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VISUAL RECOVERY FROM HIGH INTENSITY FLASHES II

NORMA D. MILLER

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July 1966

USAF SCHOOL OF AEROSPACE MEDICINE
Aerospace Medical Division (AFSC)
Brooks Air Force Base, Texas

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July 1966

USAF School of Aerospace Medicine
Aerospace Medical Division (AFSC)
Brooks Air Force Base, Texas

Contract Monitor
Major L. R. Loper, USAF, MSC
Task No. 630103

Prepared under Contract No. AF41(609)-2426
by Norma D. Miller of The Ohio State University
Research Foundation, Columbus, Ohio

FOREWORD

The research covered by this report was initiated by the School of Aerospace Medicine, Brooks Air Force Base, Texas and was monitored by Major L. R. Loper. The research was conducted through the cooperation of the Ohio State University Research Foundation under Contract No. AF41(609)-2426 with the USAF School of Aerospace Medicine. The author, Norma D. Miller, of the School of Optometry, The Ohio State University, was the principal investigator. Dr. Glenn A. Fry, Director of the School of Optometry was supervisor.

This work represents the third phase of a continuing effort in the area of the visual effect of high intensity flashes. The work described in the report covers the research results and development of instrumentation during the period 15 May 1965 through 15 May 1966. The work was in support of Project 6301, Task 630103.

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

ABSTRACT

Some new instrumentation has been developed and a number of refinements have been made in the existing special test equipment for investigating the visual recovery following high intensity flashes. The primary areas of apparatus modification were (1) increased capability for the measurement of source energy in absolute units, (2) increased precision in the measurement of recovery times, (3) extended range of flash durations for recovery measurements, and (4) inclusion of pupillographic recording as a measure of flash effect.

The consensual pupil reflex was measured for six subjects for flash energies from 1.5×10^5 to 3×10^7 td·sec. The flash durations were varied from 250 μsec to 1.5 sec. Flash fields subtendend a visual angle of 7.5° in most of the work with a 2° centrally fixated field used in one part of the study.

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VISUAL RECOVERY FROM HIGH INTENSITY FLASHES

I. INTRODUCTION

When the eye is subjected to an intense flash of light, there is an immediate loss of sensitivity. After a prolonged period in the dark following the flash, sensitivity returns to the normal level, if there has been no permanent damage. The time required to regain full sensitivity is dependent upon the amount of energy received during the flash and may also be dependent upon the rate of energy delivered. In certain practical problems involving exposure to flashes of light, it is not necessary to know the elapsed time following the flash to the instant when the eye has regained its full sensitivity, but it is only necessary to know the time required for the detection of critical detail in a visual display. This corresponds to regaining a certain level of visual acuity for some specified luminance of the display.

During the course of the research on high intensity flashes in this laboratory, we have used Sloan-Snellen acuity letters presented at various luminance levels as a measure of visual recovery. It was found that the results from one size acuity letters could be generalized to other sizes and to different levels of luminance by transforming

the data into terms of equivalent background luminance.[1] The transformation is accomplished by measuring the luminance of a superimposed veiling field which reduces the contrast of the acuity letters to threshold. It was found that the log equivalent background luminance was a linear function of the log of the time following the flash for periods as long as two minutes.

The subjective effect of high intensity flashes of durations of the order of a millisecond is that of a burst of light followed by a slowly decaying afterimage. The bright afterimage appears to be continuous with the flash; that is, there is no latency before the appearance of the afterimage. A series of experiments were performed[2] to measure the rate of fading of the bright positive afterimage following various flash energies and duration. It was found that the log luminance of an external field required to match the brightness of the afterimage at any instant was a linear function of the log of the time following the flash. The slope of the linear function was approximately 3.0 for the mean data for six subjects and was equal to the slope of the linear function between the log equivalent luminance and log of the time. Apparently, the process controlling recovery time for visual acuity is the same as that causing the appearance of the bright afterimage.

The high correlation between afterimage brightness

matching data and recovery time data for acuity letters indicates that either type of measurement could be used in determining the effectiveness of various flashes in depressing visual sensitivity. It is also evident that either type of measurement will give information that may be helpful in understanding the basic mechanisms of light and dark adaptation. For instance, Rushton[3,4] has shown that the threshold at any time following a flash is related to the regeneration of the photopigment bleached during the flash. Considerably more work in this area of correlating the basic mechanisms of the visual process with various conditions of light and dark adaptation needs to be done to provide an understanding of the visual process. A portion of the research performed under this contract was directed toward an investigation of the reciprocity relationship between duration and flash for flashes of equal integrated energy. The results showed a reciprocity failure with flash durations of less than one millisecond being less effective than the longer flashes. The range of durations was 0.5 to 5.0 msec and the energy was held constant at 3×10^7 td·sec.

During the course of the previous research, it became apparent that every effort should be made to provide the highest possible precision in the control of flash energies and in the recording of recovery times or of afterimage brightness. The psychophysical data from our group of six

to ten trained subjects showed such amazing consistency when relatively large ranges of variables were tested, that it was felt that some of the variability in testing a single condition was due to instrumentation limitations. A major effort of the past year, therefore, has been expended on developing improved instrumentation.

II. SCOPE

Improved instrumentation has been purchased and developed for the calibration of the flash sources and for the monitoring of successive flashes in a series. The major changes are in the area of photometry and radiometry equipment for the calibration of both continuous and flash xenon sources in absolute energy units. A dual beam oscilloscope was purchased and has been incorporated into the flash apparatus for the purpose of recording both the time course of the flash radiance and the integrated energy for each flash during experimental sessions.

A circuit for the automatic recording of up to 10 recovery times for different luminance levels of the acuity letters following a single flash has been designed and built. One feature of the circuit is the automatic changing of filters in the acuity letter presentation apparatus immediately following each recovery time determination.

The research effort during the period covered by this report was directed toward an investigation of the consen-

sual pupil response following various flash conditions. The pupil responses for flashes on different areas of the retina were compared. A reciprocity failure between intensity and duration was found for flashes of 2.1×10^6 td·sec with durations of 1.5 msec and 1.5 seconds. The pupil response for the shorter flashes was of the order of 2/3 that for the longer flashes. The change in pupil response for various flash energies and constant flash duration was also studied.

III. INSTRUMENTATION

1. Radiometry

The flash source, a 10,000 watt-second Sun Flash unit was originally calibrated by comparing its radiance with that of a 6v 18 amp ribbon filament lamp operated under controlled conditions. The comparison was made for various wavelength bands by using a number of interference filters and measuring the ratio of flash tube radiance to tungsten radiance for each. Phototubes were used for the calibration and the signals were displayed on a CRT for measurement. In as much as our flash energies, as ordinarily presented during experimental sessions, are within a factor of 20 below minimum burn thresholds for pigmented rabbits, it is imperative that the radiometry be precise. A standardization laboratory has been developed with a Leed and Northrup photometer bench equipped with a standard lamp as the basic calibration

instrument. The lamp was calibrated by the Electrical Testing Laboratories for candlepower at four specified color temperatures. This allows the calibration of secondary standards for the precise comparison of unknown sources. A calibrated photodiode provides a sufficiently rapid response time for use as a detector for the comparison of brief flashes against standardized tungsten. A vacuum thermopile and galvanometer coupled with a double monochromator permits the measurement of the spectral composition of the continuous sources. The new instrumentation should make possible the calibration of flash sources to within 10% accuracy for absolute energy determination.

2. Monitoring Flashes

In the studies of the reciprocity relationship between flash duration and intensity, it is necessary to control successive flashes to within $\pm$ 5% of total energy. It is also necessary to know the precise rate of delivery of the energy as a function of duration of the flash. A dual beam oscilloscope has been incorporated into the flash apparatus for the simultaneous recording of flash form and integrated energy. A thin plate of glass has been set at 45° to the optical axis directly in front of the subject's eye to reflect a small portion of each flash into a phototube for monitoring the flashes. The current signal from the phototube is fed into an operational amplifier plug-in unit in the dual beam Tektronix 555 oscilloscope. It is

converted into a voltage signal and displayed on the scope. A signal from the output jack of the operational amplifier channel is fed into the other amplifier plug-in unit arranged as an integrator circuit. The signal from the integrator is displayed on the second beam of the scope. A polaroid picture of the CRT is taken for each flash. The type of record obtained is shown in Fig. 1.

The integrator circuit has been tested over a wide range of flash energies and durations and found to be linear for our experimental conditions. Figure 2 shows the original phototube signal in the upper trace and the integrated signal in the lower trace. The middle trace is the result of differentiating the output of the integrator circuit. The similarity of the differentiated and original wave forms is strong evidence that there is no loss of information in the various display circuits.

3. Timer Control Circuitry

The timer control circuits are used in conjunction with the recovery time optics to accurately measure the time necessary for recovery to different target luminance levels. The circuits allow us to measure recovery to as many as 10 target luminance levels per flash. Immediately following the flash, the subject is presented with a series of letters, at one second intervals. His task is to correctly identify the letters presented, and he indicates his choice for each letter by pushing one of six buttons,

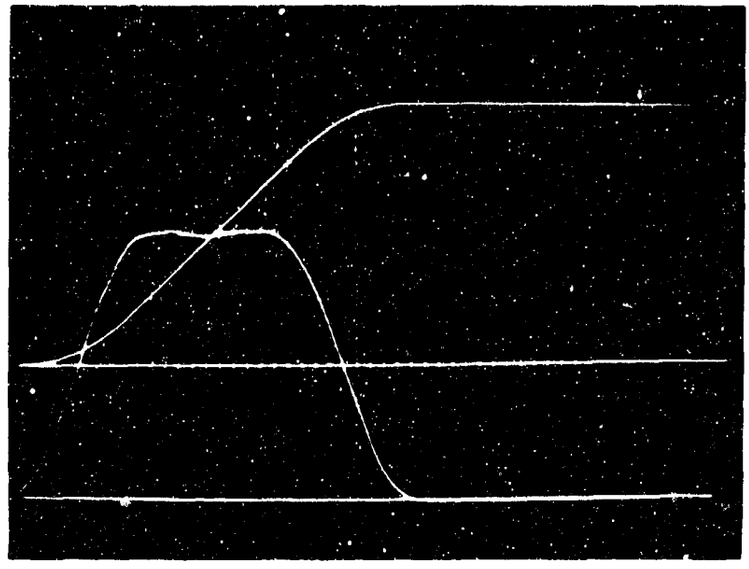

Figure 1. Photograph of CRT showing the time course of the flash radiance in the lower trace and the integrated flash energy in the upper trace.

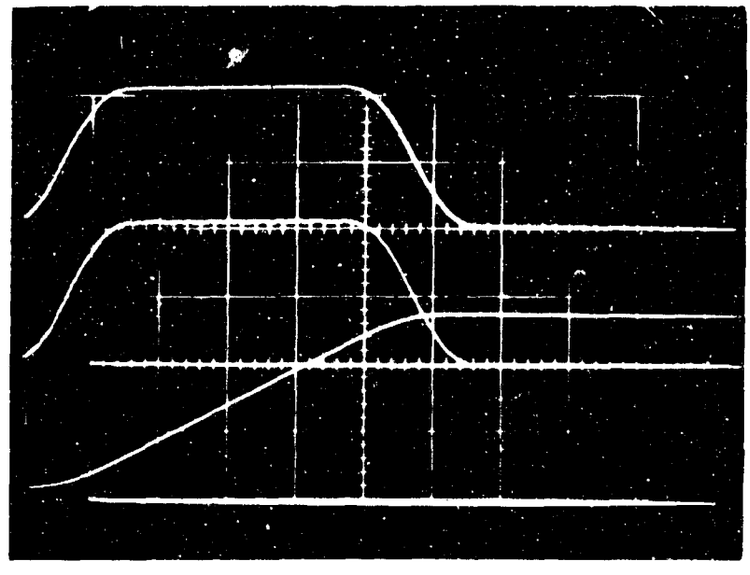

Figure 2. Photograph of CRT showing the phototube signal displayed in the upper trace, the integrated signal in the lower trace, and the result of differentiating the integrated signal in the middle trace.

corresponding to the six different letters. Our criterion for recovery to a given target luminance level is the correct identification of two letters in sequence. The timer control system is designed to start 10 clocks when a flash is presented, and to stop one clock for each pair of correct responses made after the first luminance level. Only one correct identifaction is required for the highest luminance target. As a clock is stopped, a filter wheel in the target illuminating beam is advanced one step, thereby reducing the luminance of the target letters. With 10 timers and a ten position filter wheel, it is therefore possible to measure the time to recovery for 10 different target luminances per flash. The control system is comprised of 3 major sub-units: the response, logic, and readout circuits. Each will be discribed below.

The letters are arranged around the circumference of a stimulus drum, an aluminum wheel driven by a motor through a geneva gear and reduction gear train, such that it has 30 discrete positions. The target letters are six Sloan-Snellen letters (C, H, K, N, R, and Z). Each letter appears in five positions on the drum, the position being determined from a random number table. A frame work of brass and perforated circuit board supports an array of thirty reed switches over the stimulus drum as shown in Fig. 3. The thirty switches correspond to the thirty letter positions. A permanant magnet mounted on the drum passes just below the switches

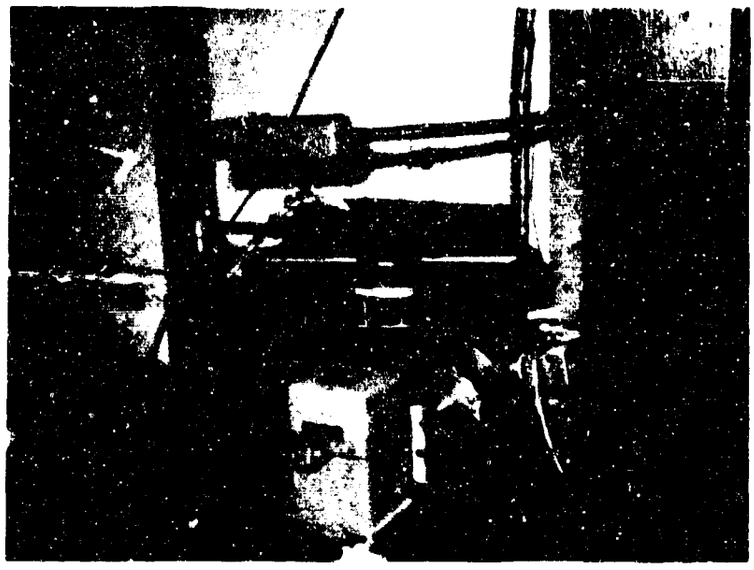

Figure 3. Photograph of circuit board for timer clocks and the stimulus drum for presenting the recovery target letter.

as the drum rotates. The magnet closes the switch directly above it. As the drum moves from position to position, carrying the magnet, the previously closed switch opens and the next one in sequence closes. The reed switch and magnet assembly form the "stimulus detector" portion of the response sub unit. Figure 4 is the "response detector" circuit. It is comprised of the six subject response switches, S 1-6, six 6volt light bulbs, L 1-6, and six CdS photocells, P 1-6. If the subject closes S 4, (indicating a response of "N"), L 4 lights up, and the resistance of P 4 drops. This optical link was used to eliminate the effect of the contact bounce normally found in simple switches: since it takes a short period of time for a tungsten light to heat up to incandescent temperatures, any sparks from the switches would not be coupled to the rest of the system, thus reducing the problem of noise induced triggering.

The logic circuit for the timer control system is, in essence, six "AND" gates, a Schmitt trigger, a bistable multivibrator, and a monostable multivibrator. In order to trace the operation of the circuit, consider stimulus and response detector circuit 4. In the first case assume that the letter "N" is presented, and the subject's response is also "N". One of the reed switches in circuit four is therefore closed by the magnet, and the light falling on the photocell P 4 has lowered its resistance. Current then flows through P 4, the 1 K r istor, the closed

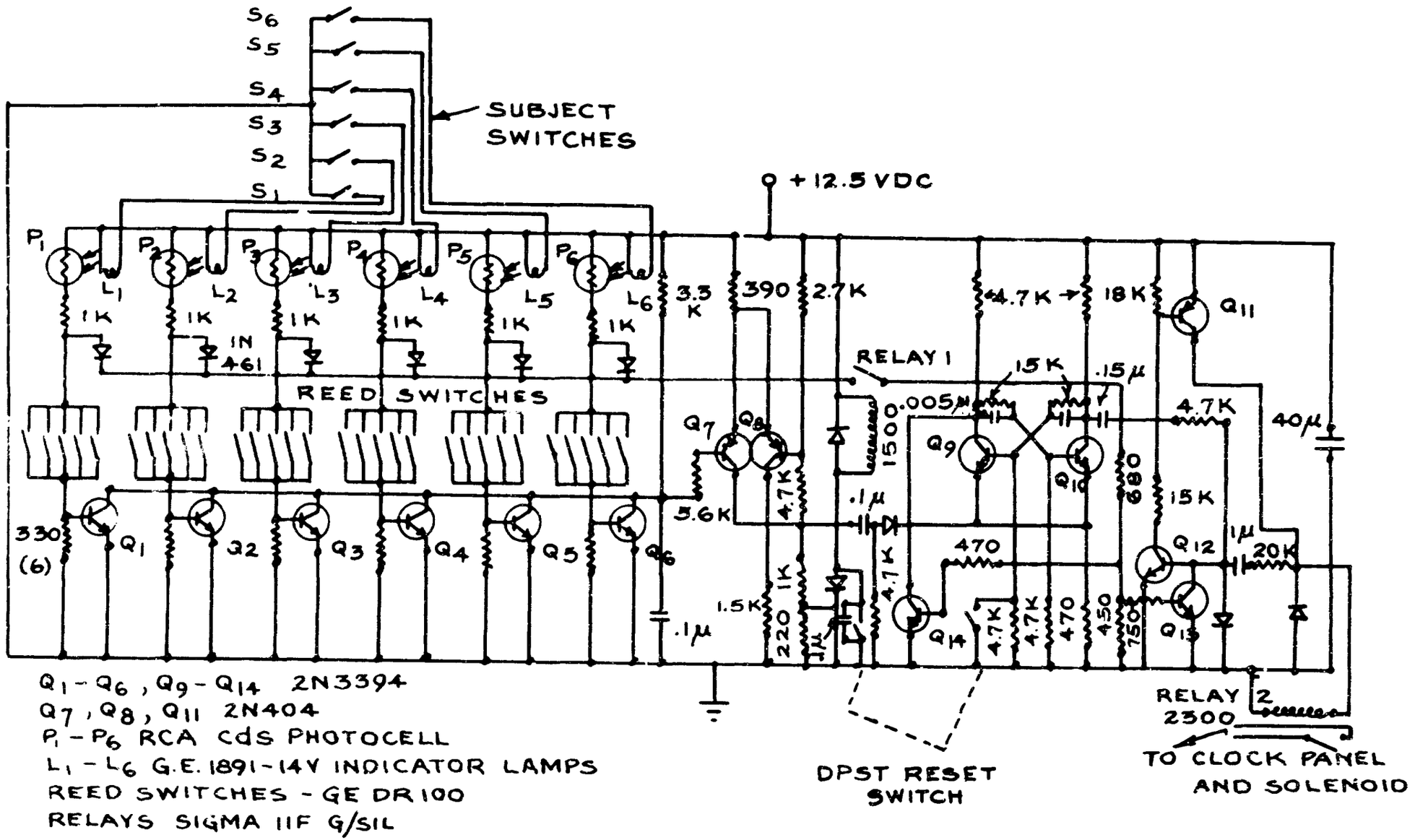

Figure 4. Circuit diagram for the "response detector" unit of the recovery timer control apparatus.

switch and the 330 Ω resistor to ground, increasing the bias on transistor Q4 such that current flows from the collector to emmitter and thence to ground. This results in a voltage drop across the 3.3 K resistor, which in turn biases Q7. Transistors Q7 and Q8 form a Schmitt trigger whose output passes through the differentiator formed by the 0.1 μf capacitor and the 4.7 K resistor. For the time being, we will not consider relay 1 or the SCR circuits. The differentiated signal then triggers the common emmitter flip-flop, 1 output signal appears at the collector of Q10, and, after differentiation by the 0.15 μf capacitor, triggers the monostable multivibrator formed by Q11 and Q12. For each spike input, the monostable multivibrator provides about a 0.2 sec duration output pulse, which closes relay 2. The contacts of relay 2 are in series with a 110V AC line, and when they are closed, supply power to a solenoid which drives the filter wheel, and to a twelve position stepping relay which stops the individual clocks. These last two operations will be discussed more fully under the topic of readout units.

In the event of an incorrect response by the subject, the reed switch corresponding to his response is not closed, and current flows instead through the diode corresponding to his response. If relay 1 is open, the remainder of the circuit is unaffected. If, however, relay 1 is closed, current flows through the 680Ω, 450Ω, 750Ω, and 470Ω voltage divider resistors, first biasing Q_{13} and then Q_{14} conduction.

Q_{13} shorts any output from the flip-flop to ground, so that it cannot trigger the monostable multivibrator. Q_{14} resets the flip-flop to await another input. After an error, then, two correct responses are necessary to close relay 2.

Relay 1 closes when the first correct response of a trial is made. When the schmitt trigger is pulsed by a correct response, current flows throurgh Q_7, the 1 K resistor, and the 220 Ω resistor biases the gate of the SCR into conduction. Current flows through relay 1 and the SCR to ground, closing and catching the relay.

In order to set the circuit for a trial, the momentary contact reset switch is depressed. This turns off Q_9 and turns off the SCR. The first correct response will close relay 1 and change the flip-flop's state, so that an output appears at Q_{10}'s collector, resulting in a closure of relay 2.

The connector block is the programmable element of the timer control circuit. Each block corresponds to one randomized arrangement of letters on the stimulus drum, the block plugs into a Vector Electronics 100 hole patch board, and telephone tip plugs are used for connectors.

The connector block links the reed switches with logic circuit units 1-6. Essentially, both ends of each switch are connected to separate holes in the patch board, and the logic circuit connections are on still different holes.

Five lead patch cords were made, and the common end of one of these cords was plugged into one of the logic circuit connections, while its five "fan-out" leads were plugged into switch connections. Refering to Fig. 4 the circuit numbers 1-6 each correspond to one of the six stimulus letters used in the following arrangement:

Circuit Number	1	2	3	4	5	6
Stimulus Letter	C	H	K	N	R	Z

As an example of the programming connections, from the randomization tables it was decided that reed switches 1, 4, 6, 10, and 12 would be programmed for "correct response" when N was indicated by the subject. A patch cord was then inserted into the hole for circuit 4, and the five leads were plugged into the holes corresponding to switches 1, 4, 6, 10, and 12. The stimuli were so arranged that letter positions 1, 4, 6, 10, and 12 all presented letter N.

The readout portion of the timer control system consists of both the clock panel shown in Fig. 5 and the filter wheel. Kodak neutral density filters are taped over the holes in the filter wheel, and are transilluminated by a ribbon filament lamp run at 16 amps. A cold mirror protects the filters from the heat of the tungsten source. The mirror system reflects the filtered light up and out through the letters mounted on the stimulus.

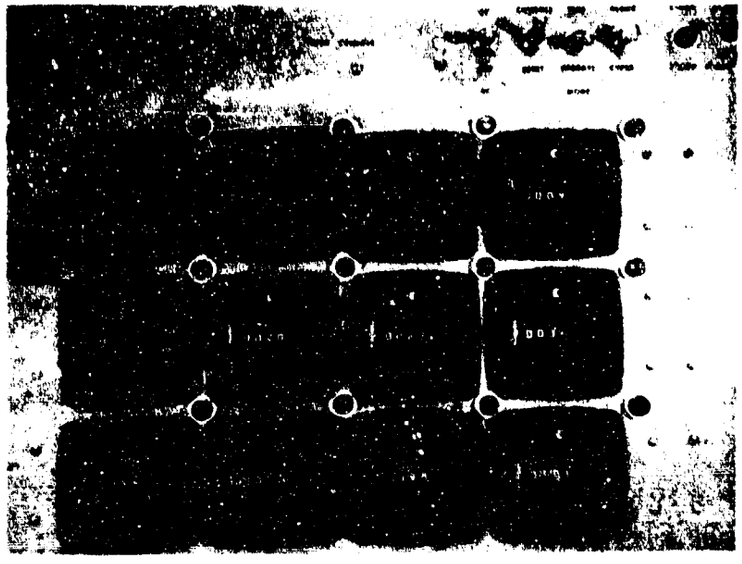

Figure 5. Photograph of clock panel for the recording of recovery times to various target luminances.

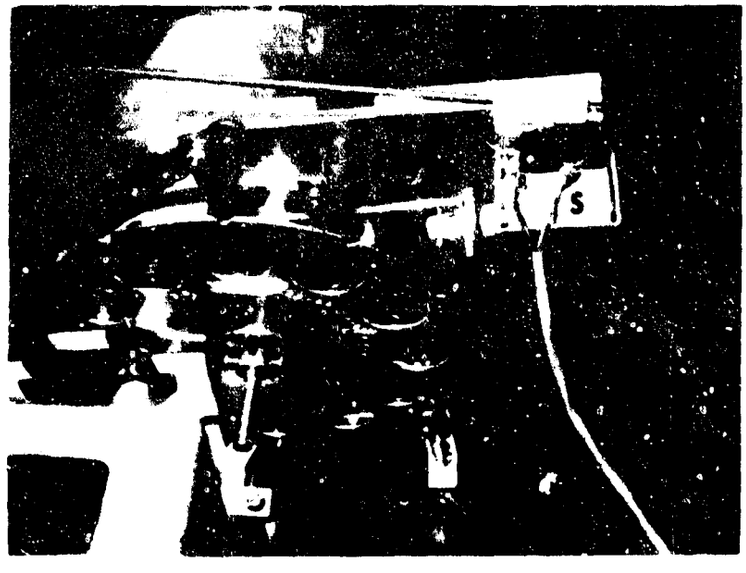

Figure 6. Photograph of the filter wheel showing the solenoid, S, which allows the wheel to turn to the next filter condition when two correct responses have been made in sequence.

drum, down the optical path to the subjects eye. When relay 2 is activated by the logic circuit, line voltage is fed to the solenoid indicated in Fig. 6. The solenoid pulls in the ratchet arm, turning the gear and filter wheel one step, thereby decreasing the letter luminance.

The clock panel circuitry shown in Fig. 7, provides mounting for 12 timers, a 24 V power supply, a Sodeco counter, 10 timer relays, a 12 position stepping relay and a two-coil mechanical latching relay. A light activated SCR (GE L9B) is mounted near the flash tube with a 2 ND filter covering it. Gate to cathode resistance of 1.5 K was found to increase the systems stabiltiy. When the xenon flash is triggered, the LASCR turns on, allowing current to flow through the console reset switch to coil A or B of the mechanical latching relay. The contacts of the relay first starts one of the two flash interval timers and then provide power for the ten remaining timers through the second side of the console reset switch. The flash timer operating before the flash is turned off when its contacts at the mechanical latching relay are broken, and since it was started by the preceding flash, records the interval between the two flashes. When relay 2 of the timer control system is activated, the coil of the 12 position stepping relay is temporarily energized, advancing the contact one position. This is turn energizes the coil

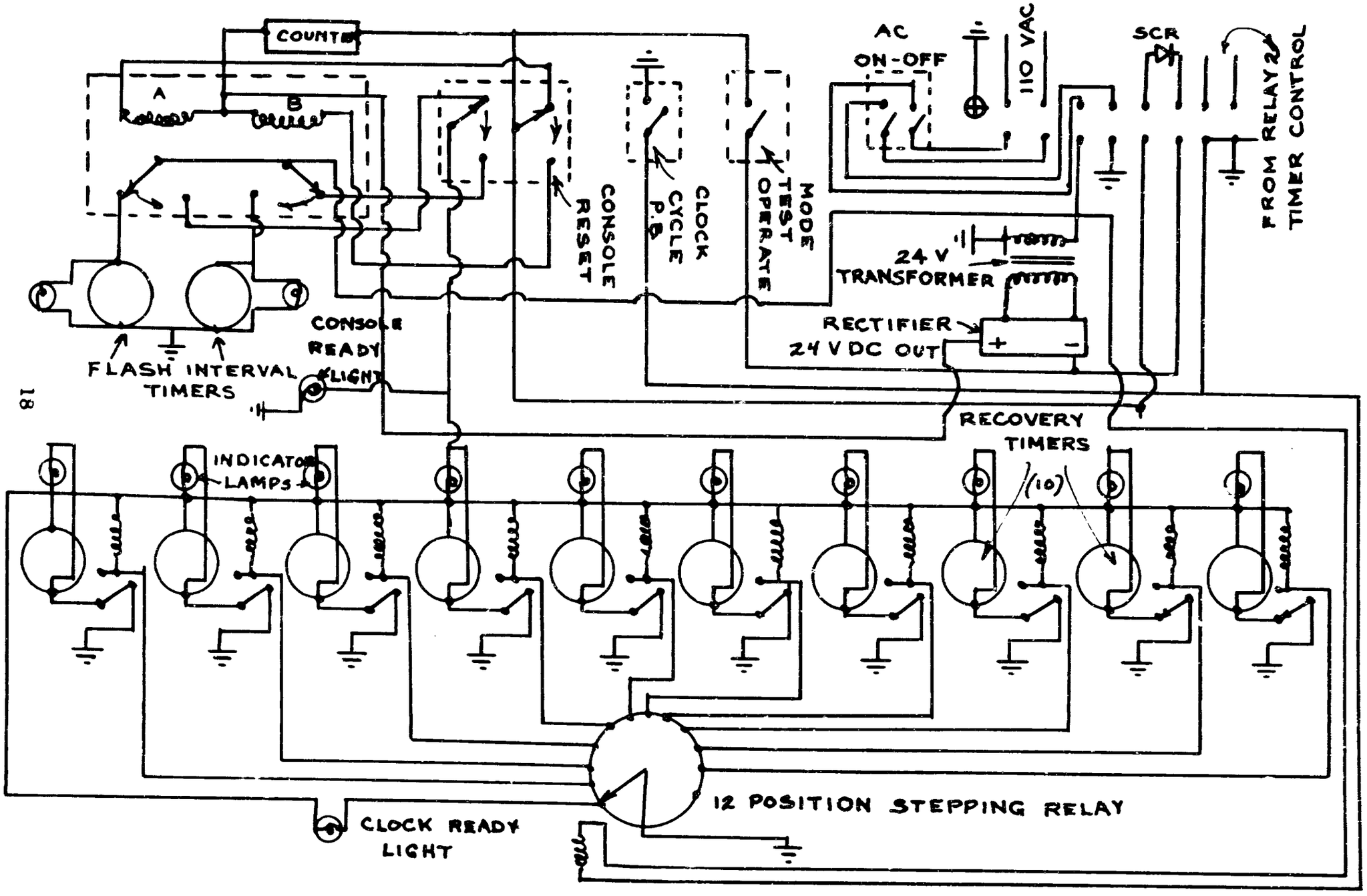

Figure 7. Circuit diagram of the clock panel unit of the recovery timer control apparatus.

of the appropriate timer relay, breaking the timer's power connection and latching the relay. When all 10 clocks have been stopped, a push-button (not shown) breaks the connection to the LASCR, and halts current flow through the latching relay. A flash counter (Sodeco impuse counter) in parallel with both coils of the latching relay is also de-energized. A picture of the clock array is then taken, providing the following information: interval between the preceding flash and the flash for which the data are presently displayed, the number of the present flash in the series for a given subject on a given day, and the recovery times for the 10 different target luminances.

After the picture is taken, the clock cycle pushbutton is depressed, activating the coil of the stepping relay, until the relay is brought around to its starting position. The console reset switch is thrown, providing a path for current from the LASCR (after it is triggered by the flash) through the other coil of the mechanical latching relay. When the flash is triggered, the coil of the relay is activated, stopping the running flash interval timer and starting the other, energizing the flash counter and starting the 10 recovery time clocks. The mode switch was added as a simple means of testing the timer console without triggering the flash, and simply shorts out the LASCR.

IV. CONSENSUAL PUPIL RESPONSE FOLLOWING HIGH INTENSITY FLASHES

An infrared pupillograph for the continuous recording of pupil diameters was constructed for use with the flash apparatus. The design was a modification of the instrument developed by King[5] for Lowenstein and Lowenfeld. The original model is commercially available but was designed for clinical use and is more elaborate than is needed for a research project. The simplified model built for use in the laboratory permitted a continuous horizontal scan of the right eye prior to and for any period of time following a flash delivered to the left eye. In general we recorded continuously for one minute following each flash and in some of the work we recorded for an additional ten seconds at the end of each of the next five minutes.

1. Apparatus

The flash source was the same as in the previous work, a 10,000 watt-second Sun Flash unit. The schematic drawing in Fig. 8 shows the optical system for the flash field and for the scanning beam for the pupillograph. A bright segment of the flash tube was imaged on the entrance slit A_1 by a short focal length lens. The entrance slit was at the focus of a 48 inch telephoto lens to provide collimated light at the first surface mirror M_1. The light reflected

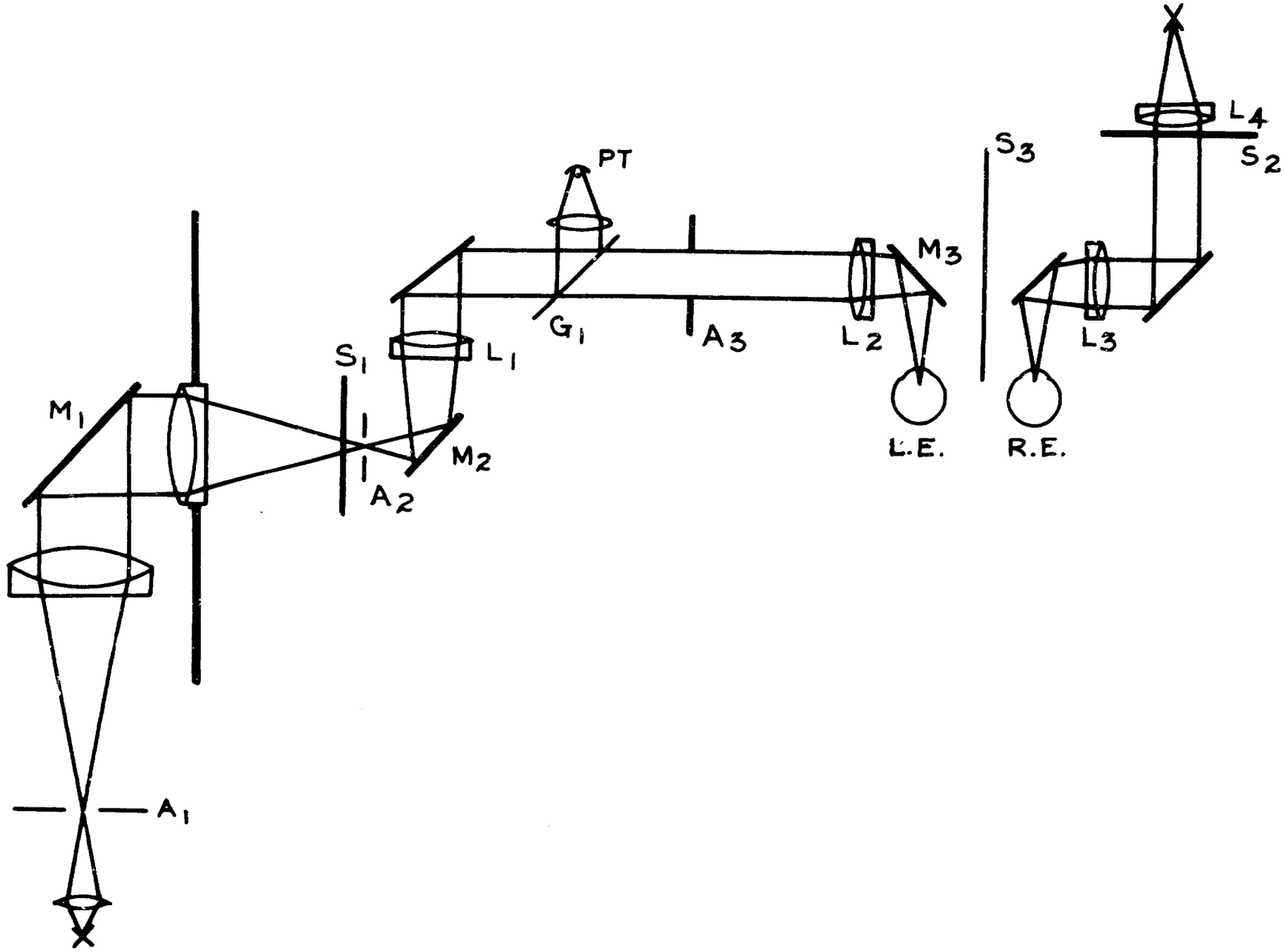

Figure 8. Schematic drawing of the apparatus for presenting the flashes and for scanning the pupil with infrared light for the pupillograph recording. See text for complete description of the optical system.

from the mirror passed through a 20 inch telephoto lens mounted in the wall between the source room and the subject's room. A second aperture at A_2 was at the focus of the 20 inch lens and was conjugate to the entrance pupil of the subject's left eye. A sector disc S_1 was driven at 1725 rpm and the sector opening determined the flash duration. An additional slit sector was cut at a different radial position to permit a beam of light to strike a light activated SCR to trigger the flash tube prior to the instant when the leading edge of the main sector started across A_2. A rotary solenoid activated shutter was mounted between the sector and the triggering light to block activation of the SCR until the time for a flash. A simple switch opened the shutter and allowed the next opening of the sector to fire the flash tube. By the proper positioning of the triggering sector, it was possible to insure that the tube radiance had risen to peak value before the shutter sector opened to admit the flash through the optics. Cardboard sector discs, 10 inches in diameter were used in all experiments because of the ease of cutting suitable openings. It was possible to make small adjustments in the timing of the trigger or of the exposure duration with pieces of black electrical tape fastened over one edge of the openings.

The light at A_2 became the effective flash source for the Maxwellian beam optics consisting of mirrors M_2, M_3, and M_4 and the achromatic lenses L_1 and L_2. The aperture

A_2 was focused on the entrance pupil of the subject's eye at a 1:1 magnification providing a 4.1 x 4.2 mm beam entering the eye. The field stop in the collimated beam at A_3 determined the configuration and visual angle subtended by the flash. It was placed at the focus of the 18 cm achromat so the edges were in sharp focus for the subject with relaxed accomodation. A glass plate G_1 reflected a small portion of each flash into the monitoring phototube, PT. The phototube signal was fed into an integrating circuit and displayed on the CRT.

The subject's head was positioned by a bite bar and forehead rest to assure perfect alignment for the flash and the pupillograph scan. A septum at S_3 prevented any light from the flash from reaching the right eye and contaminating the pupillograph traces. The infrared scanning beam of the pupillograph was produced by a tungsten light at the focus of L_4. A infrared filter blocked all visible light from passing through the scanning optics except for a very deep red which was visible only after several minutes in the dark. The sector disc S_2 was driven 1725 rpm and consisted of an aluminum disc 10 inches in diameter with 24 holes drilled around the circumference. The holes were imaged on the entrance pupil of the right eye by means of L_3 providing a beam approximately 0.5 mm in diameter which swept across the eye with the sector rotation. The

arrangement provided 700 scans per second so minor fluctuations were easy to detect.

The light reflected by the eye was picked up by an infrared photomultiplier and the signal was fed into a circuit shown in the block diagram in Fig. 9. The signal from the amplifier 1 consisted of the signal due to the light reflected from the sclera, the iris, and the portion due to the traverse of the pupil with only stray light and noise. The portions due to the scleral and iris reflection were clipped from the wave form by means of the white clip circuit and the output was amplified again. The output of amplifier 2 went into a sawtooth generator which integrated each pulse, so the peak voltage for each sawtooth was proportional to the time required for the scanning beam to traverse the pupil. A peak detector rode the maximum voltage for each sawtooth and its output was continuously recorded by either a Sanborn or a Brush recorder.

2. Calibration

The pupillograph gain was adjusted for each subject to provide a minimum trace deflection for the dark adapted eye. It was, therefore, necessary to calibrate the instrument by means of infrared photographs to find the absolute pupil diameters for each subject. A 16-mm camera with a 180-mm, f/4.5 lens was positioned in front of the subject's left eye for photographing the pupil at approximately 1:1 magnification. An enlarged image of a tungsten ribbon

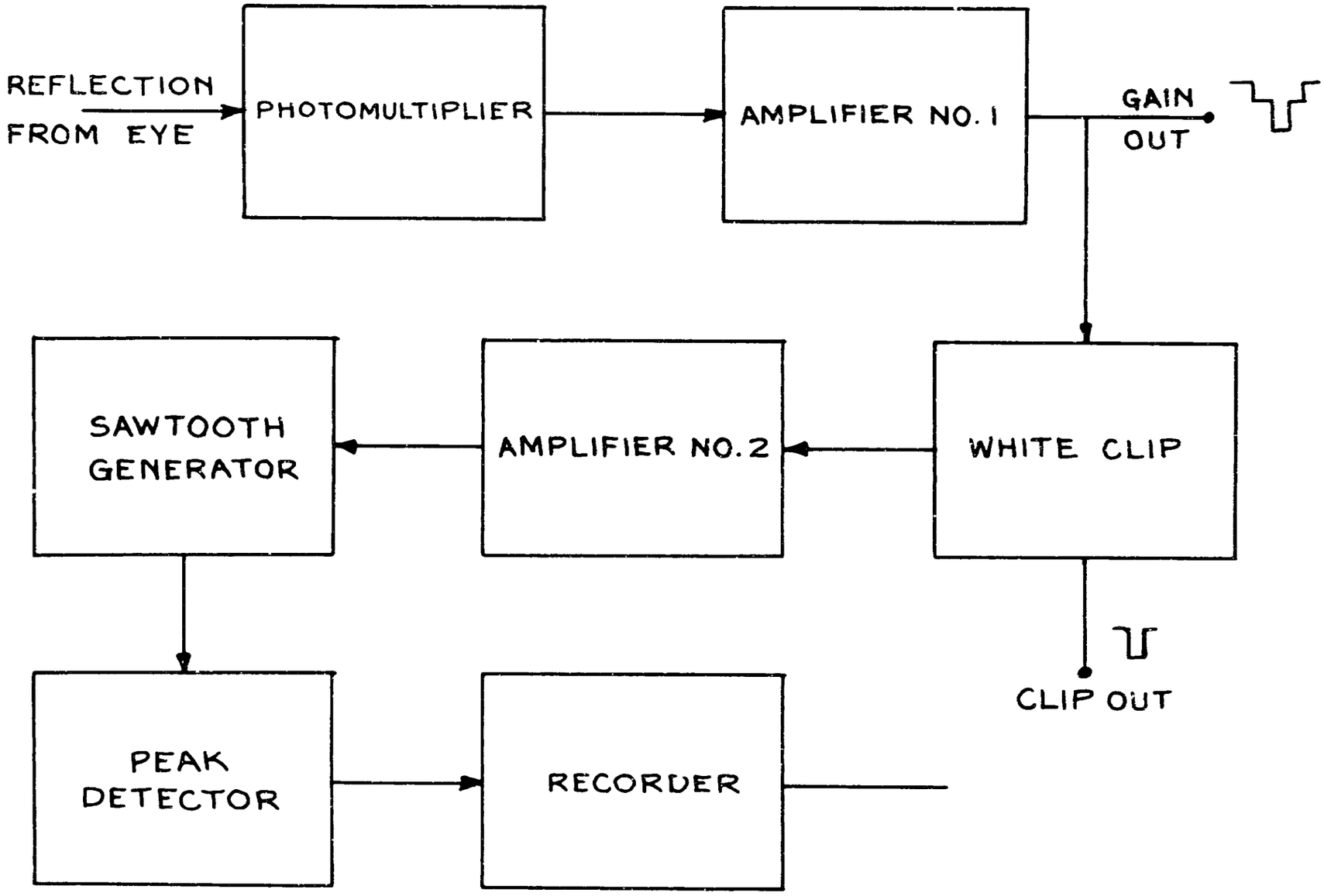

Figure 9. Block diagram of the electronic circuit for the infrared pupillograph.

filament was focussed on the subject's pupil to provide illumination for the photographs taken on high-speed infrared film. The light was filtered by a Wratten 87C filter so only infrared light fell on the eye. Photographs were taken simultaneously with the pupillograph recording for a number of flashes for each subject to calibrate the recording system. A few photographs were taken one minute before a flash and immediately after the flash a mirror was removed from the optical system to provide an unobstructed camera field and pictures were taken at a 1/75-sec exposure each second following the flash for one minute. A series of 10 pictures at one-second intervals were taken at the end of each minute thereafter for five minutes. A millimeter scale was placed in the apparatus in the plane corresponding to the subject's entrance pupil before and after each session and photographed to provide a check on the camera magnification. The pupil diameters were read from the photographs by projecting them on graph paper. The projector was adjusted by means of the millimeter-scale photographs to provide a 20X enlargement of the pupil. The event marker of the Sanborn recorder indicated each picture as the camera was triggered so the photographic records could be correlated with continuous recording. Figure 10 shows the results for one subject for the first and last flash of a series of eight flashes spaced six minutes apart. There was some drift in the recorder as shown by the dis-

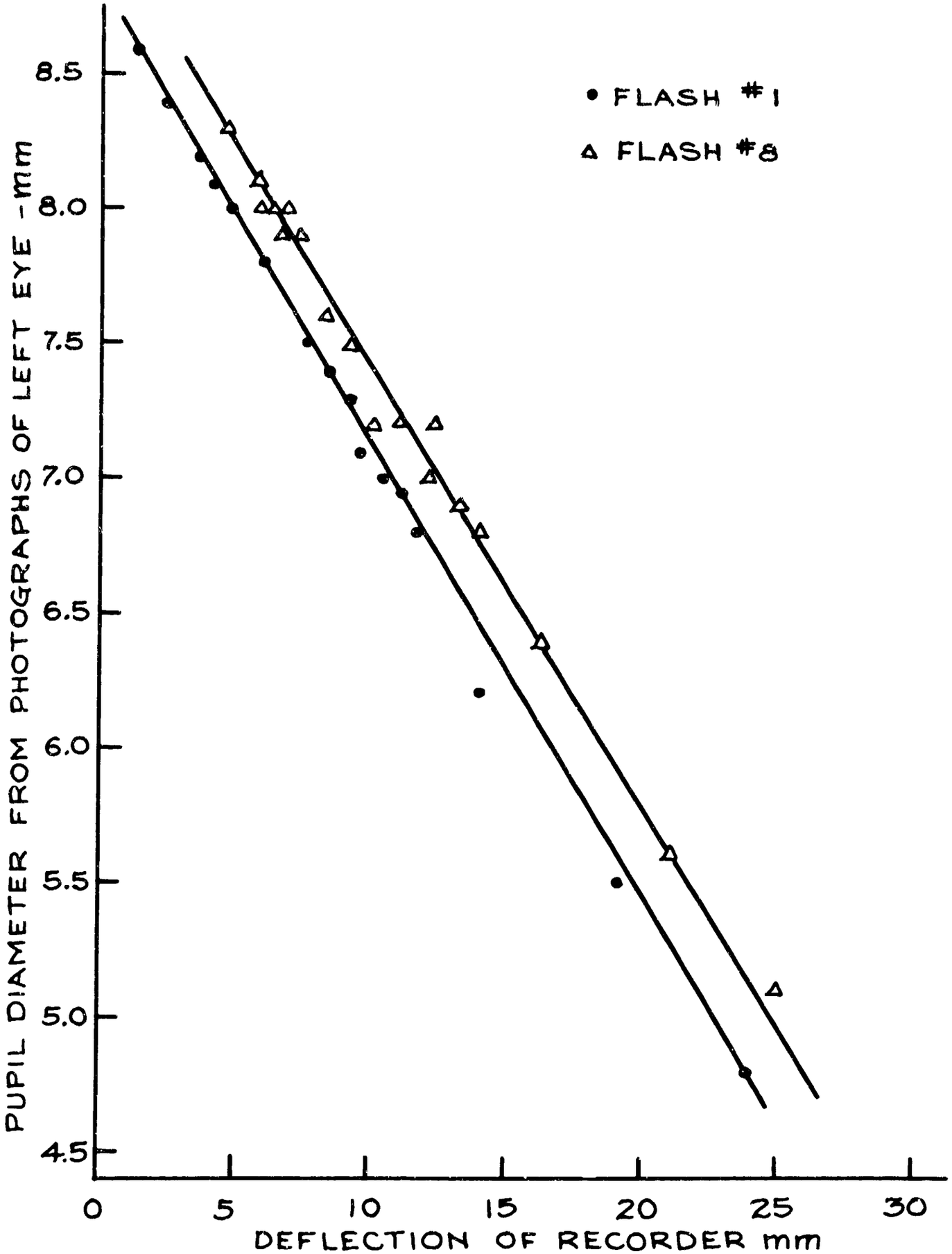

Figure 10. Calibration data for absolute measure of pupil diameters from pupillograph traces. The ordinates are the pupil diameters in mm from measurements of infrared photographs of the left eye taken simultaneously with the pupillograph recording from right eye.

placement of the two graphs, but the excellent linearity of the pupillograph is evident.

3. Comparison of Foveal and Peripheral Flashes

Seven subjects participated in an experiment to test the pupil response for flashes covering a 2° central field compared with annular flashes concentric with the fovea. The 2° flash field was just slightly larger than the rod free portion of the retina and the annular flashes had an inside diameter of 2.5° so they covered an area surrounding the fovea but providing no foveal stimulation except from light scattered into the region by the ocular media. Figure 8 shows the arrangement of the apparatus for recording the consensual pupil response following the flashes.

A 1.5 msec flash of 3×10^{7} td·sec was chopped from the flash tube discharge by the rotating sector at S_1. The tube was triggered in synchronization with the sector to insure that the 1.5 msec exposure was always chopped from the peak luminance of the discarge. A glass plate at M_3 reflected a small portion of the flash into a phototube for monitoring the flash energy. The phototube signal was put through an integrating circuit before being displayed on the oscilloscope. A polaroid picture was made of each oscilloscope trace so the flash energy could be checked and maintained within $\pm$ 5% of the nominal value. Field stops at A_3 provided the flash field configurations pre-

sented to the subjects' left eye. The infrared scanning beam for the pupillograph recording was swept across the right eye.

The pupil responses showed large individual variations which, however, were quite consistent for each individual. The pupil diameters as a function of time for the first 10 sec following the flashes are shown for each subject in Figures 11 and 12. The upper trace in each case represents the pupil response for the 2° centrally fixated flash field. It is clear that the 2° flash produced a much smaller response in each case than the annular flash. The smaller flash was received by cones almost entirely while the annular flash fell on both rods and cones. The annular flash also covered a larger area of the retina. The ratio of the area covered by the central flash to that of the annular flash was 0.076.

A considerable amount of time was spent in trying to find a means of analyzing the complex pupil response records to permit a valid comparison of conditions. The diameter of the pupil at maximum constriction was not a satisfactory index of response because our instrumentation provided relative pupil sizes rather than absolute except when the infrared camera was used for calibration. There seemed to be a day to day variation in the absolute diameters for each subject that introduced an additional level of variability. The duration between the 50% points of

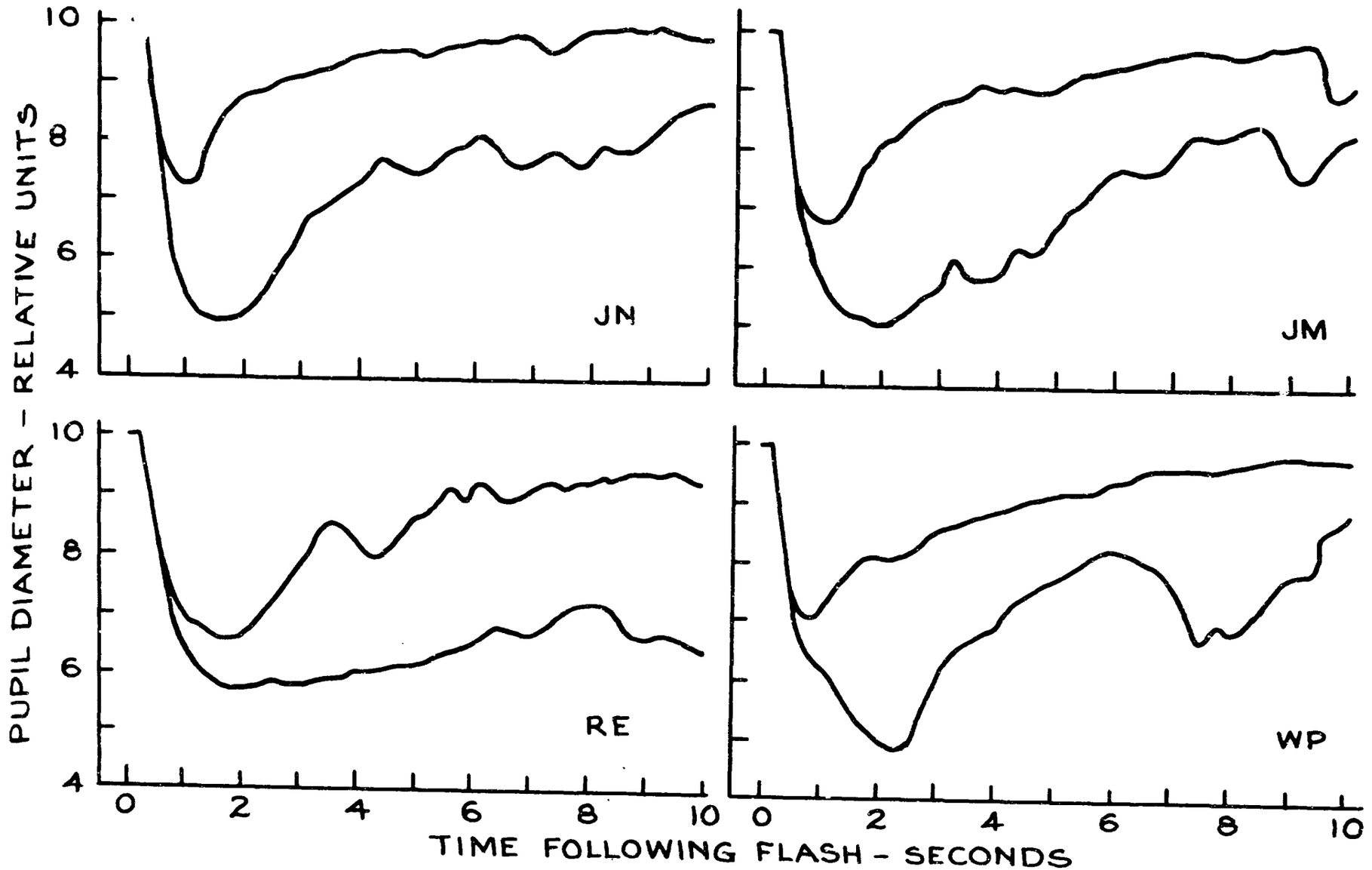

Figure 11. Pupillograph records for the individual subjects following different flash sizes. The upper traces in each graph is a record of the pupil response following a 2° centrally fixated flash of 3×10^{7} td·sec. The lower traces are the results for an annular flash of the same energy but with 7.5^{o} outside diameter and 2.5^{o} inside diameter concentric with the fovea.

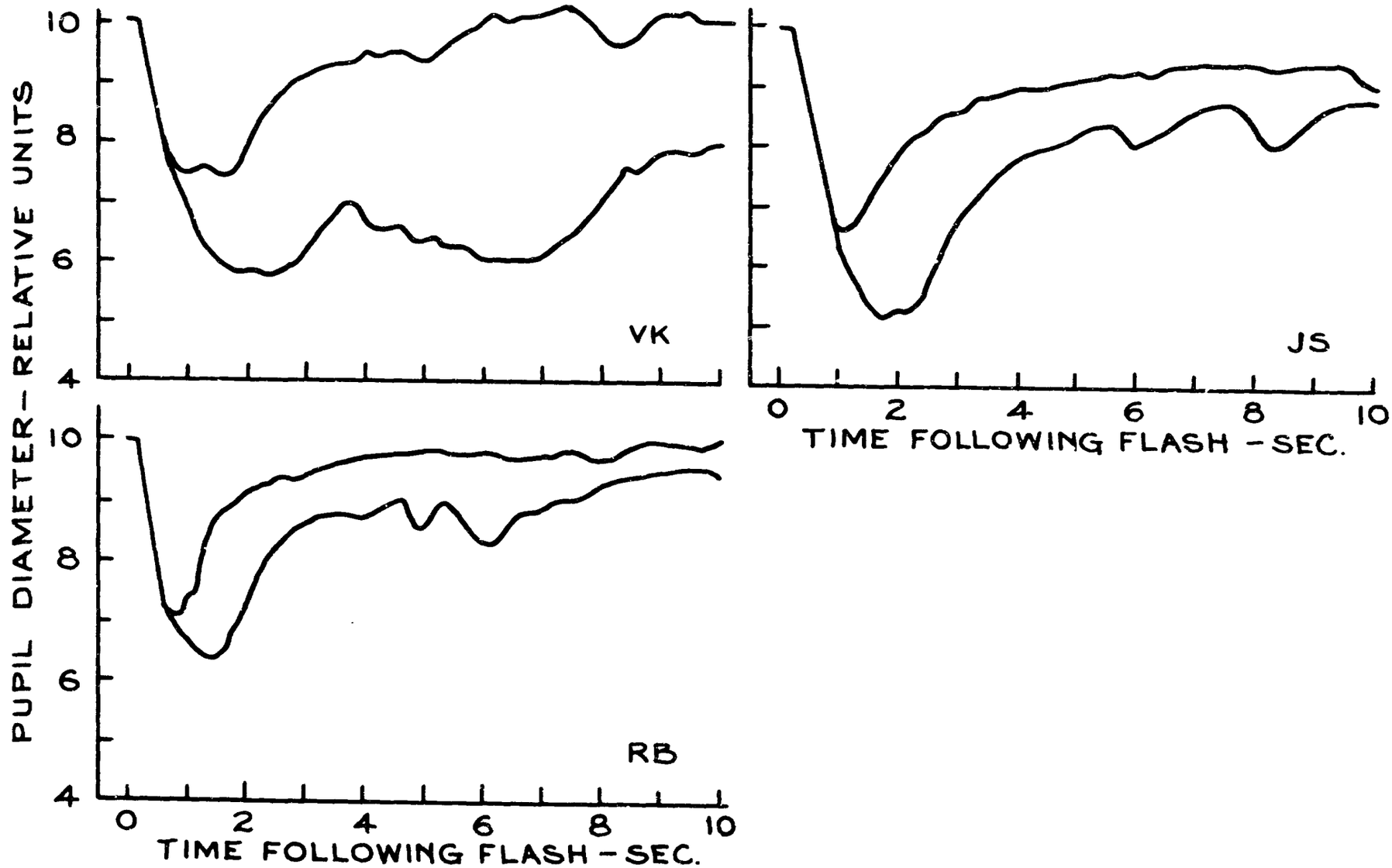

Figure 12. Pupillograph records for the individual subjects following different flash sizes. The upper traces in each graph is a record of the pupil response following a 2° centrally fixated flash of 3×10^7 td·sec. The lower traces are the results for an annular flash of the same energy but with 7.5° outside diameter and 2.5° inside diameter concentric with the fovea.

the pupil diameter traces was a consistent measure for some subjects but poor for V. K. and R. E. who showed exceptionally long recovery curves for the higher energy flashes. It was finally decided that the best measure of the pupil response was the time interval from the flash to the maximum pupil constriction. The values of this interval for each subject for the two flash configurations are listed in Table I.

The same subjects participated in another experiment to determine the pupil response to 1.5 msec flashes of 7.5^{o} visual angle. The flash field was centrally fixated and was presented at seven luminance levels ranging from that giving a 3×10^{7}td·sec flash to 5×10^{5}td·sec. The successive luminance levels were acheived by the addition of neutral density filters in the flash beam. Each subject received one flash at each energy level during a single session with the flashes presented at 6 min intervals. The various conditions were independently randomized for each subject. Figure 13 shows a typical set of pupil diameter traces for one subject for flash energies of 3×10^{7}, 8×10^{6}, and 10^{6}td·sec. It is evident that the time to maximum pupil constriction increases with the flash energy. The times for maximum constriciton for each of the flash energies is recorded in Table II by subject.

The mean time to maximum constriction for the seven subjects is shown on a log scale in the graph of Figure 14

Table I. Time in Seconds From Flash to Maximum Pupil Constriction for 3×10^7 td·sec Flashes of 1.5 msec Duration.

Subject	2° Central Flash	Annular Flash 7.5°o.d.-2.5°i.d.
R. B.	0.80	1.35
R. E.	1.70	2.40
V. K.	1.25	2.25
J. M.	1.00	1.90
W. P.	0.80	2.30
J. S.	1.00	1.90
Mean	1.071	1.957

Table II. Time in Seconds from Flash to Maximum Pupil Constriction for 7.5° Flashes of 1.5 msec Duration and Varing Flash Luminance

	LOG FLASH ENERGY						
SUBJECT	7.5	7.2	6.9	6.6	6.3	6.0	5.7
R. B.	2.65	2.15	1.30	0.80	0.90	1.10	0.95
R. E.	2.50	2.20	2.00	2.40	2.00	1.60	1.15
V. K.	2.00	2.00	1.65	1.30	1.10	1.00	0.90
J. M.	2.20	2.65	2.00	1.40	1.65	1.30	0.85
J. N.	2.10	1.40	1.45	1.45	1.10	1.30	1.00
W. P.	2.00	2.20	2.10	1.60	1.50	0.90	0.80
J. S.	2.30	2.10	1.95	1.50	1.25	1.20	1.20
Mean	2.250	2.100	1.779	1.493	1.357	1.200	0.979

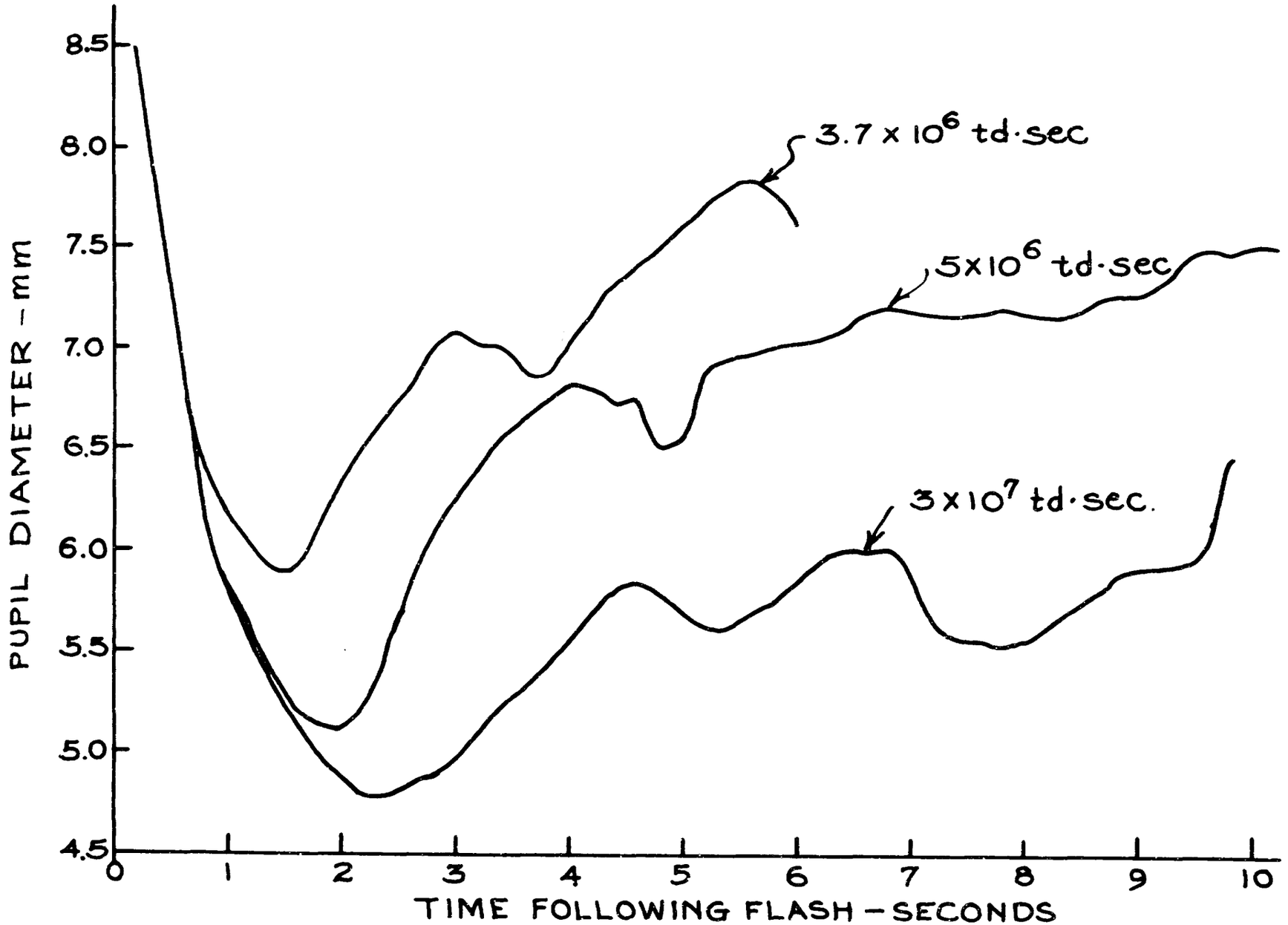

Figure 13. Pupil responses for one subject for different flash energies produced by varying the luminance of the flash field and holding the duration constant 1.5 msec.

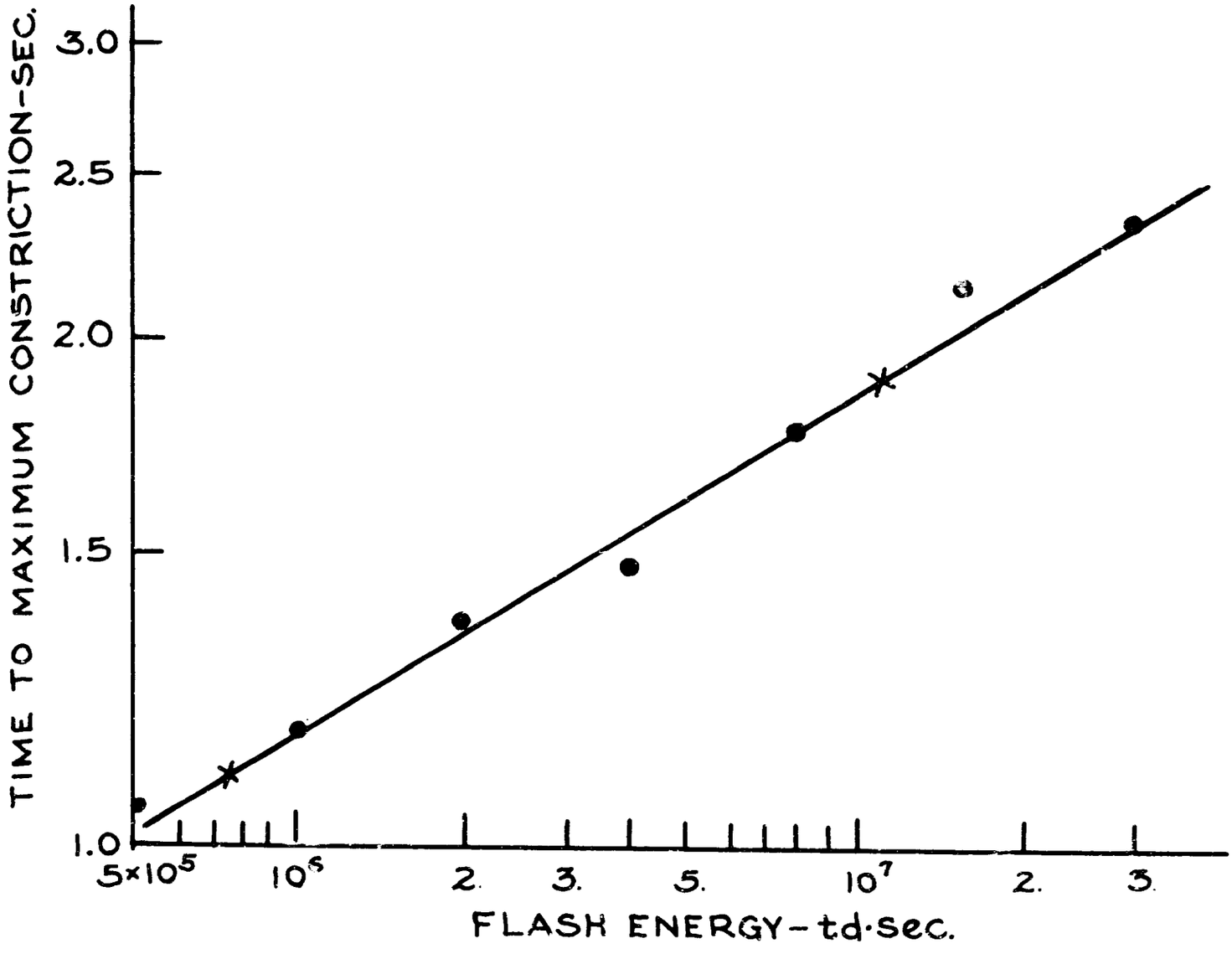

Figure 14. Mean data for six subjects for the time required to reach maximum pupil constriction following flashes of different energies. All flash durations were 1.5 msec.

as a function of the log flash energy. There is a linear relationship between the log of the variables over the range tested. The two crosses on the line drawn through the data points correspond to the mean times for maximum constriction for the 2° central flash and the annular flash. They are equivalent to a log flash energy difference of 1.18. The log of the ratio of the areas of the two flash configurations is 1.12.

The results of the two experiments described indicate that the pupil response is a function of the total energy received by the retina and there is a reciprocity relationship between the area of the flash field and luminance over the range tested.

4. Reciprocity Failure in Pupil Response

The pupil constriction following the 7.5^{o} flashes of 3×10^{7}td·sec was surprisingly slight. The average pupil diameter at maximum constriction was about 5 mm. The flash durations were of the order of a millisecond or less so the event was over long before the end of the latency for the pupil reflex. It seemed that the brief duration of the flash might account for the small pupil response and hence indicate a reciprocity failure between time and intensity of the flashes. In order to test this hypothesis, two extreme durations were chosen, 1.5 msec and 1.5 sec. The longer flash extended well beyond the latency period and was easily obtained with a tungsten ribbon filament source. The short duration flash was provided by the

10,000 watt-second xenon tube used in the previous work.

Both the tungsten and the xenon flashes were filtered through a 555 mμ interference filter to prevent any effect of the different spectral compostion of the two sources from influencing the pupil response. A 929 phototube was used to measure the intensity of the light from the two sources and the phototube signals were displayed on a 533A Tektronix oscilloscope. The tungsten light was chopped by a sector disk so both signals were displayed on the same time base. Calibrated neutral density filters were used in addition to the 555 mμ interference filter to reduce the xenon flash intensity to the same level as that from the tungsten through the interference filter. The xenon flash required 3.3 density filters to match the trace height of the tungsten hence was 2000 times the tungsten luminance. A 0.3 neutral density filter was used during the experimental sessions with the xenon flash to provide the same integrated energy in the two flashes of 1.5 msec and 1.5 sec durations.

The flash luminance for the tungsten source was measured by placing a MacBeth test plate 20 inches behind the image of the source which was formed at the entrance pupil plane of the subjects eye. MacBeth Illuminometer measurements of the illuminance of the test plate were made with and without the interference filter. The Maxwellian beam cross section at the plane of the subject's entrance pupil

was 1.65 x 4.1 mm. The total integrated energy in the flashes calculated from the MacBeth measurements was 2.1×10^6 td·sec.

The pupillograph records of the pupil responses for the two flash durations for the six subjects are shown in Figs. 15-20. The records are reproduced for the first nine seconds following the onset of the flash to show the constriction phase of the pupil response and the early phase of the subsequent dilation. A reciprocity failure is marked in all cases with the longer flashes producing an increase in pupil constriction. The shorter flashes resulted in a minimum pupil diameter in about one second following the flash, but the longer flashes produced an increased constriction for 0.1 to 0.5 seconds following the cessation of the flash The data for pupil diameters for the various subjects are summarized in Table III. The 1.5 msec flashes resulted in a mean constriction only 70% as great as the 1.5 sec flashes of equal energy.

The records indicate another interesting fact about the pupil response. The rate of constriction for both flash durations is constant for each subject. This is of interest because the rate of delivery of energy for the longer flashes is only 1/1000 that for the short flashes. It was suggested that the constriction rate measured from the pupillograph measurements might be limited by the response time of the instrumentation. This is unlikely since the

Table III. Pupil Constriction Following Tungsten Flashes of 1.5 sec and Xenon Flashes of 1.1 msec with Total Integrated Energy of 1.5×10^7 td·sec

Subject	Pupil Diameters			Maximum Constriction	
	Before Flash	Min. 1.5 sec	Min. 1.1 msec	1.5 sec	1.1 msec
R. B.	8.0	4.4	5.8	3.6	2.2
R. E.	6.8	3.2	3.8	3.6	3.0
J. M.	7.8	4.6	5.6	3.2	2.2
J. N.	7.1	2.85	4.4	4.25	2.7
W. P.	7.5	4.2	5.3	3.3	2.2
J. S.	8.3	3.75	4.9	4.55	3.4
Mean	7.58 mm	3.83 mm	4.97 mm	3.75 mm	2.61 mm

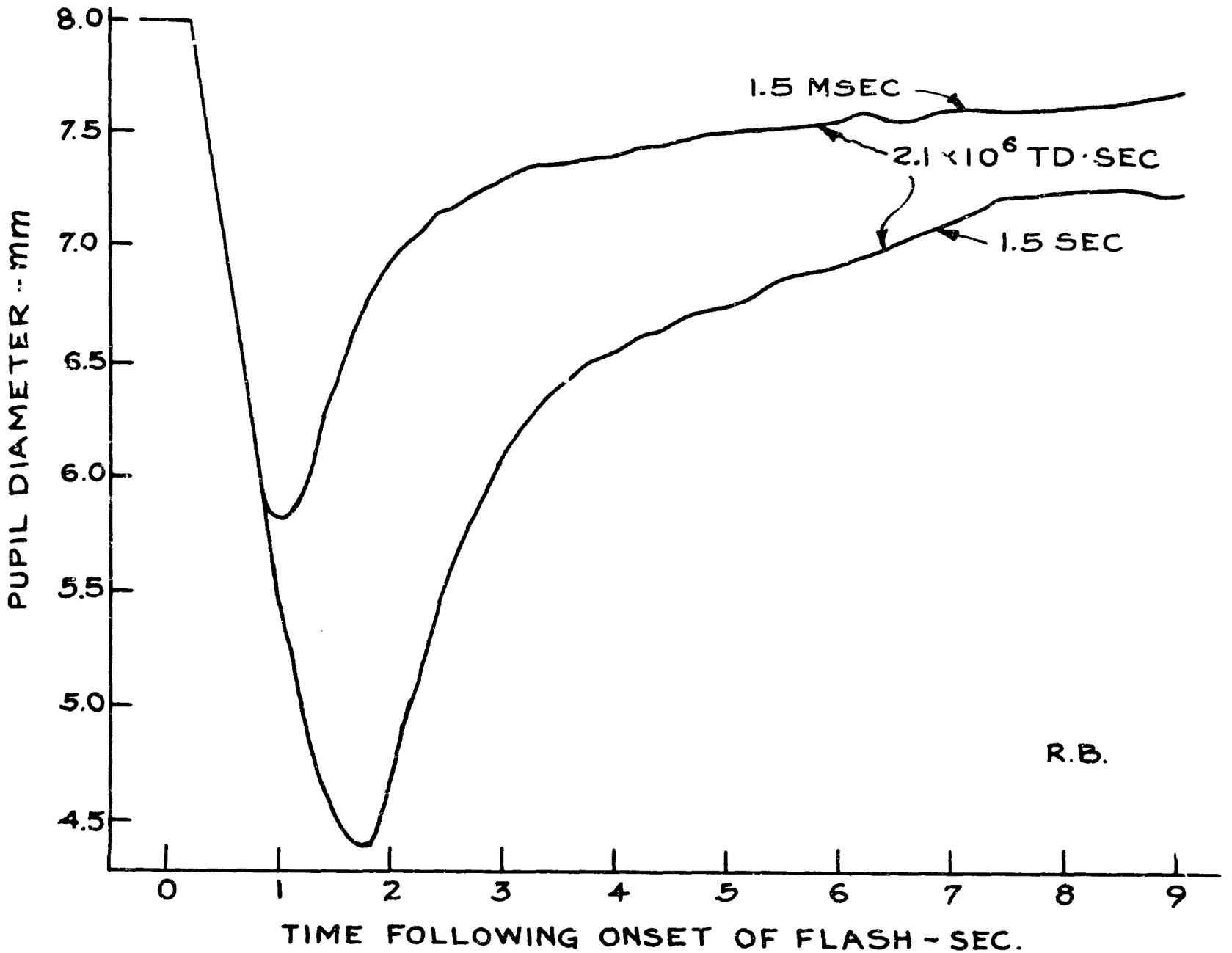

Figure 15. Pupil response records for one subject to 2.1 x 10^6td·sec flashes of 555 mμ light. The upper trace is for a 1.5 msec flash and the lower for a 1.5 sec flash.

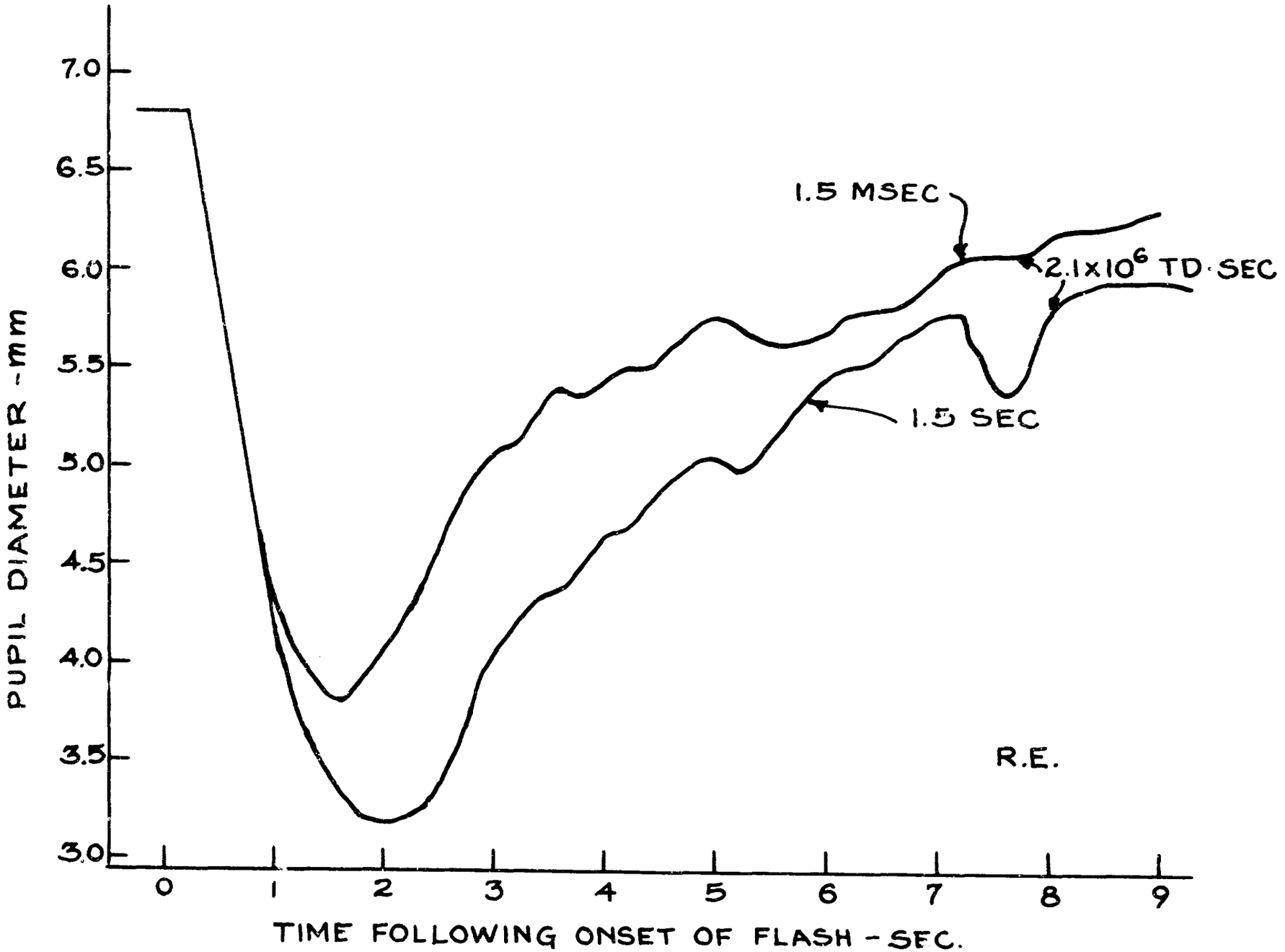

Figure 16. Pupil response records for one subject to 2.1 x 10^6 td·sec flashes of 555 mμ light. The upper trace is for a 1.5 msec flash and the lower for a 1.5 sec flash.

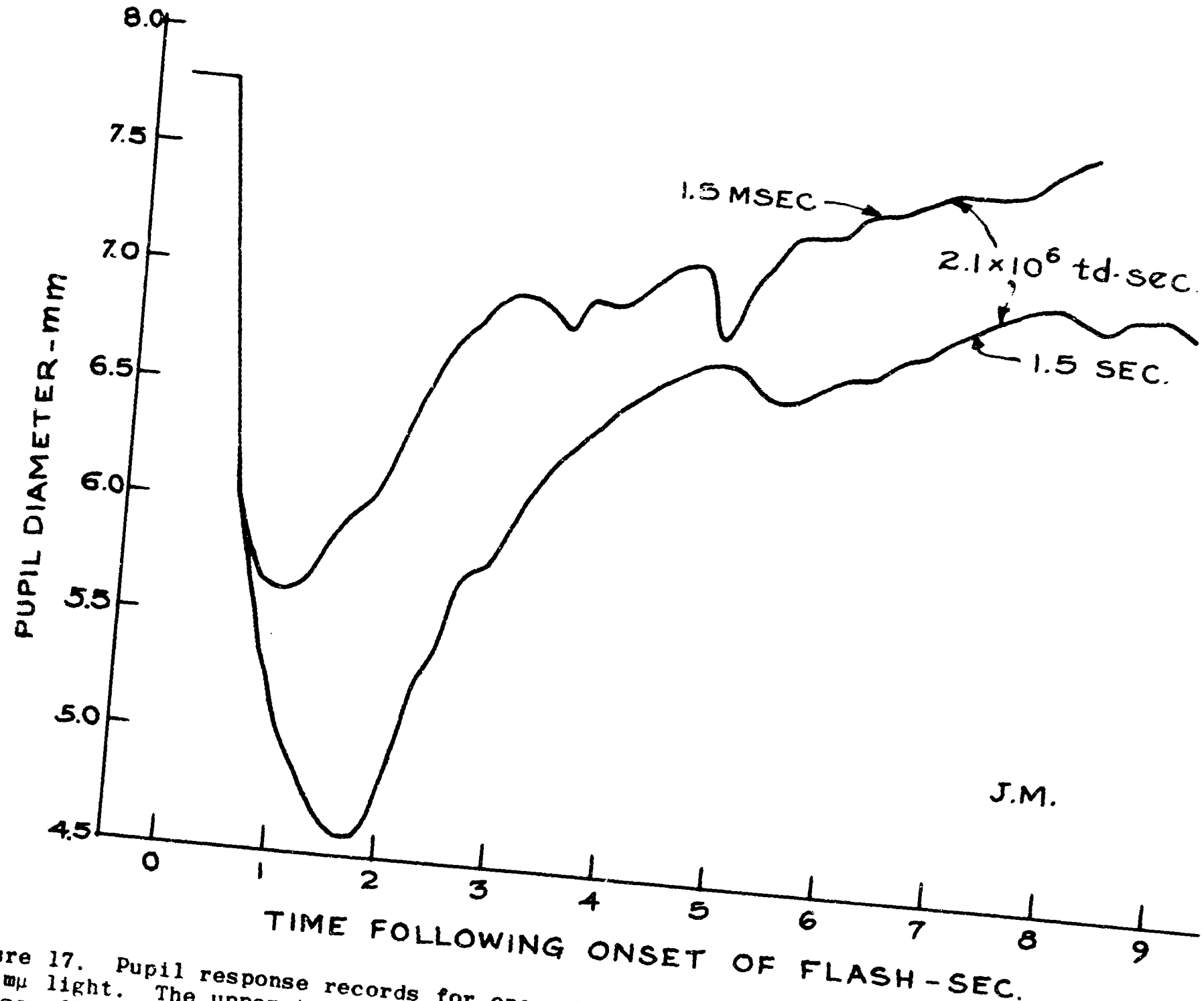

Figure 17. Pupil response records for one subject to 2.1×10^6 td·sec flashes of 555 mμ light. The upper trace is for a 1.5 msec flash and the lower trace for a 1.5 sec flash.

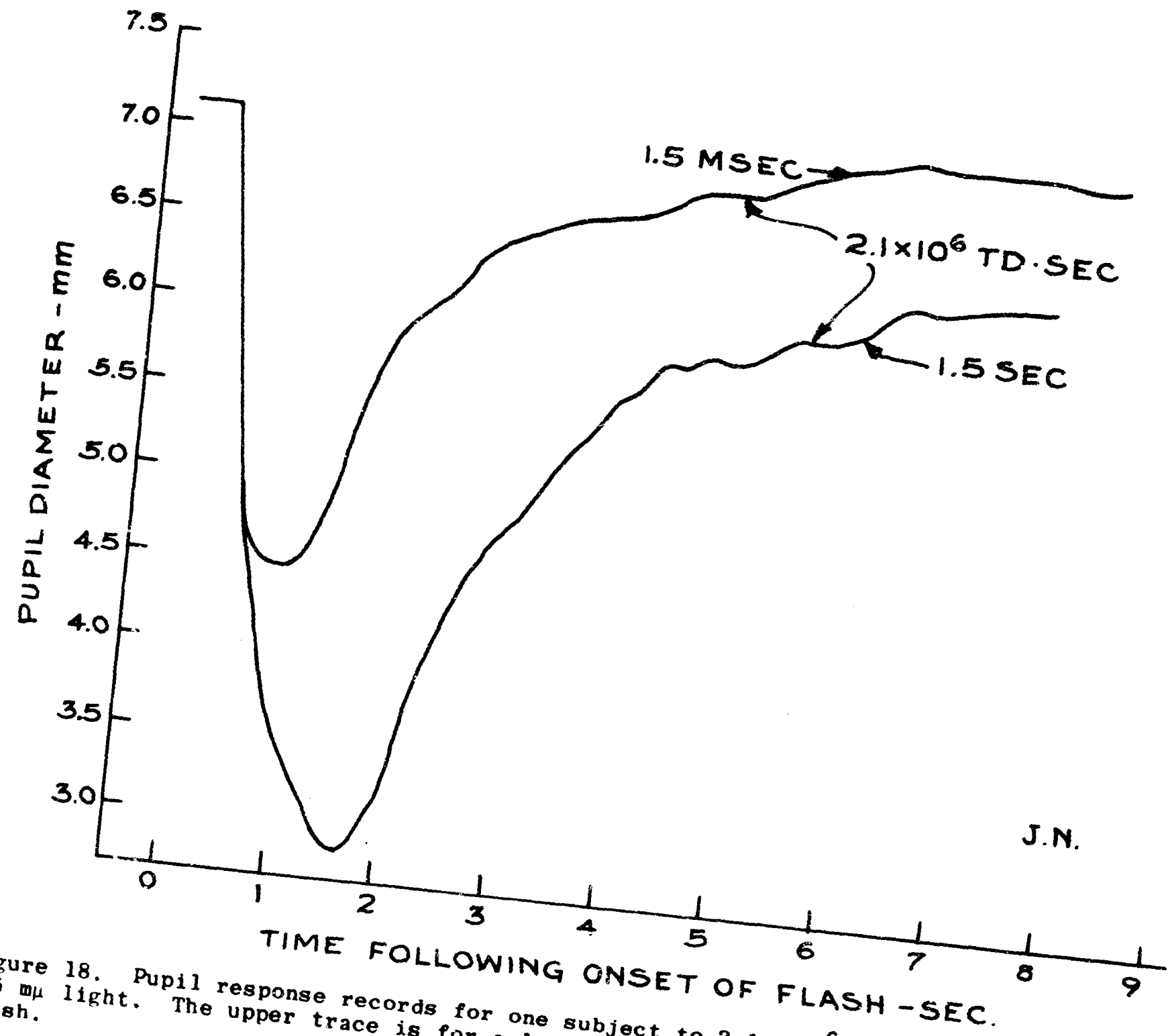

Figure 18. Pupil response records for one subject to 2.1×10^6 td·sec flashes of 555 mμ light. The upper trace is for a 1.5 msec flash and the lower for a 1.5 sec flash.

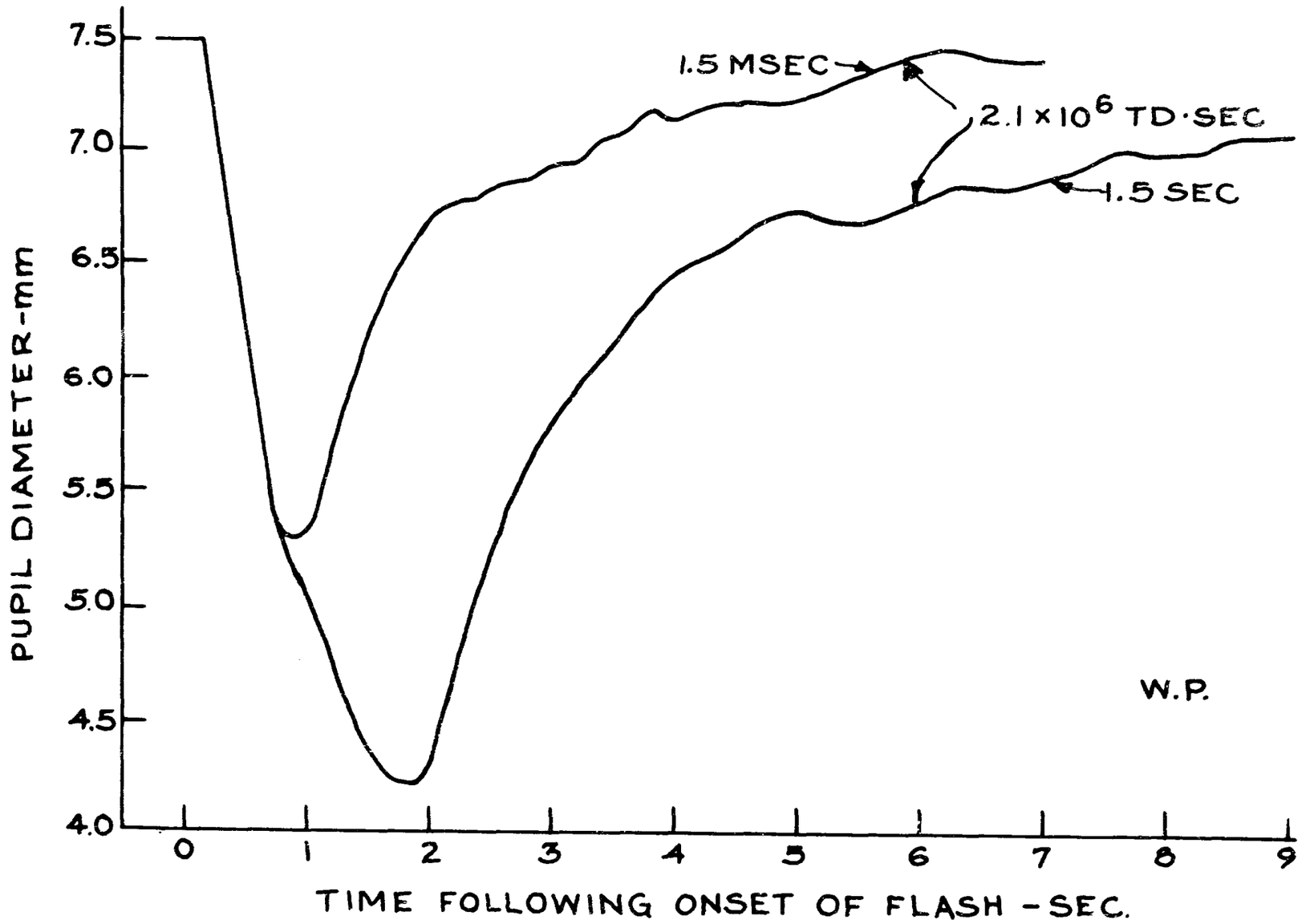

Figure 19. Pupil response records for one subject to 2.1 x 10^6 td·sec flashes of 555 mμ light. The upper trace is for a 1.5 msec flash and the lower for a 1.5 sec flash.

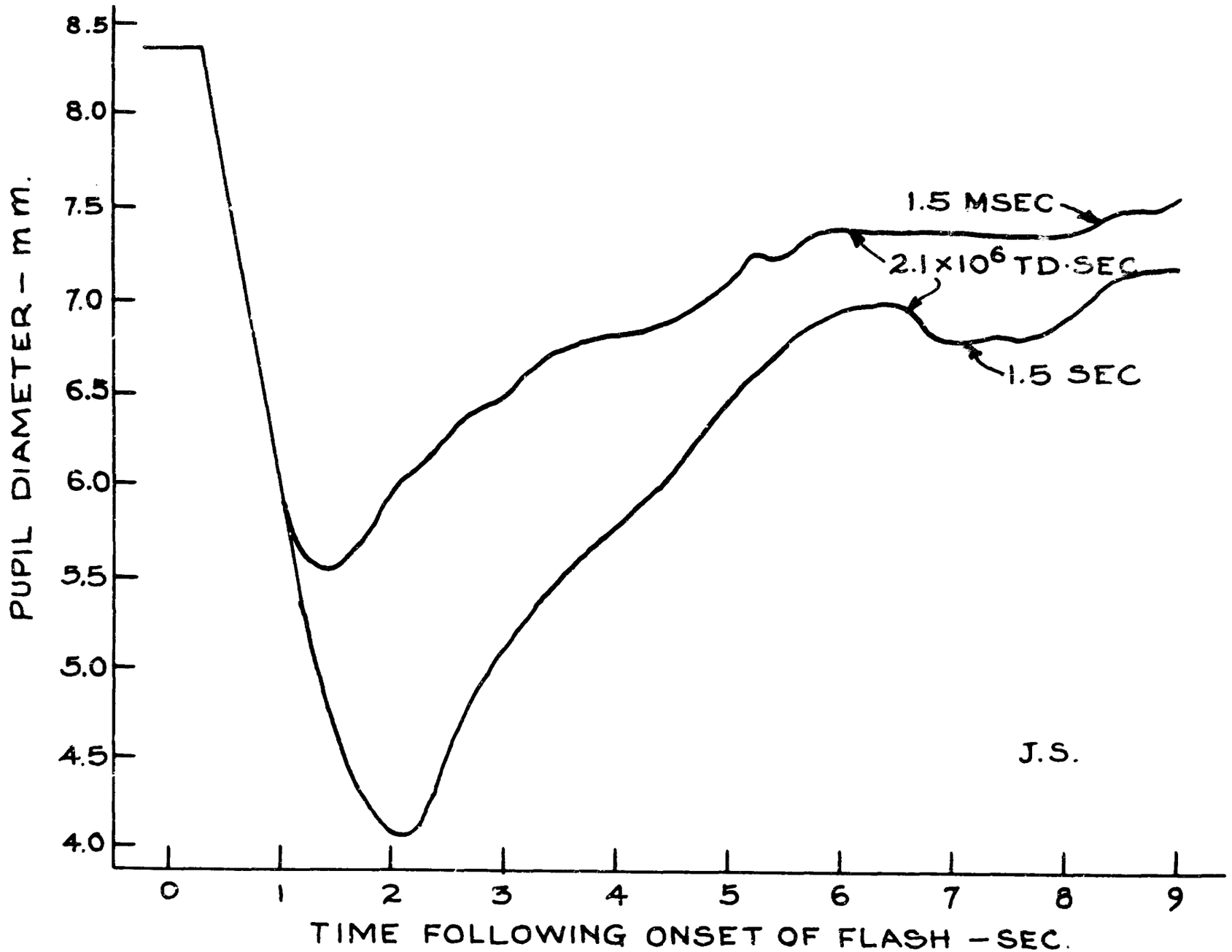

Figure 20. Pupil response records for one subject to 2.1 x 10^6 td·sec flashes of 555 mμ light. The upper trace is for a 1.5 msec flash and lower for a 1.5 sec flash.

pupil is scanned 700 times per sec and there are no obvious sources of lag in the electronics and the recorder writing speed is greater than the constriction rate. The constriction rate in mm of change in diameter per sec is tabulated in Table IV for the different subjects. The data show large individual variations and are evidence that the initial slope is not limited by the instrumentation.

5. Pupil Recovery Following Intense Flashes

The form of the recorded pupil response for the brief, high-intensity flashes shows a rapid constriction which is linear with time almost to the point of maximum constriction. For most subjects the pupil begins to dilate immediately after reaching the minimum diameter. Inspection of the records in Figs. 15-20 suggests an exponential form of the dilation portion of the response. Plotting the data for pupil diameters on a log scale did not produce the linear relationship with time that the exponential form would require so different relationships were investigated. The one that proved fruitful was based on a hypothesis concerning the underlying mechanism controlling the pupil diameter during the recovery period.

During the course of our earlier investigations on the relationship between visual recovery and afterimage brightness[6] we found that the afterimage brightness was a power

Table IV. Rate of Constriction of the Pupil Following 2.1×10^6 td·sec Flashes of 1.5 msec and 1.5 sec Durations.

Subject	Rate of Constriction mm/sec
R. B.	3.35
R. E.	3.38
J. M.	5.00
J. N.	5.60
W. P.	3.76
J. S.	3.37

function of the time following the flash. It seemed reasonable that the dilation rate of the pupil might be controlled by the afterimage brightness. The data were analyzed by taking the diameter of the dark adapted pupil as the base line and considering any constriction from the dark adapted diameter as an indicator of the effect of the flash at that instant. Figure 21 shows a graph of the dilation portion of the pupil response for one subject analyzed in this manner. His dark adapted pupil measured 8.6 mm in diameter on the day that the experiment was performed. He was given several 1.5 sec flashes to tungsten light through a 555 mμ interference filter. Flashes were 2.1×10^6 td·sec in integrated energy. The amount of residual constriction in mm is plotted on a log scale as a function of the time following the cessation of the flashes also on a log scale. The data for a five minute period following the flashes fall on a straight line with some scatter at the time interval when the greatest amount of flash induced hippus occurs. There is, therefore, the same type of power function between the pupil dilation with time as there is between afterimage brightness fading and time.

It is apparent from the data that a measure of pupil diameter change from the dark adapted state is a valid measure of the remaining afterimage brightness. In order for this measure to be sufficiently precise a number of precau-

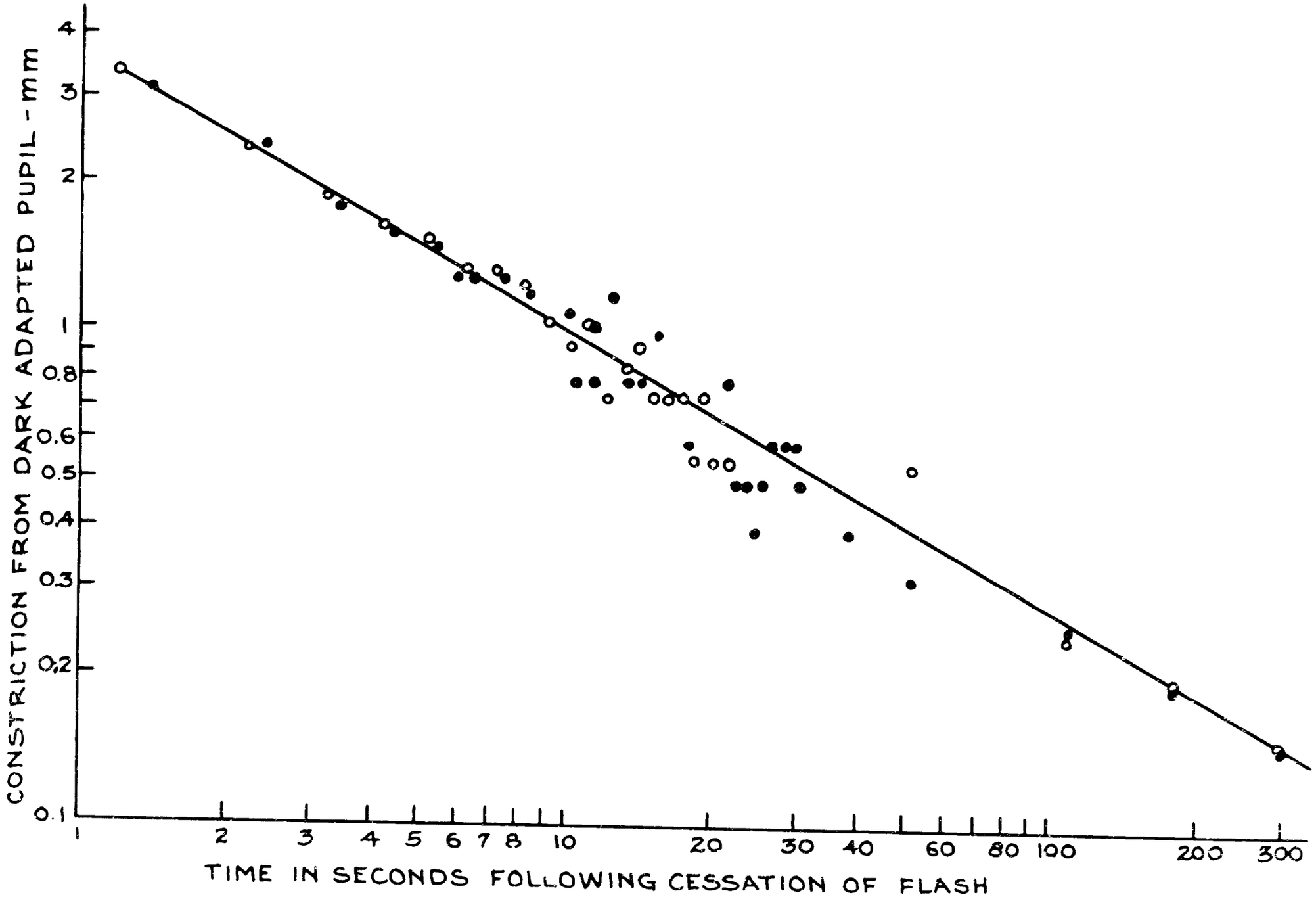

Figure 21. The relationship between the amount of constriction from the dark adapted pupil and the elapsed time following the flash.

tions must be taken that were not included in our routine pupillograph recording.(1) The dark adapted pupil diameter must be known accurately since a slight error in this measurement changes the slope of the linear function between the logarithms of the variables.(2) The relationship between the pupil diameter and the luminance of an external field over the range of matching afterimage brightnesses should be established for each subject.(3) The recording of pupil diameters following flashes must extend over a sufficient time range to prevent erroneous conclusions from the brief spontaneous constrictions due to hippus. These precautions are easily controlled and the results of the pilot study indicate that continued effort in the area of pupil recording would be fruitful.

6. Blink Reflex

At the beginning of the pupillograph recording, it was anticipated that the trace would provide a precise measure of the latency of the blink reflex. With the pupil occluded during a blink, the signal from the photomultiplier loses the characteristic form of the usual scanning beam reflection and the trace from the recorder shows a marked distortion. It came as a great surprise, therefore, that blinks were found in only a small fraction of the traces. In the course of the investigation, 757 flashes were delivered to 8 subjects and there were no blinks recorded during the first 30 seconds in nearly 700 traces.

During the portion of the work on calibrating the pupillograph with infrared photographs, it was necessary for the experimenter to remove a mirror immediately in front of the subjects eye after the flash. The motion of the experimenter's hand toward the subject's eye always produced a blink reflex and was a convenient marker in the trace for the start of the series of photographs. It is difficult to explain the absence of the blink following the flashes, even those of 1.5 sec duration, when the normal avoidance reflex was present.

V. SUMMARY

The pupillograph recording of pupil response following the high intensity flashes resulted in some interesting conclusions about the pupil action.

1. The rate of constriction is constant over a wide range of field luminance for each subject with some individual variation in rate.

2. The time to maximum constriction is a useful measure of the total pupil response and is a power function of the total energy received by the retina.

3. There is a large reciprocity failure between time and intensity of flashes for durations between 1.5 msec and 1.5 sec, with the longer flashes producing a greater response.

4. The dilation of the pupil following the constriction from a flash is a power function of the time following the cessation of the flash if the dilation is measured in terms of

the residual constriction in mm of diameter from the dark adapted pupil for any instant.

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13. ABSTRACT

ABSTRACT

Some new instrumentation has been developed and a number of refinements have been made in the existing special test equipment for investigating the visual recovery following high intensity flashes. The primary areas of apparatus modification were (1) increased capability for the measurement of source energy in absolute units, (2) increased precision in the measurement of recovery times, (3) extended range of flash durations for recovery measurements, and (4) inclusion of pupillographic recording as a measure of flash effect.

The consensual pupil reflex was measured for six subjects for flash energies from 1.5×10^5 to 3×10^7 td·sec. The flash durations were varied from 250 μsec to 1.5 sec. Flash fields subtendend a visual angle of 7.5° in most of the work with a 2° centrally fixated field used in one part of the study.

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