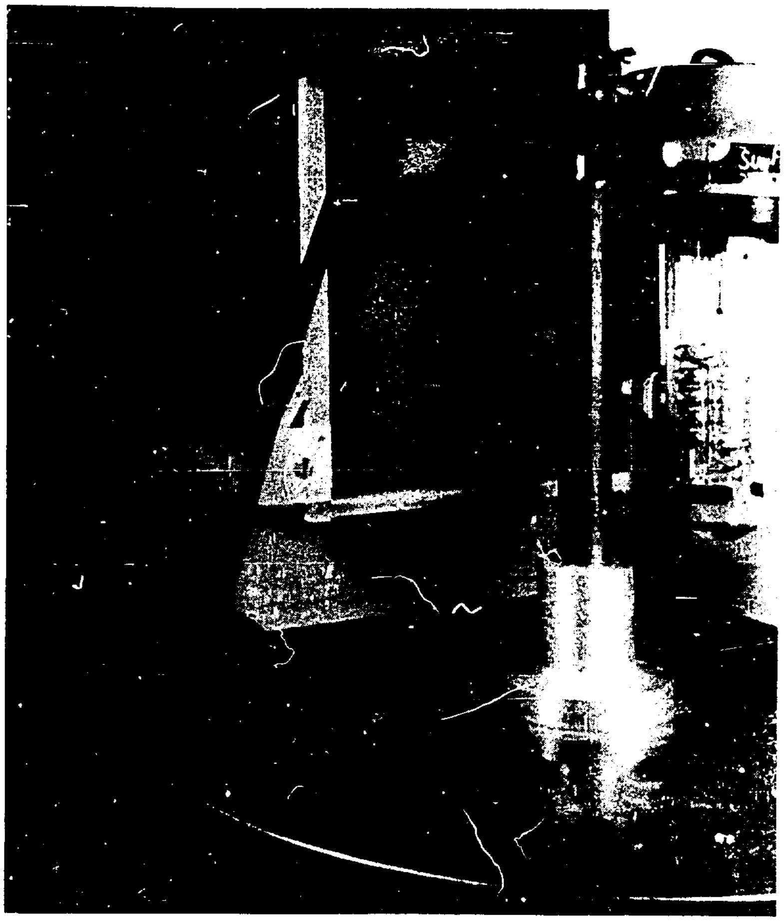

FIGURE 4

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

exposures, but the hazards involved in driving a 36-in. sector disc at 1,800 r.p.m. 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° flash field for exposure times as low as 50 μsec. A system utilizing a rotating mirror in a collimated beam was finally decided on. 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 in. 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 1,725 r.p.m. 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 figure 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 panel, 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

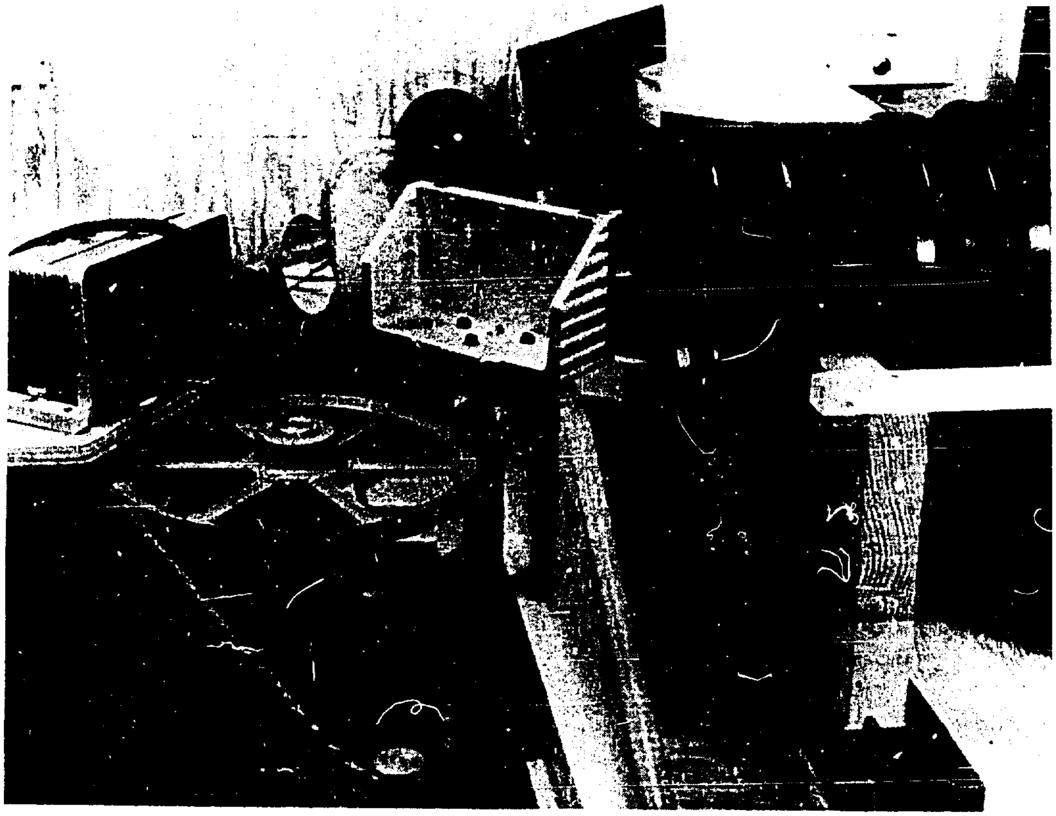

FIGURE 5

The rotating mirror mount with the 48-in. collimating lens and the 20-in. lens.

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 theoretic 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. Since 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. Therefore, 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 in. (508 mm.) from the nodal point. The linear velocity of the image can be calculated from the formula for the circumference of the circular path of the image and from the speed of rotation of the mirror:

$$\text{Velocity of image (mm./sec.)} = \frac{2\pi \times 508 \times 2 \text{ r.p.m.}}{60}$$

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:

$$t = \frac{2 \times 4.1 \times 60}{2 \times 508 \times 2 \text{ r.p.m.}} = \frac{0.07712}{\text{r.p.m.}}$$

The maximum and minimum speeds available with our pulleys were 1,820 and 55 r.p.m., yielding maximum and minimum pulse durations of 1.4 msec. and 42 μsec.

Although the decision to substitute the rotating mirror unit for the sector disc shutter introduced a few time-consuming problems, they were eventually solved. The mirror mount shown in figure 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 that 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 because of 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.

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 delay of 1 msec. 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 delay of 1 msec. 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. Furthermore, 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 the highest speed it was 11°.

It was found that the external triggering phototube supplied with the unit would respond to an auxiliary xenon flash, but not to tungsten light. 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.

As the General Radio Strobotac is an adequate source to operate the external phototube, several attempts were made to trigger the Strobotac 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 in that a long

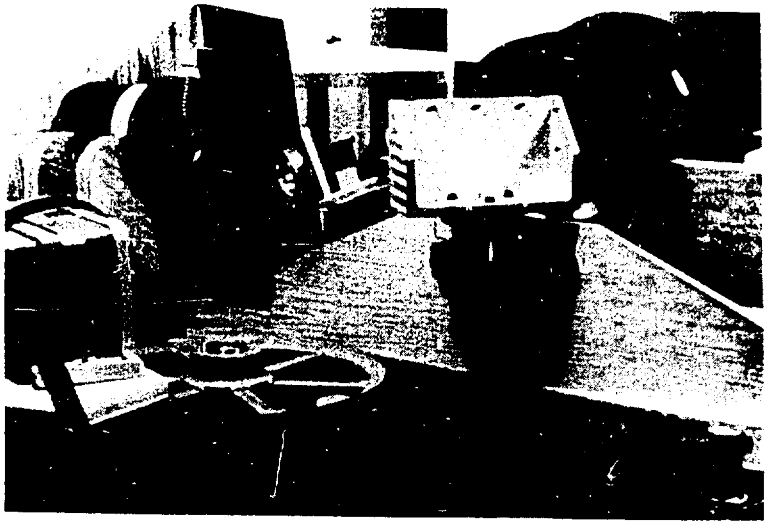

FIGURE 6

Lens and beam splitter for triggering flash in phase with mirror rotation.

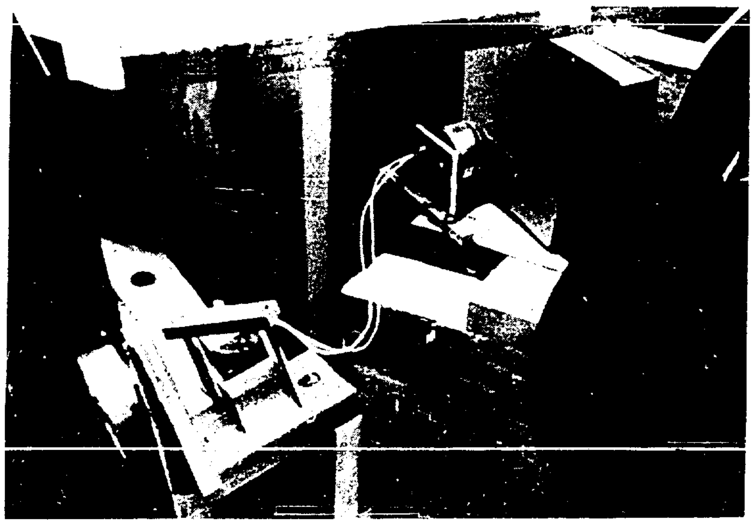

FIGURE 7

Detail of beam splitter showing rotary solenoid shutter over phototube.

optical lever was utilized to provide a fine adjustment on positioning the photocell. The system failed because the response of the photocell varied with previous light exposure and temperature. A lag as high as 20 msec. occurred.

The final arrangement was even more complex but had the advantage of great stability and quite adequate precision. The apparatus is shown in figure 6, with additional detail in figure 7. The Strobotac was fired by the external contactor maunfactured 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. Furthermore, 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

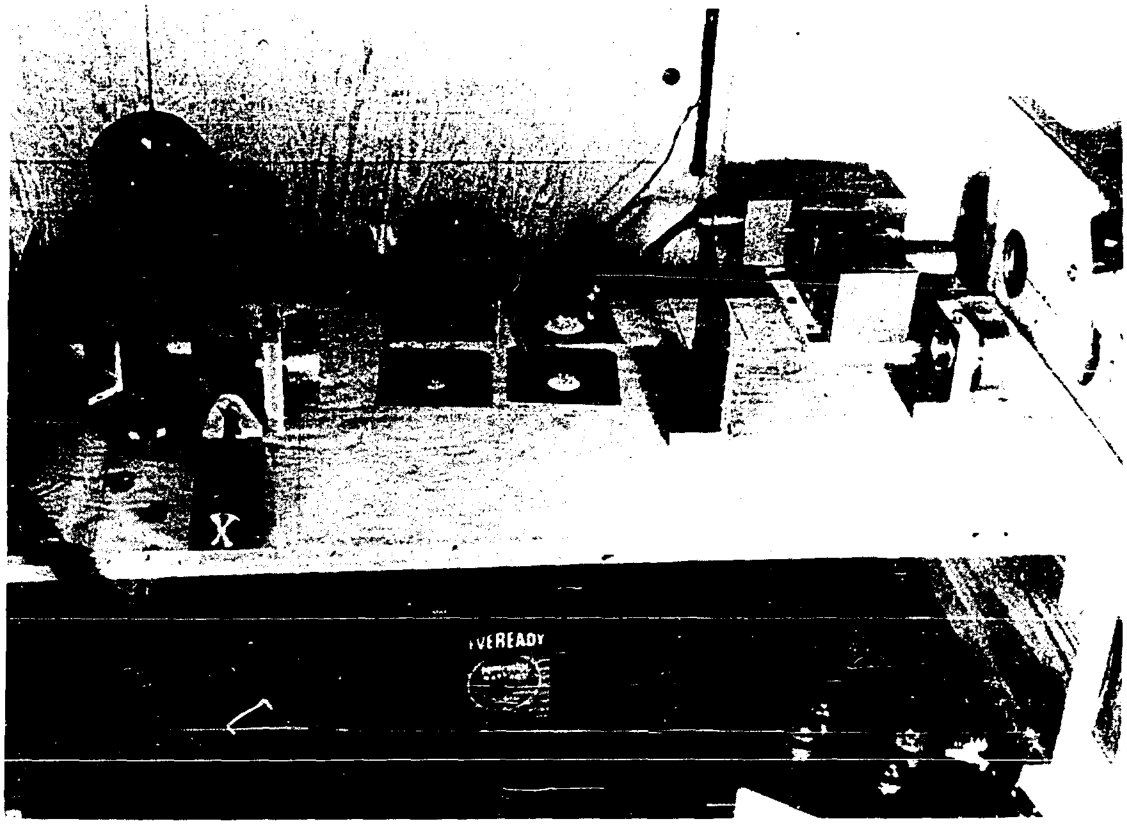

FIGURE 8

Maxwellian view system for flash exposures showing exposure limiting aperture.

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 on 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 1 msec. before the correct mirror orientation 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 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. With careful adjustment of the contactor on the mirror shaft, however, it could be kept within acceptable tolerance.

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 door 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 that 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 that 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; therefore, 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.

Monitoring the flashes

The phototube chassis, shown in the upper right of figure 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. Therefore, a 10× attenuating probe was used for the coupling resulting in a definite improvement in displayed signal. Some loss was still experienced at the shortest exposure time, and the problem has not yet been solved. The arrangement was quite adequate, however, to 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.

Adapting field system

The view of the apparatus from the subject's side of the board, seen at the right of figure 8, is shown in figure 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 a.c. line and the 6 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 that its image could be centered in 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 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 transilluminated by the lamp through a red filter. Since the subject controlled the luminance of the markers with the Variac, 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.

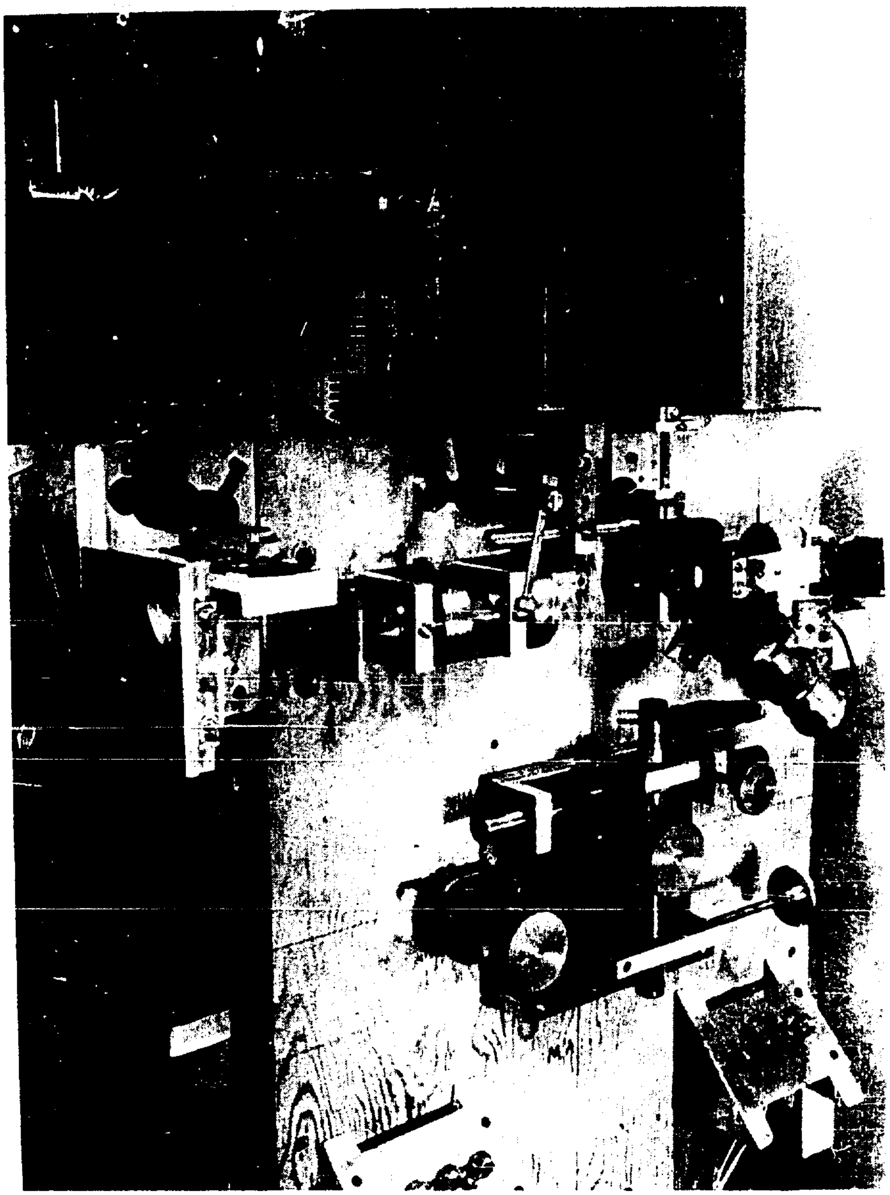

FIGURE 9

Adapting field system and bite plate mounting.

During the portion of the experimental sessions involving the adapting field, an additional lamp housing, holding a 100-w. frosted lamp, was added above the adapting field optics. It is shown in the upper left of figure 9. It provided the source for projecting an image of the fixation cross through an auxiliary 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. As the adapting field was turned off immediately after the flash, 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.

The beam splitter cube in the center of figure 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.

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 millimeters in front of it—i.e., closer to the beam splitter. This provided a peephole 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 peephole 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 figure 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 peephole 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 the sighting device in figure 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 Maxwelliam 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.

Stimulus letters

Recognition of Sloan-Snellen letters was chosen as the criterion 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 proved 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 one-fifth 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 Grether (4) cite the height of numerals and letters on instrument panels of 0.15 to 0.30 in. for a viewing distance of 28 in. for low luminance viewing, and 0.10 to 0.20 in. for higher luminances down to 10 ft.-L. These figures represent visual angles of 18.4 to 36.8 minutes 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 minutes 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, the subjects were unlikely to memorize the order of the letters. The position of the drum relative to the rest of the

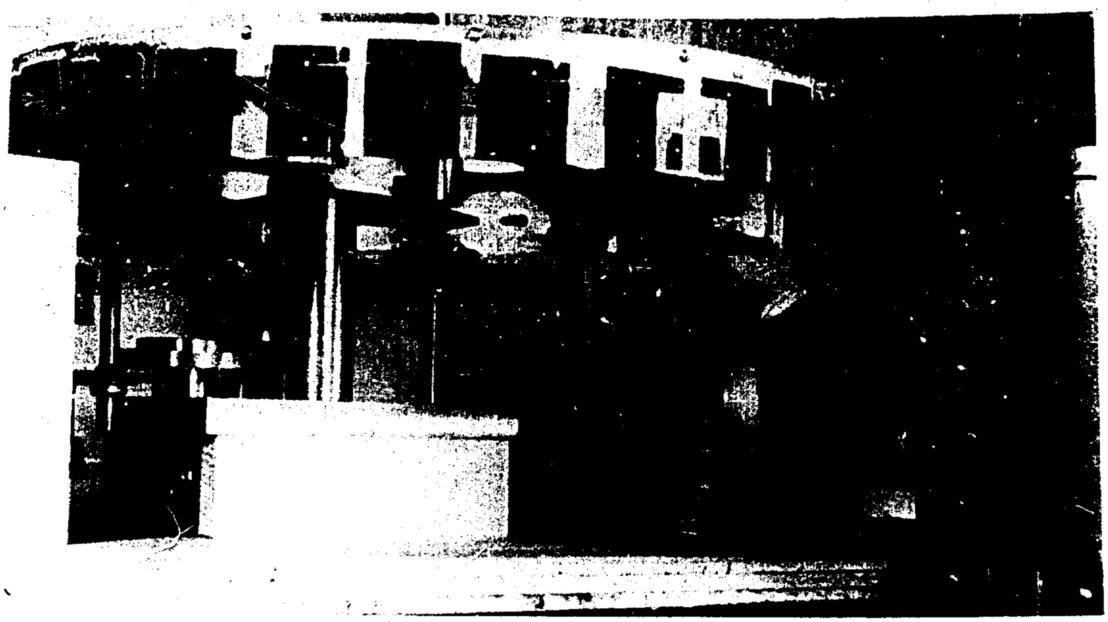

FIGURE 10

The stimulus drum for presenting the test letters.

apparatus is shown at the top left of figure 9. The driving mechanism and illuminator are shown in greater detail in figure 10. Two drums were machined so that the different sized letters could be alternated easily, and usually two different sized letters were mounted on one drum so that the recovery times for two sizes could be determined with one flash. The drums were mounted on a shaft driven by a 1,725 r.p.m. 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 that 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 figure 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 figure 9. The opening in this plate was 9 mm. in diameter and it was conjugate to the subject's pupil through the 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

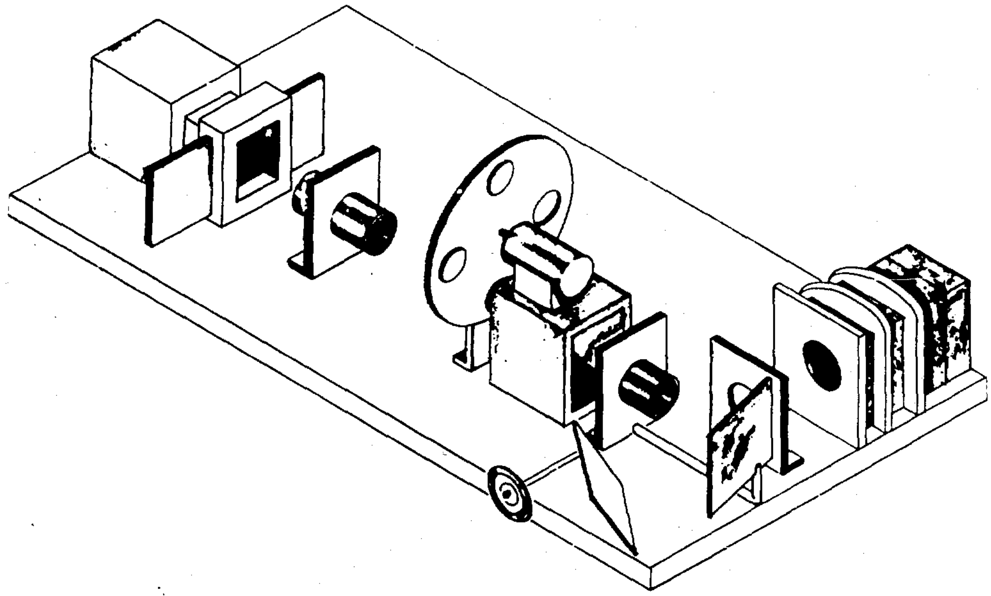

FIGURE 11

Schematc of optical systcm of the pupillograph.

arranged near the back of the stimulus drum so that the experimenter could compare the subject's responses with the letter just exposed.

Measuring the recovery times

An electric clock with a 110-v. direct current 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 alternating current 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 signaled 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 1 sec. intervals. When he scored two correct responses, the experimenter recorded the time and then when one of the smaller groups 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 signaled the responses so that the experimenter could record the time when the criterion was reached.

The pupillograph

An infrared pupillograph, for automatically recording the changes in the pupil diameter, was built by King's description (5), with slight modifications. 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 figure 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 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 that the

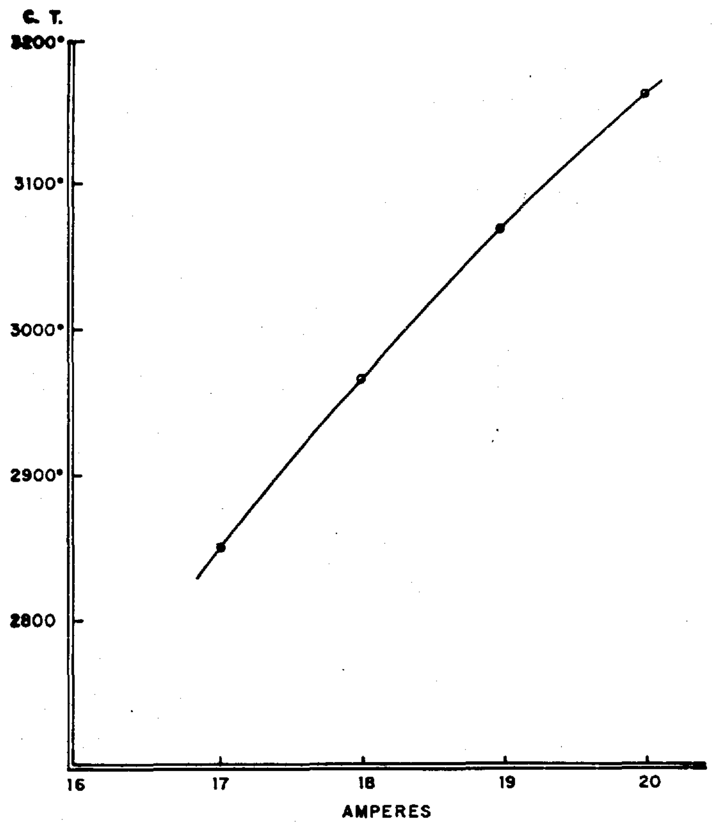

FIGURE 12

Color temperature of ribbon filament as a function of current.

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. It is in a form for clinical use, however, and embodies 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 that 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 commercal instrument.

4. CALIBRATION

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 mμ and the other at 400 mμ. The ribbon filament lamp was chosen as the standard source because of its stability and its rather large uniformly bright surface. As precise measurements of the characteristics of tungsten ribbon have been made in the past by Forsythe and others, its spectral distribution and luminance are well established as a function of the current. Figure 12 is a curve redrawn

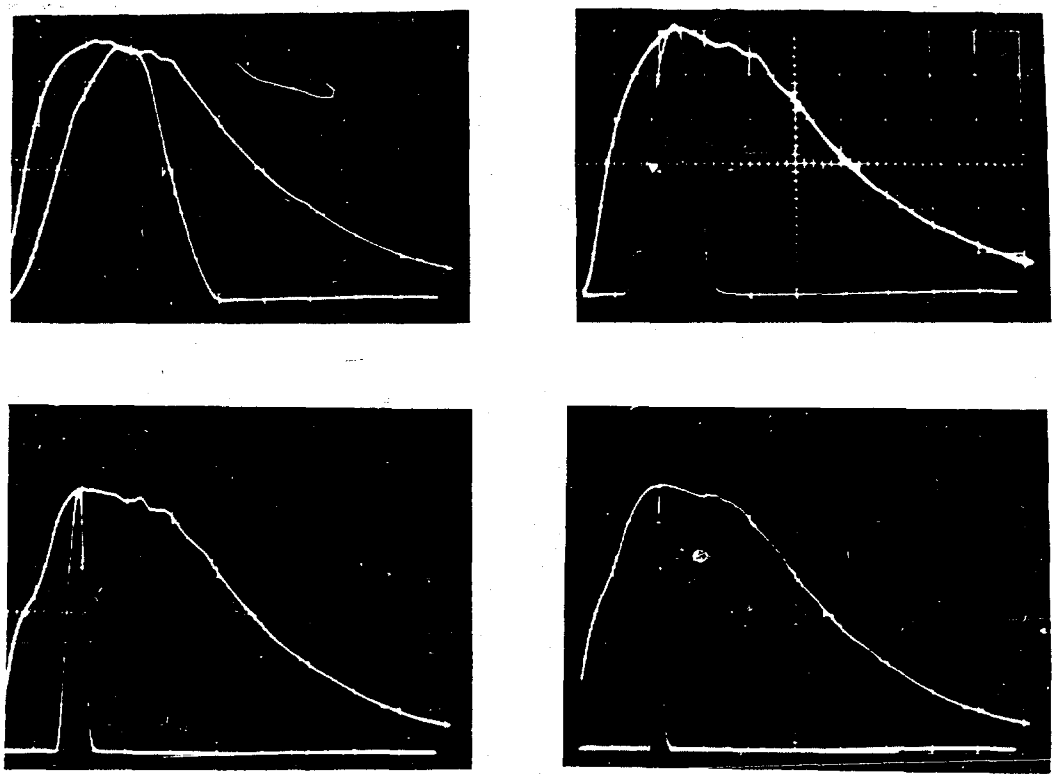

FIGURE 13

Spectral steradiancy of tungsten ribbon filament at 2,965° color temperature.

from the data of Forsythe and Worthing (6) 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-mμ 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 a. throughout the calibration. The current and voltage were held constant by using a power supply with less than 1% ripple connected to the a.c. line through a voltage regulator. A sensitive ammeter was monitored continuously during the exposures. The spectral steradiancy for the ribbon filament under these conditions of operation is shown in the curve of figure 13 interpolated from the data described above. From figure 12, the color temperature of the filament at 18.0 a. would be 2,965°. As a check on the values interpolated from energy curves and plotted in figure 13, the luminance of the filament was calculated by using standard photopic luminosity factors. This calculation indicated a filament luminance of 867.16 candles/cm.^{2}

The lamp was substituted for the flash tube and focused on the entrance aperture which was masked down to an 8.2 mm.^{2} Since the image of the filament was larger than the aperture, it acted as a uniformly bright source. The luminance was measured with a MacBeth illuminometer by placing the reference plate 20 in. from the aperture and measuring the illumination of the plate. This gave a value of 938 candles/cm.^{2} 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 1,100 mμ were measured on a spectroradiometer. There were 24 bands in

TABLE I

Spectral steradiancy of Sun-Flash tube

λ (mμ)	Flash (tungsten) (919)	Flash (tungsten) (929)	Flash (tungsten) (av.)	w.λ (tungsten) (w./cm.²/ 10 mμ)	w.λ Flash (w./cm.²/ 10 mμ)
423		1318	1318	0.0322	42.4
434		1330	1330	0.0380	50.6
435		1800	1800	0.0381	68.6
443.5		1750	1750	0.0421	73.9
457.5		1850	1850	0.0498	92.2
464.8		1200	1200	0.0540	64.9
477	2020	1875	1998	0.0615	122.8
503.4	944	1165	1054	0.0790	83.4
510	901	1065	983	0.0836	82.2
532.6	939	902	920	0.0996	91.7
554.2	685	714	700	0.1162	81.4
555	701	702	701	0.1165	81.7
570	554	628	591	0.1278	75.5
580	498	472	485	0.1345	65.3
621.9		344	344	0.1626	55.9
640.4	344	301	323	0.1748	56.4
657.8	314	311	313	0.1853	58.1
685.9		352	352	0.1998	70.3
701.3	262		262	0.2065	54.2
828	239		239	0.2476	59.1
887	342		342	0.2530	86.5
1005	716		716	0.2420	173.2
1015	686		686	0.2404	165.1
1050	665		665	0.2342	156.0

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 10× 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-in.-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 that the same time scale could be used on the measuring oscilloscope as was used with the flash source. With 1-megohm load resistors in the phototubes, this arrangement yielded signals of from 0.1 to 5 v. with the 919 tube, and 0.6 to 20 v. with the 929 tube. 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

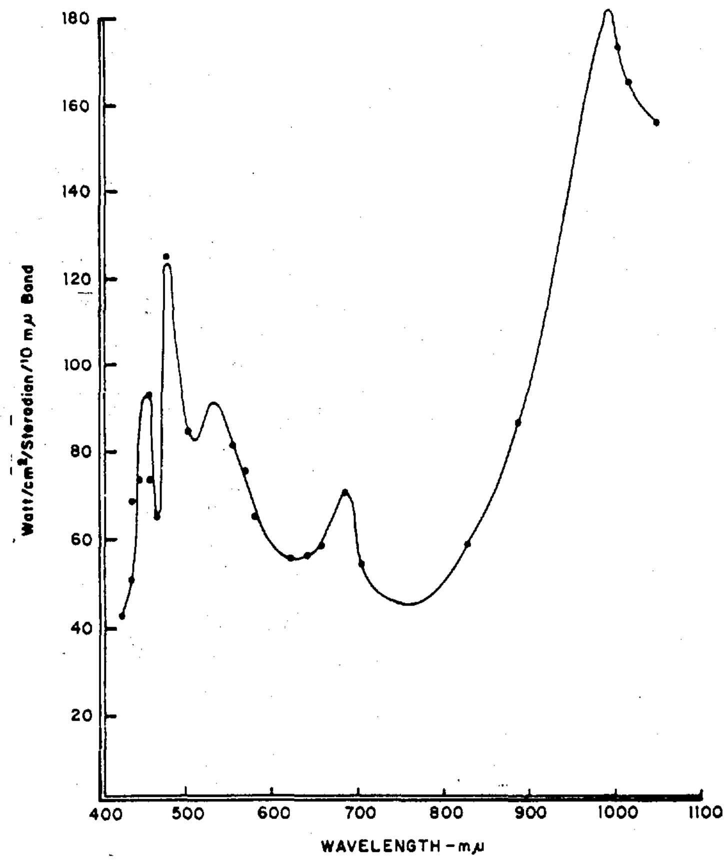

FIGURE 14

Spectral steradiancy of Sun-Flash tube.

and the tungsten ribbon filament is shown in column 2 as measured with the 919 tube, and in column 3 with the 929 tube. Column 4 gives the average ratio of the two sources, and column 5, the energy in w./cm.^{2}/10 mμ band for tungsten at each of the transmission peaks. The values were interpolated from figure 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 figure 14. When the energy of the flash is multiplied by the standard photopic luminosity factors, and the sum multiplied by 680 lm/w., the luminance of the brightest portion of the Sun-Flash tube is found to be 5.45×10^5 candles/cm.^{2} Six weeks later, at the end of the experimental sessions, during which time the tube was in use 6 to 8 hours a day, this value had dropped by 10%.

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. After the luminance of the flash source was determined, 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 that 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 candles/cm.^{2} 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 candles/cm.^{2} 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 manufacturer's 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 in. behind the filament image and the illumination was 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 candles/cm.^{2} for the field luminance.

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 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—that is, 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 that 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 are 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.

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

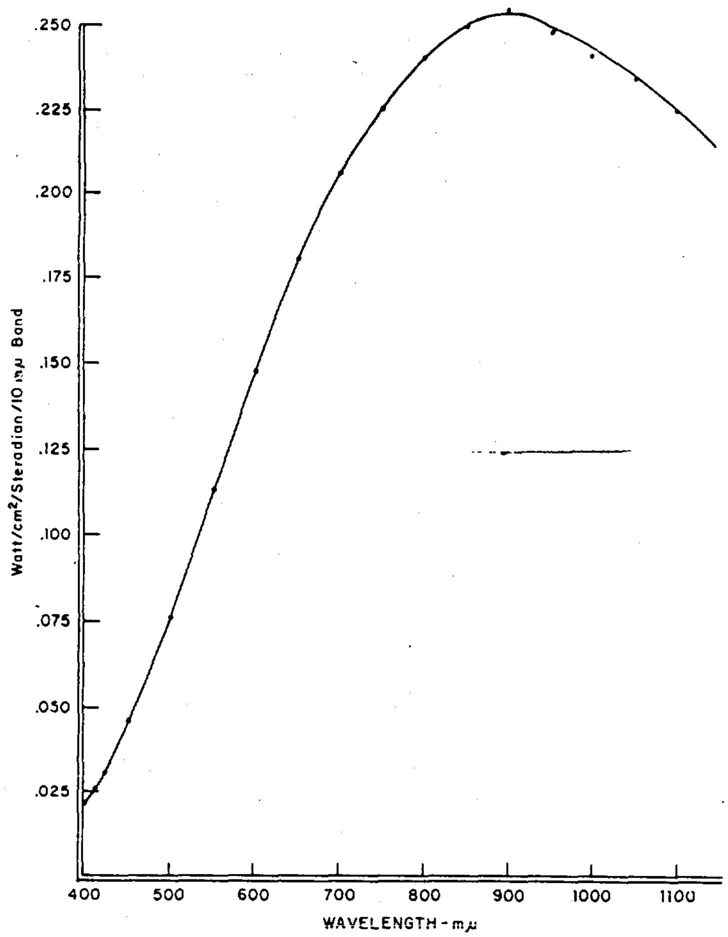

FIGURE 15

Oscilloscope traces of the different pulse durations showng the portion of the total flash used with the different mirror speeds.

TABLE II

Exposure durations and the product of retinal illuminance and exposure for the different mirror speeds

Rotational speed (r.p.m.)	Exposure calculated (msec.)	Exposure measured (msec.)	Log energy (Troland 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
1,820	0.042		5.94

illuminating the adapting field was controlled with a Variac between the line and the 6 v. transformer. Walsh (8) gives as the luminance of clear blue sky 1.25 L.; therefore, 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, the value was equivalent to 1.83×10^4 Troland sec. According to Rushton's data (9) on the bleaching of foveal pigments, 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 3 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 technic, 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. Since the adapting field was extinguished immediately after the flash, the test letters were seen against a dark field for all conditions.

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 that 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 instrument 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 minutes 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 5 in others. They were all students in, or recent graduates of, the School of Optometry, except for one psychology student. Since they had all taken part in the final assembly and in the calibration of the apparatus, 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 staff of the Statistical Laboratory to insure the validity of the subsequent statistical analysis.

Effect of removing the infrared on the recovery times

A KG-3 filter was used to absorb all radiation past 850 mμ to find if the large energy band at around 1,000 mμ in the flash contributed significantly to the length of recovery. The transmission curve of the 3-mm.-thick KG-3 filter is shown in figure 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. Since the flashes were presented 3 minutes apart, 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 (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.

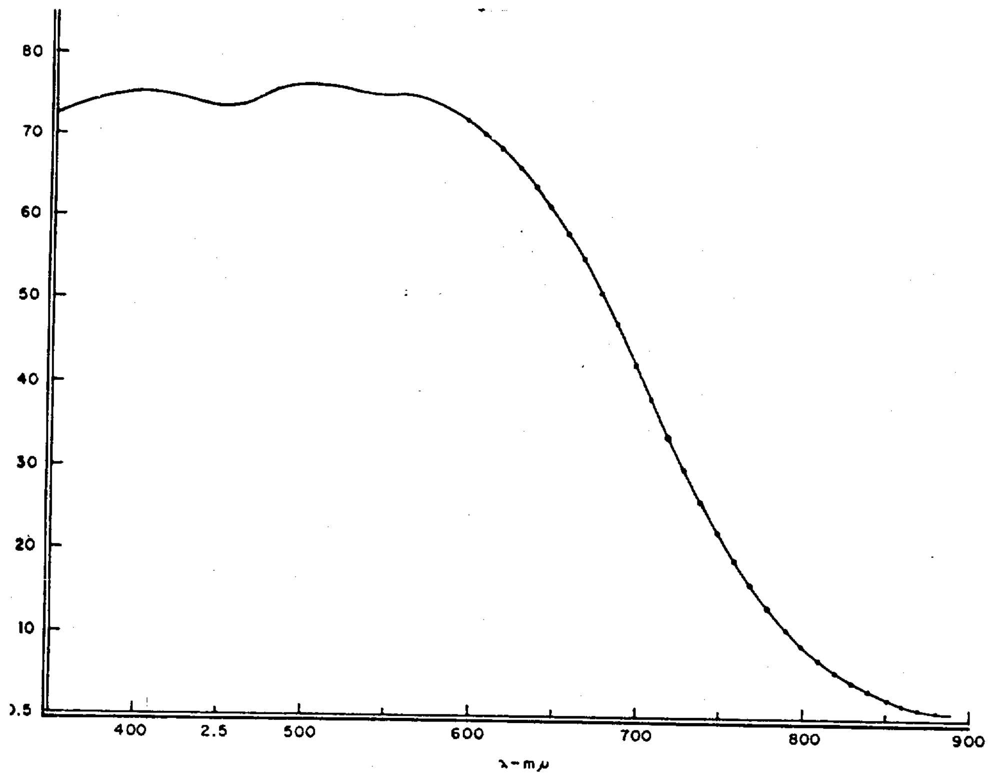

FIGURE 16

Transmittance of KG-3 filter, 3 mm. thick.

TABLE III

Effect of removing the infrared on the recovery times for a 0.066-mL. test letter

Subject	KG-3	0.13 Neutral	Unfiltered
Visual angle, 28.6 min.			
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
V. K.	62.85	65.00	67.80
Means	65.34	60.52	79.80
Visual angle, 20.3 min.			
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
V. K.	84.20	84.01	80.64
Means	81.88	77.95	94.42

Effect of exposure durations on recovery times

The recovery times for the identification of a 0.066 mL. test letter subtending 20.3 minutes of arc were measured following flash exposures of five different durations, ranging from 0.42 to 1.40 msec. Each of the 6 subjects received four flashes of each duration. The flashes were presented 3 minutes apart, except when the recovery time exceeded the interflash interval; the subject was given 30 sec. 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 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 is listed by subject for the two orders of conditions.

The mean of all of the data for each exposure duration is shown in figure 17, plotted against the log of retinal illuminance times exposure time. On the same curve are the data of Metcalf and Horn with the ordinates in units of log Troland sec. No correction for the Stiles-Crawford effect has been made in calculating

TABLE IV

Effect of exposure durations on recovery times for a 0.066-mL. test letter, 20.3 min. visual angle

Subject	0.042 msec.	0.103 msec.	0.223 msec.	0.558 msec.	1.401 msec.
Order of flashes from shortest to longest duration					
V. K.	14.55	85.48	70.42	167.76	213.88
J. C.	8.95	14.47	16.75	53.88	116.30
D. H.	29.80	44.15	48.25	102.95	145.72
D. M.	9.57	18.60	22.47	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					
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.	9.60	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	103.42
Means	20.30	32.19	50.47	72.34	134.94

the retinal illuminance for their pupil, 6 mm. in diameter, or our Maxwellian beam, 4 mm. square. 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 μsec, our shortest exposure time. As an additional check on this relationship, 6 subjects tested the recovery times following 42 μsec. flashes, and following 559 μsec. 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 μsec, and 17.54 for 42 μsec.

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 canceled out. The test letter for measuring the recovery times subtended 20.3 minutes 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 5 subjects for each of the fields and exposures. The analysis of variance has not been completed yet, but the recovery for the four larger fields, subtending angles of 10°, 7.5°, 5.0°, 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-ft. field.

The data for the four larger fields are plotted in figure 17 as open circles. It is probably more valid than the data taken with successive flashes at the different durations.

TABLE V

Recovery times for the different combinations of field size and exposure

Field size	0.042 msec.	0.103 msec.	0.223 msec.	0.558 msec.	1.401 msec.
L. L.					
10.0°	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 min.	6.5	5.3	7.3	10.5	123.0
V. K.					
10.0°	14.2	37.5	23.0	65.6	149.8
7.5°	8.0	41.5	79.0	75.5	163.3
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 min.	7.5	15.0	5.7	15.5	38.4
D. H.					
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 min.	3.6	12.4	5.1	16.8	37.0
E. H.					
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 min.	17.5	10.0	5.3	30.0	14.9
J. C.					
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	34.2
2.5°	7.3	16.6	36.6	78.8	118.7
20 min.	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.	0.103 msec.	0.223 msec.	0.558 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 min.	8.05	10.15	5.67	16.02	43.77
Mean of the four larger fields	14.22	27.89	51.97	74.19	109.71

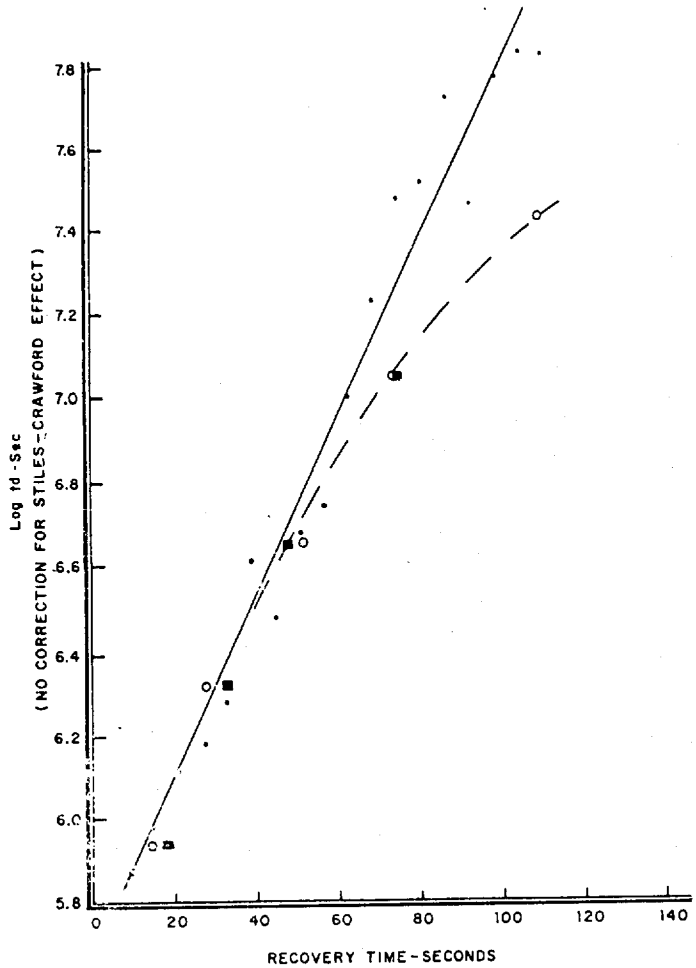

FIGURE 17

Recovery time as a function of flash energy.

Metcalf and Horn (3), 0.1 sec. exposures.

Present study with successive flashes of same exposure, 3 minutes apart.

Present study with randomized flashes with four field sizes, 3 minutes apart.

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 VII

Effect of preadaptation prior to the flash recovery times from a 0.56-msec. flash to a 0.066-mL. letter subtending 20.3 min.

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.	90.1	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

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 minutes of arc and a luminance of 0.066 mL. Three adaptation levels were used with the luminance of the 10° adapation 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 show 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.

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 (3), for constant duration and varying luminance, suggests 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 addi[illegible] before the sta[illegible] icance of the [illegible] The form of th[illegible] one condition must be [illegible] large body of data fo[illegible] determine if the standa[illegible] are valid in th[illegible] type of [illegible]

The effect of field [illegible] appears to be negligibl[illegible] enough to expose the [illegible] fovea. [illegible] dicates that the luminance of the flash [illegible] hence the retinal illu[illegible] of the [illegible] is the determining factor, [illegible] not the illumi[illegible]tion at the eye. It would appear to be [illegible] therefore, to express the energy in [illegible] Troland seconds for any [illegible] angle greater than 2.5 [illegible] down to 40 μsec.

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