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VISUAL RECOVERY FROM HIGH INTENSITY FLASHES

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July 1965

USAF School of Aerospace Medicine
Aerospace Medical Division(AFSC)
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FOREWORD

This report was prepared by the Ohio State University Research Foundation under Contract No. AF41(609)-2426 with the USAF School of Aerospace Medicine, Aerospace Medical Division, Brooks Air Force Base, Texas. Norma D. Miller of the School of Optometry was the principal investigator.

The project was initiated by the School of Aerospace Medicine, Brooks Air Force Base, Texas and was monitored by Major, L. R. Loper. Dr. Glenn A. Fry, Director of the School of Optometry, The Ohio State University was supervisor.

This work represents the second phase of a continuing effort in the area of the visual effect of high intensity flashes. The work described in this report covers the research conducted during the period 15 May 1964 through 15 May 1965, under 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

High intensity flashes of 0.04 msec to 1.4 msec duration were used to determine the afterimage brightness as a function of time following the flash. Six human subjects made continuous matches of the afterimage for periods up to six minutes following the flashes. The flash energies ranged from 3×10^7 to 8×10^5 td·sec or from 0.012 to 0.0003 cal/cm^2 at the retina, neglecting losses in the ocular media. The mean afterimage brightness, 5 sec following the highest intensity flashes, was 10^5 td. The afterimage brightness data were correlated with recovery time measurements for Sloan-Snellen letters presented at luminance levels from 280 mL to 0.07 mL.

The reciprocity relationship between the duration and luminance of flashes subtending 7.5° visual angle was investigated for constant flash energy of 3×10^7 td·sec. Seven flash durations from 0.5 to 5.0 msec were tested. The recovery times for the Sloan-Snellen letters at various luminance levels increased approximately 30% following 1.5 msec flashes compared with the 0.5 msec flashes. There was no apparent change for the mean recovery times for four subjects following flashes from 1.5 msec to 5.0 msec in duration.

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VISUAL RECOVERY FROM HIGH INTENSITY FLASHES

I. INTRODUCTION

In designing efficient protective devices for pilots who may be subjected to intense flashes of light, a number of variables of visual function must be considered. The ideal protective goggles or windshield would be almost perfectly transparent under ordinary conditions of ambient illumination, darken to a sufficiently high density to reduce the illumination from a high intensity flash to that comparable to the ambient level, complete the change in density within an infinitesimally brief period following the onset of the flash, and clear again to perfect transparency at the end of the flash. Obviously such an idealistic solution to the prevention of flash blindness is not feasible with existing materials, so the various possible compromises must be examined. The best available solution can be chosen only when we have adequate knowledge of the relative effects of various durations, sizes, and intensities of the flash field in reducing visual performance.

Inasmuch as some loss of performance will always be suffered with anything less than the ideal eye protection, it is important to examine the characteristics of visual recovery following such a temporary loss. With adequate knowledge of the recovery parameters, it should be possible to design floodlighting for instrument panels and the size of the visual display to insure that the pilot can perform the critical visual tasks within a few seconds following a flash exposure with existing protective devices.

The problem has theoretical as well as practical significance, and data are needed on the rate of decay of the brightness of the positive afterimage in order to attain a more complete understanding of the underlying mechanism.

A failure in the reciprocity relationship between flash duration and intensity for constant integrated energies has been observed in the bleaching of rhodopsin solutions. Williams[1] developed a mathematical model to explain the reciprocity failure assuming a two-stage bleaching process, starting with absorption of a quantum of light by a molecule of photopigment. After the absorption of the quantum, there is a delay of around 1 msec before the molecule enters the second or thermal bleach stage of the process. If the energy density is sufficiently high, there is a finite probability of a second quantum being absorbed by one molecule during the 1 msec refectory period. The second quantum acts to reisomerize the molecule and prevent the second stage of the process from occuring.

The previous work in this laboratory on recovery times for flashes from 1.4 msec to 0,04 msec in duration showed no reciprocity failure between time and intensity within the limits of experimental error. In the earlier work, the Sloan-Snellen letters were presented at 0.07 mL following flashes of 10^6 td·sec. Hill and Chisum,[2] working with flash durations of 33 μsec, 165 μsec, and 9.8 msec, found that the recovery times for the long flashes were almost 50% greater than for the short ones when equal integrated energies were used for all durations.

One of the difficulties in performing an exhaustive investigation of the reciprocity failure in the living eye has been the lack of light sources with sufficiently high, sustained radiance to produce flashes of high energy over a suitable range of durations. The radiance of all existing thermal sources is too low to produce flashes of 1 msec duration with enough integrated visual energy to provide the high quanta densities required. The xenon flash sources all have the same general time course of radiance with a rapid rise to peak radiance, a brief period of constant radiance, and an exponential decay. Any attempt to prolong the constant radiance portion of the discharge results in a decrease in total integrated energy. In the current study, the flash discharge was chopped by a sector disc carrying a graded neutral density strip over the opening to maintain uniform flash luminance to 5 msec duration.

II. SCOPE

Seven subjects participated in the experimental work. The subjects were optometry students in their early twenties. All were tested for acuity and visual fields with small targets before starting the experimental sessions and again several months following the termination of the sessions.

There were no significant changes in the findings. All subjects participated both as observers and experimenters during the sessions and assisted with the data analysis. The broad participation in the program helped to maintain a high level of motivation.

Several major areas of the current study are covered in this report. The apparatus was essentially the same as that used in the previous study and is fully described elsewhere.[3] The design and calibration of the apparatus is briefly described in Section III with the details of the refinements in electronic circuitry for monitoring the flash energies. Some modifications in the apparatus were necessary for the different experiments performed, and the changes are covered in the sections on the experimental procedures.

Several types of photometric fields were employed for matching the afterimage with the standard field for periods up to four minutes following the flash. The brightness matches were made both monocularly and binocularly and were automatically recorded. Various flash energies were used in producing the afterimage. The recovery times for two sizes of test letters, subtending 28.7 and 16.3 min. of arc, were measured for a range of letter luminances from 140 mL to 0.007 mL following the various flash energies. Each subject determined the luminance of a uniform 10° field required for threshold recognition of the letters when they were superimposed on the uniform field with the various luminance levels employed in the recovery time determination. The data are described in Section IV and are compared with the decay of the afterimage brightness.

The reciprocity relationship between the intensity and the duration of the flashes was investigated for durations between 0.54 msec and 5.0 msec. The recovery times for the 28.7' letter and the 16.3' letter at various luminance levels were used as the criterion measure of the effectiveness of the flashes of constant energy and varying durations. The total integrated energy was maintained at 3×10^7 td·sec (0.012 cal/cm^2 at the retina) for the full range of durations. There were some individual variations in the results, and the data were analyzed both on the basis of subject means and the individual data for each subject. The experimental procedure and results are covered in Section V.

III. APPARATUS

The flash source was a 10,000 watt-second Sun Flash unit with a xenon-filled lamp. A segment of the lamp was focused at the plane of the entrance pupil of the subject's eye to provide a Maxwellian view field of 10° diameter. The essential elements of the original apparatus and calibration are described briefly below with the details of the modifications for the different experiments covered in the following sections describing the experiments.

A schematic drawing of the optical system is shown in Fig 1. An enlarged image of a segment of the flash tube was focused on an aperture plate at A_1, filling the 20 x 10.5 mm. aperture. A 48-inch telephoto lens, L_2, colimated the light; and the rotating mirror, M_1, the 20-inch

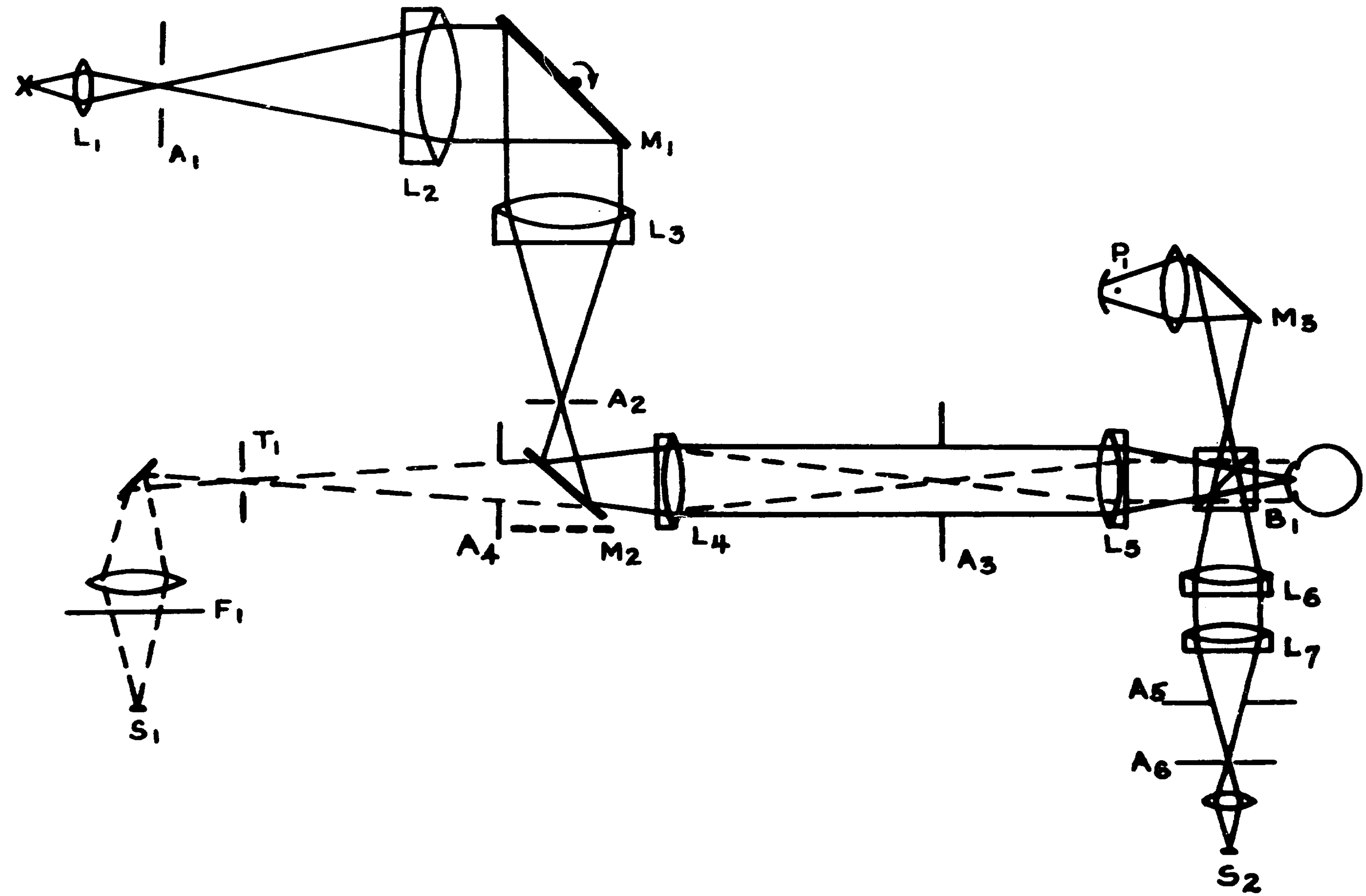


Figure 1. A schematic drawing of the optical system for producing a 10^{o} flash field and for the presentation of the recovery targets.

telephoto lens, L_3, and the aperture, A_2, completed the shutter system. Light reflected from M_1 into L_2 was brought to a focus and swept past the aperture, A_2, which was 4.1 x 4.3 mm. The ratio of the width of the image of A_1 and the width of A_2 determined the duration of the flash. The mirror was driven through a pulley system with five interchangeable combinations to provide speeds from 1820 rpm to 55 rpm, resulting in flash durations from 0.04 msec to 1.4 msec. The flash tube was triggered in phase with the mirror so the tube reached maximum radiance at the instant that the image of A_1 reached the edge of A_2. This arrangement insured the same peak radiance for all flash durations.

The light from A_2 was reflected from a first surface mirror, M_2, through lenses L_4 and L_5 and was focused at a 1:1 magnification at the plane of the subject's pupil. A field stop, A_3, at the focal point of L_5 provided a 10° flash field. The beamsplitter, B_1, reflected a portion of the flash to a first surface mirror, M_3, where it was reflected into a phototube. The oscilloscope traces of the phototube signals were photographed for all flashes during the experimental sessions. Lenses L_6 and L_7 provided another Maxwellian view system with a 10° field. The field stop at A_5 was seen by the subject in the plane of A_3 and coincident with it after reflection from the beamsplitter, B_1. A fixation target was placed at A_5 to aid in maintaining central fixation for the flash and the recovery targets.

Immediately after the flash, the mirror, M_2, was swung out of the beam to the position shown by the dotted lines. The recovery targets at T_1 were transillumiated by the ribbon filament lamp at S_1. Filters at F_1 controlled the luminance of the recovery targets. The lens, L_4, imaged the targets at a 2:1 reduction in the plane of A_3 where they were viewed by the subject with relaxed accomodation.

The target luminances were measured by a MacBeth Illuminometer. The flash tube radiance at the peak of the discharge was determined by comparison with a standard ribbon filament lamp operated at 3000° color temperature. The comparison was made through a series of interference filters at 24 narrow regions of the spectrum from 400 to 1100 mµ. Figure 2 shows a logarithmic plot of the steradiancy of the tungsten filament and of the flash tube at peak. The middle curve of Fig. 2 is the steradiancy of the tube after filtering through a 3 mm. thick KG-3 filter to remove the infrared. The filter was used during all experimental sessions. The luminance of the flash field was calculated from the steradiancy and the measured transmission of the optical system to be 4×10^5 L at peak.

In the earlier work, the flashes were monitored by a RCA 929 phototube with a one megohm load resistor. The voltage signal was connected to a 533A Tektronix oscilloscope with a fast-rise time amplifier through a 10X attenuating probe to reduce the RC time constant. It was found that there was sufficient distortion in the displayed trace to invalidate the

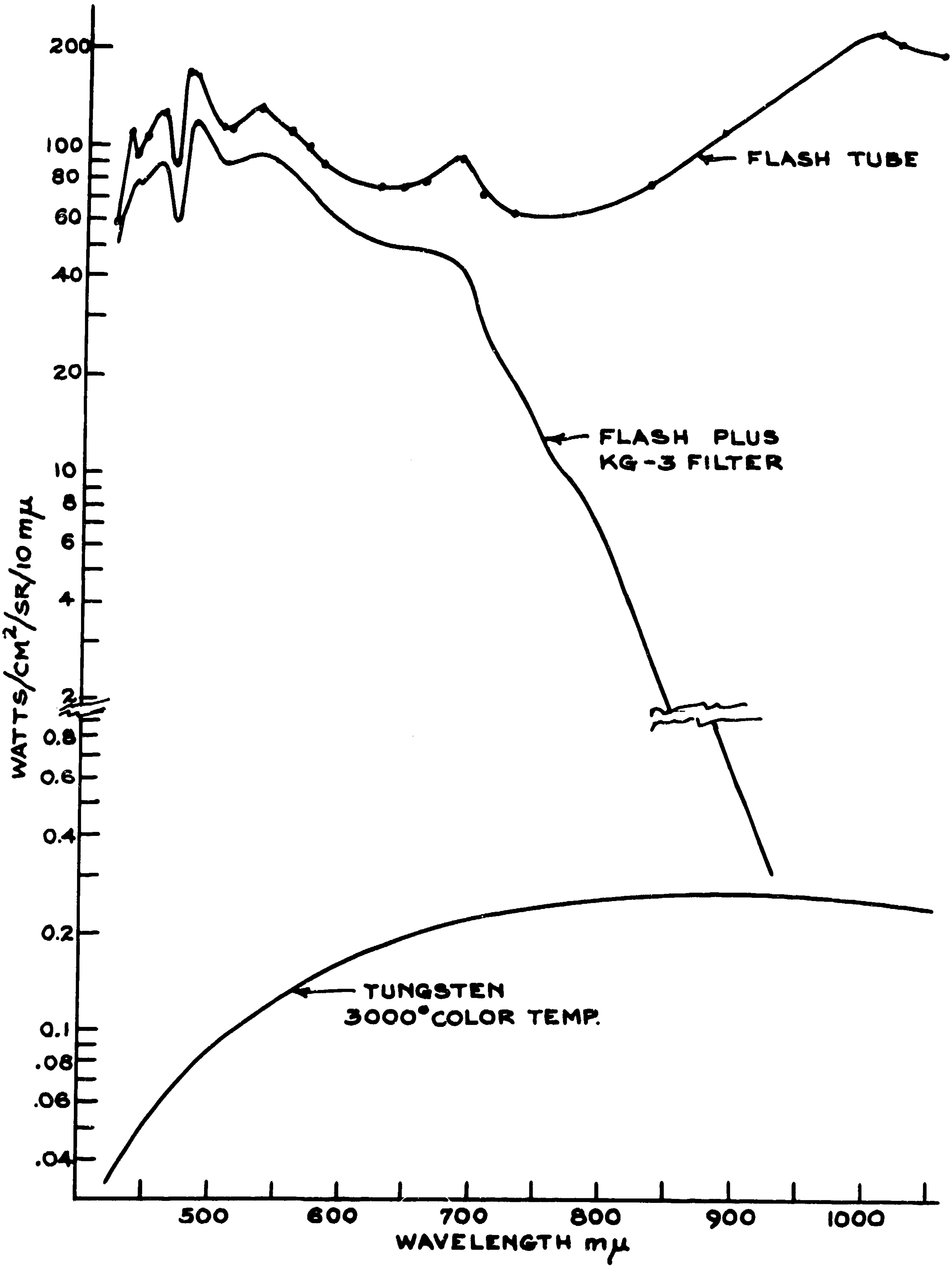


Figure 2. The steradiancy of the flash tube compared with tungsten at 3000° color temperature.

measurements of the flash energies from the traces. The shortest flashes of 0.04 msec were the most seriously affected. The anticipated form of the trace could be calculated from the optical design of the rotating-mirror shutter system, and should have been trapezoidal. The limiting aperture, A_2, was one half the width of the image of A_1, so the rise time to the full radiance should have had a constant slope with a duration equal to the constant radiance portion, and the decay portion should have been the same as the rise time except for a negative slope. The actual trace for a 0.54 msec flash through the attenuating probe is shown in Fig. 3. It is obvious from the rounded appearance of the trace and its lack of symmetry that the displayed wave form was not an accurate recording of the phototube current. Part of the curvature at the peak of the trace may have been due to nonuniformity of the light filling the entrance aperture.

In order to investigate the amount of distortion of the signal and to refine the measurements, an operational amplifier plug-in unit was used with the oscilloscope. The unit consists of two operational amplifiers and a vertical preamplifier which can be used as an independent oscilloscope preamplifier or to monitor the output of either of the operational amplifiers. Figure 4(a) is a trace of the phototube signal connected through a coaxial cable to the input of the vertical preamplifier. The input characteristics of the preamplifier are one megohm paralleled by 47 pf. The flash was produced by using a uniformly luminous ribbon filament to fill the entrance aperture and was slightly longer in

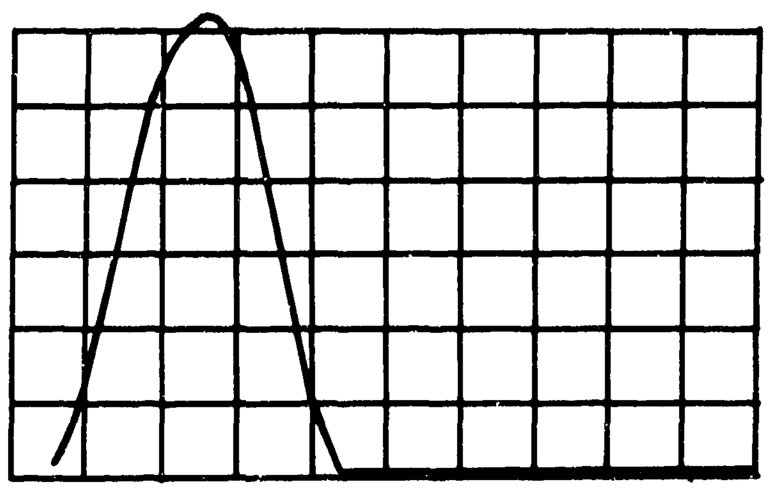


Figure 3. Oscilloscope trace of the phototube signal for the 0.54 msec flash produced by the rotating-mirror shutter system synchronized with the flash tube discharge. The mirror speed was 138 rpm, and the oscilloscope sweep rate was 0.2 msec per grid division.

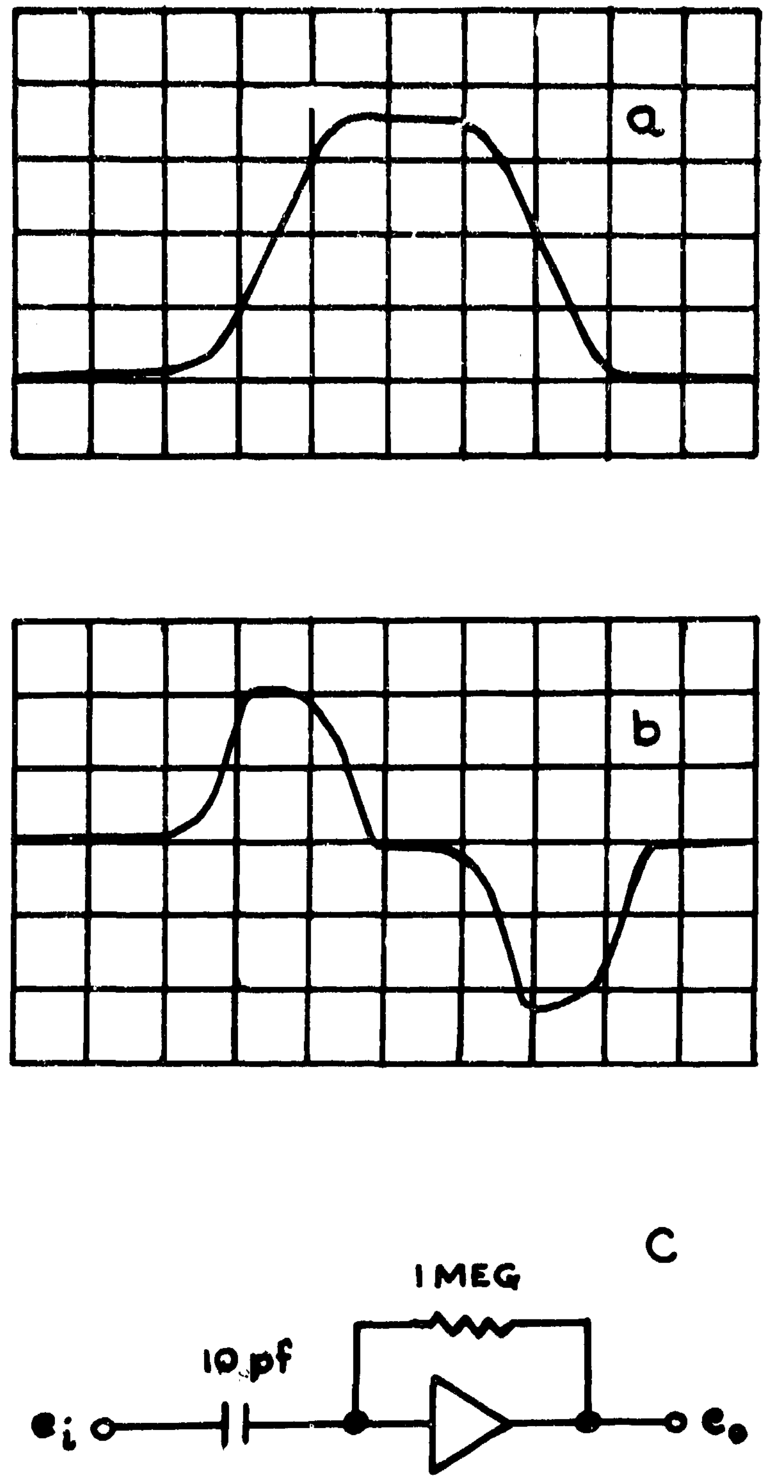


Figure 4. (a) Oscilloscope trace of the phototube voltage signal for a tungsten source flash of 0.75 msec duration. (b) The differentiated wave form of the trace shown in (a) obtained by connecting the phototube signal to the oscilloscope amplifier through the circuit shown in (c).

duration than the flash of Fig. 3. Figure 4(b) is the trace obtained by connecting the coaxial cable to the input of one of the operational amplifiers used as a differentiator as shown in the diagram in Fig. 4(c). If there were no signal distortion, the differentiated flash would have a rapid rise to a positive value corresponding to the slope of the rise time of the flash then drop to a ground level for the same duration as the positive level, and then drop to a negative level equal to the positive value. The actual trace of Fig. 4(b) indicates the rather large amount of distortion present.

The input impedance of the operational amplifier is really a combination of the signal source impedance and the impedance of the amplifier; and with the capacitance of the cable, the RC time constant might be expected to be too high for accurate recording of the phototube current. To reduce the time constant, the load resistor was removed from the phototube, and the current signal was applied to the input of one of the operational amplifiers through a simple shielded cable where it was converted to voltage by the arrangement shown in Fig. 5(a). The resulting trace is shown in Fig. 5(b), and the improvement in the recording can be seen by the close approximation to the theoretical trace.

The voltage output of the operational amplifier was applied to the input of the second operational amplifier used according to Fig. 4(c) for differentiating the signal. The resulting crt trace is shown in Fig. 5(c). There is still a little distortion shown in the rounding of

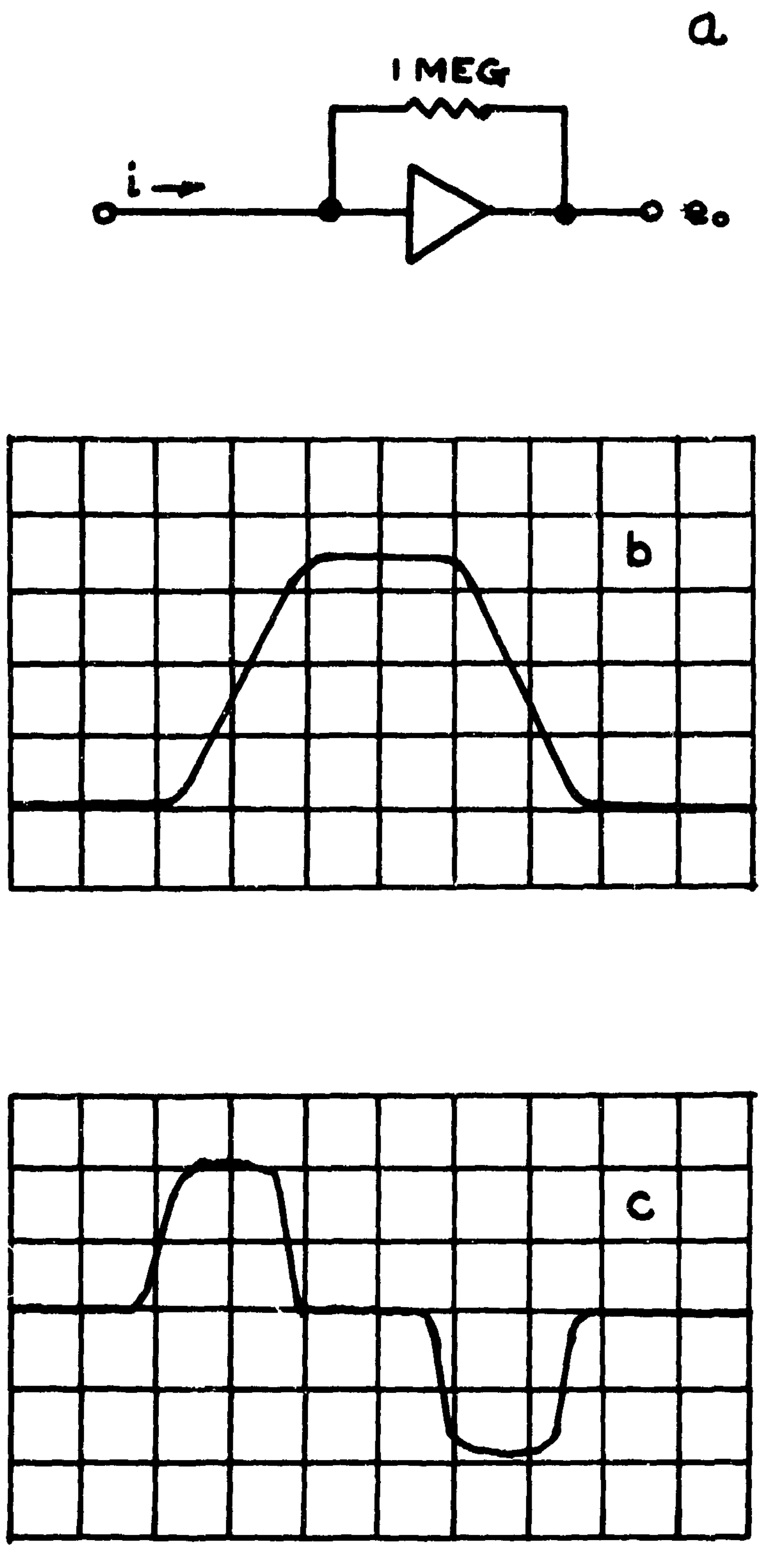


Figure 5. (a) The circuit of the oscilloscope operational amplifier for current to voltage conversion. (b) The crt trace obtained by connecting the phototube current signal to the input of (a.). The 0.75 msec flash was from a tungsten ribbon filament source. (c) The differentiated wave form of the trace in (b).

the positive and negative levels, corresponding to the rise and decay slopes, but the recording is sufficiently accurate for flashes longer than 20 μsec.

IV. AFTERIMAGE BRIGHTNESS

Crawford[4] in 1947, suggested the use of equivalent backgrounds to generalize the recovery times for various target configurations and luminance levels. He showed that the threshold for any target was raised at any given time following a flash as though the subject were viewing the target against an equivalent, external background field. By measuring the external background luminance for threshold recognition of the various recovery targets, the dark adaptation following a flash could be plotted as a relationship between equivalent background and time, and it was consistent for various target configurations and luminances. Our earlier recovery time measurements with Sloan-Snellen test letters were transformed in the manner suggested by Crawford and were reported in the Technical Report[3] previously cited. The results indicated that five seconds after a 3×10^7 td·sec flash, the threshold was raised as though the target were viewed against an external field of 5 L or with a retinal illuminance of 5×10^4 td. Five seconds later, the equivalent background was decreased by a factor of ten. There was nearly linear relationship between the log of the equivalent background and the log of the time following the 3×10^7 td·sec flash up to 100 sec.

The positive afterimage following the high intensity flashes appears as a bright area with the same shape and visual angle as the flash. It seemed desirable to measure the luminance of an external field that subjectively matched the afterimage and compare it with the equivalent background data from the recovery time measurements.

1. Apparatus

The apparatus was modified according to the diagram in Fig. 6 to permit automatic recording of the luminance of a matching field. The unit was designed to allow either binocular or monocular matching with several photometric field configurations. A pair of circular neutral density wedges, F_1, were crossed to produce a uniform density sector that could be varied to attenuate the light in the matching field over 8 log units. The circular wedges were mounted in gears and driven by a reversible motor. The motor unit had a solenoid operated driving gear which retracted as soon as the power was interrupted so there was no overdrive of the wedges after the subject opened the switch. A rocker type switch was mounted below and to one side of the bite-plate, and the subject could make the field lighter or darker by pressing with either his thumb or fingers on the sides of the switch bar. The gear ratio was selected to insure that the density of the wedges could be changed faster than the anticipated drop in the afterimage brightness. A 1.0 density step could be achieved with the motor running for 2.6 sec. The position of the wedges was continuously recorded on moving paper as the subjects maintained a photometric

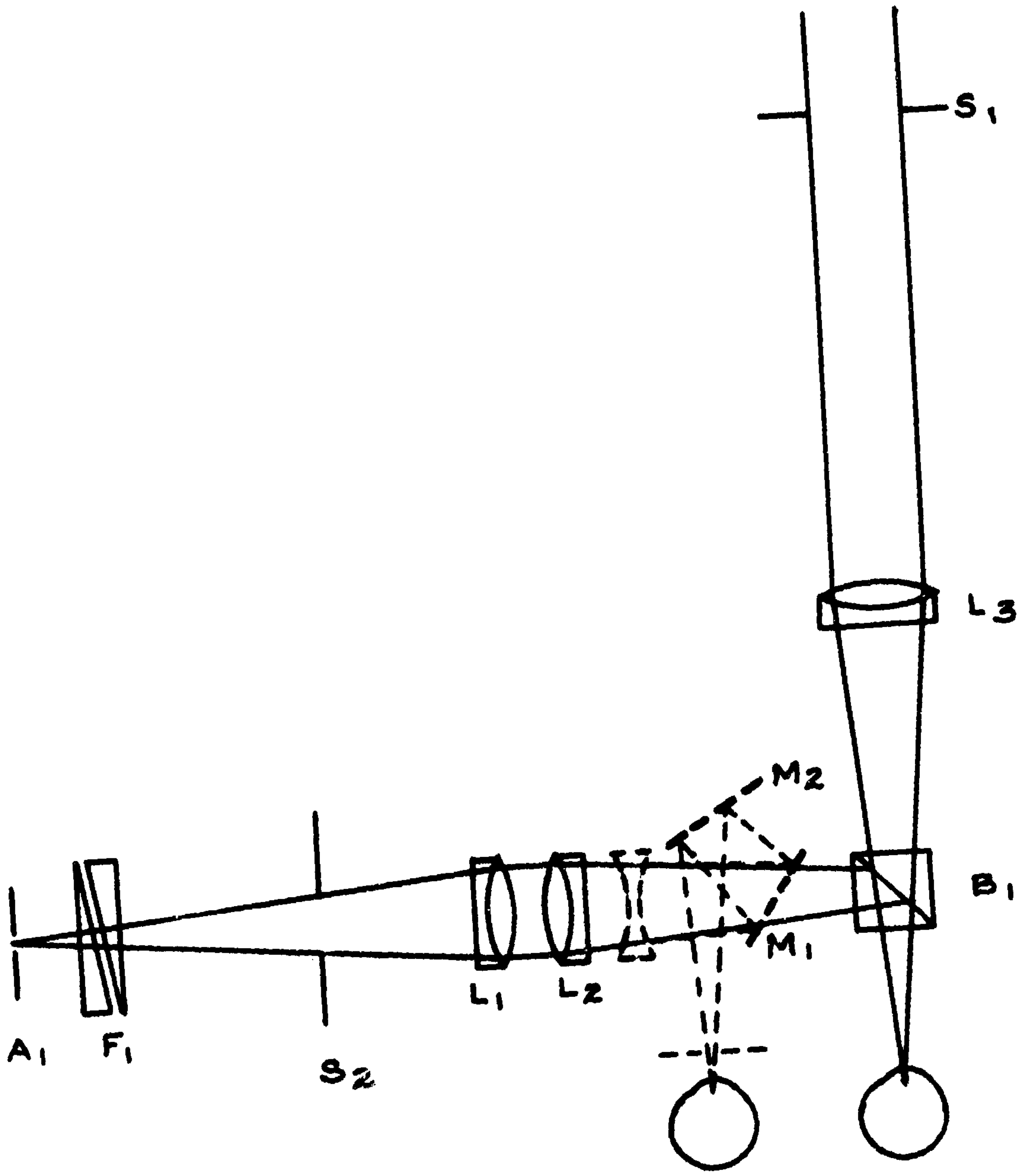


Figure 4. Schematic drawing of the optical system modification for monocular and binocular matching of the afterimage brightness. The broken lines show the elements and the ray path when binocular matching was used with the standard field in the left eye and the afterimage in the right eye.

match. Calibration of the wedges and pen drive allowed the density and hence the field luminance to be plotted as a function of time following the flash.

The source for the matching field was a standardized ribbon filament lamp run at 18.0 amps. The filament was imaged on the 2-mm circular aperture at A_1 which was imaged at 1:1 magnification in the plane of the subject's pupil by the lenses L_1 and L_2. For monocular matching, the light path was that shown by the solid lines in Fig. 6. The additional components shown by the broken lines were added for binocular matching. The filament was then imaged in the plane of the entrance pupil of the left eye to provide the matching field with the afterimage in the right eye. The field stop at S_2 was adjustable so the image could be made to coincide with that of the flash field stop at S_1. Masks were inserted at S_1 and S_2 for various configurations of the photometric field.

2. Monocular Bipartite Matching of Afterimage Brightness

A simple bipartite photometric field with a vertical dividing line was produced by blocking one half of the flash field stop at S_1. The opposite half of the matching field was blocked at S_2. It was hoped that the semicircular afterimage could be brought into juxtaposition with the matching field by fixating on the vertical edge of the matching field. The problem with such an arrangement is that the afterimage moves with the eye, and an image of an external object moves in the opposite direction.

The result is that all compensatory movements for maintaining the two fields in juxtaposition were in the wrong direction, and the subjects complained that the two fields either overlapped or were separated by a wide band. In spite of the fixation problem, a number of consistent traces following the flashes were obtained for six subjects. There was considerable variation between the records for the different subjects as shown in Fig. 7. Each curve is for a different subject and is the mean of at least five separate determinations of the retinal illuminance necessary to maintain a brightness match over a 140 sec interval following flashes of 0.56 msec duration. The mean drop in afterimage brightness for all subjects over a 2 min period is about 5 log units.

The differences between the curves in Fig. 7 appear to be true individual differences and may reflect a difference in the brightness of the afterimage for the various subjects or may be a criterion difference in matching. Figures 8(a) and 8(b) show composite records for three flashes for two different subjects. The consistency is amazing considering the difficulty of the task. The afterimage goes through a series of colored phases with quite saturated colors, and all subjects reported that the afterimage would disappear for brief intervals. There was some day to day variation for any given subject, but the magnitude was much less than the intersubject variations.

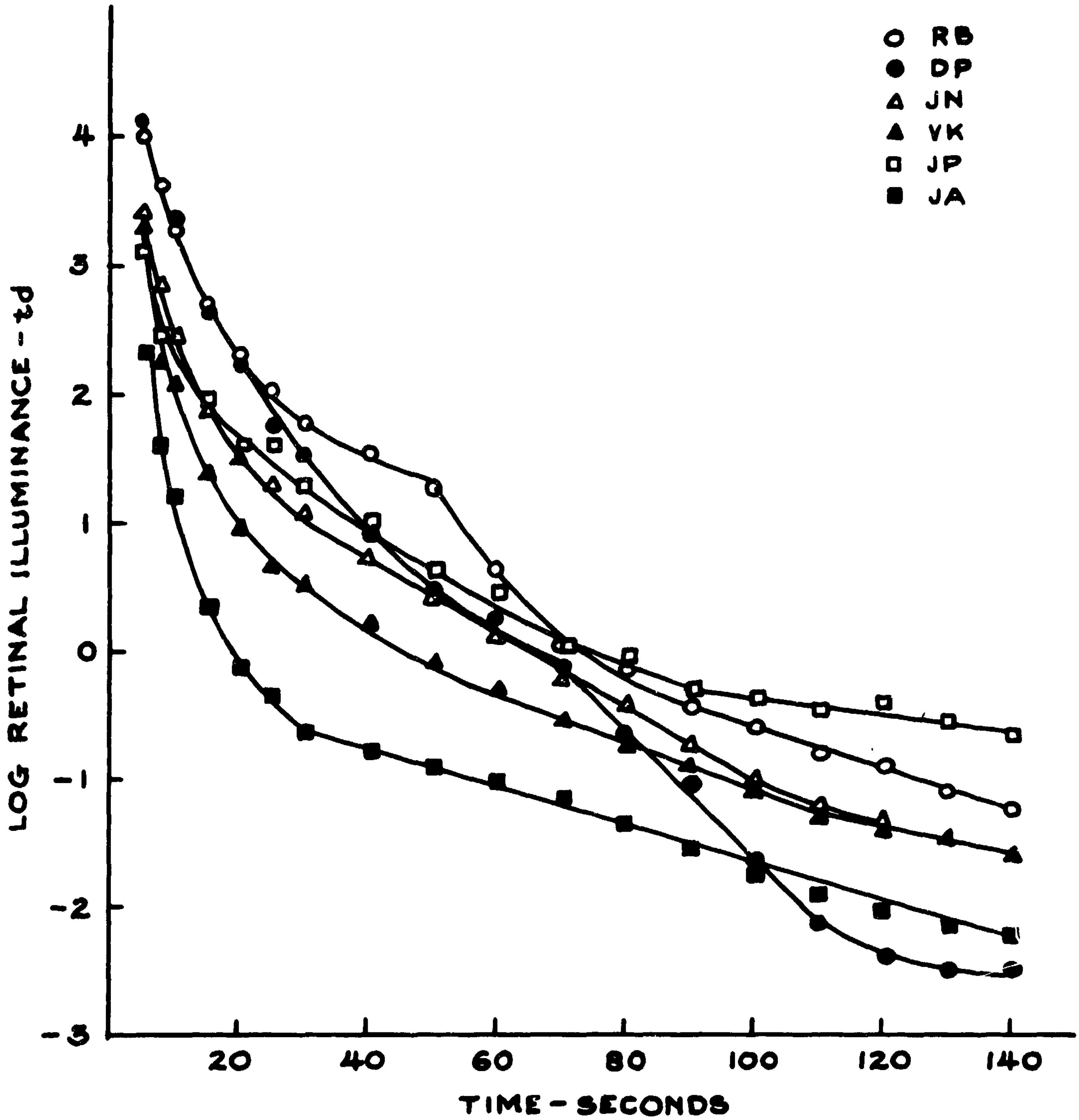


Figure 7. Individual variations in afterimage brightness decay as measured monocularly with a bi-partite photometric field. The ordinate is the logarithm of the retinal illuminance from an external semicircular field that matches the afterimage. The flashes were 0.56 msec duration, and the flash luminance was 4×10^5 L (0.005 cal/cm^2 at the retina).

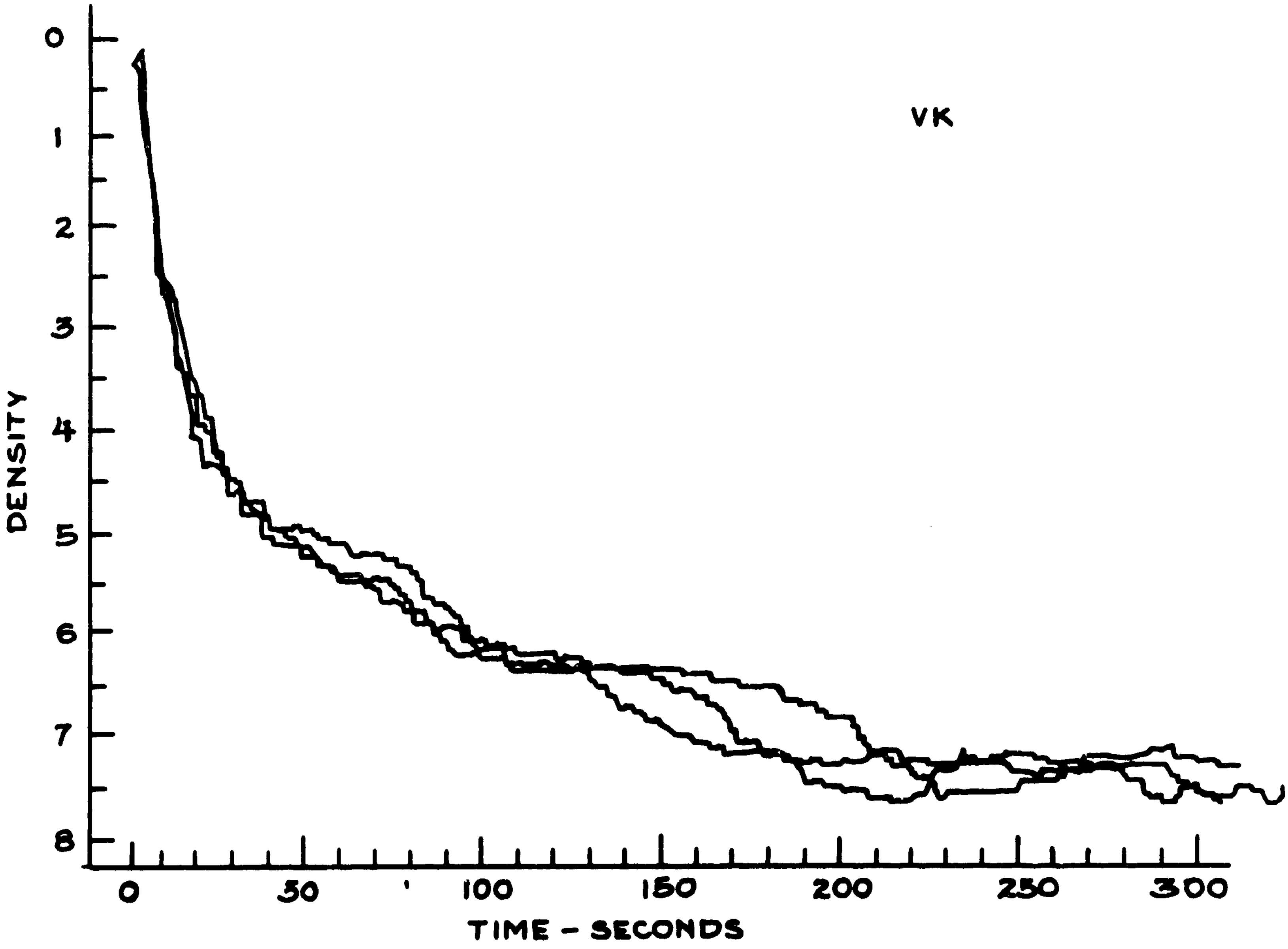


Figure 8a. Composite records of the afterimage brightness matching following three flashes of 1.4 msec duration to a 4×10^5 L field (0.012 cal/cm^2 at the retina). The ordinate is the density of the crossed neutral wedges required for maintaining a photometric match between the standard field and the afterimage.

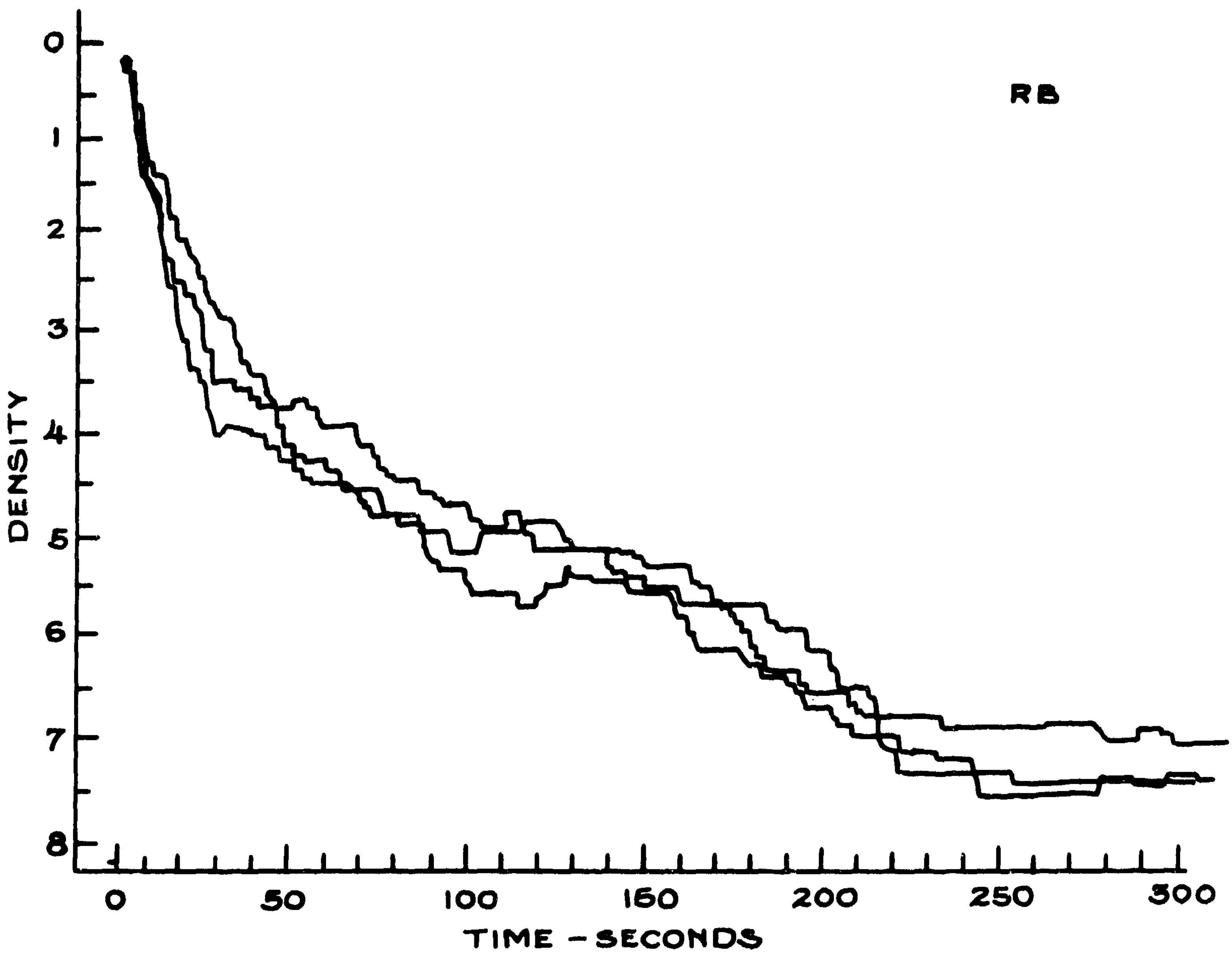


Figure 8b. The same type of record as Figure 8a for a different subject.

The group means in Fig. 9 for the 0.56 and 1.4 msec exposures to the 4×10^5 L flash field show the effect of reducing the integrated energy in the flash. The field luminances required for matching the afterimage during the first 20 sec following the flashes are surprisingly high. Previous work on afterimage matching[5-7] has indicated that retinal illuminances of the order of 150 td are sufficient to match the afterimage following quite intense flashes. The previous work always showed a dark period following the flash with a perceptible growth of afterimage brightness. Our subjects reported that there was no latency, and the afterimage started to decay from the initial brightness which seemed to be a continuation of the flash itself.

5. Comparison of Afterimage Brightness and Equivalent Background Luminance

An experiment was designed to compare the equivalent backgrounds for two recovery target sizes at ten luminance levels with the measured brightness of the afterimage following 3×10^7 td·sec flashes. Six subjects participated, and each tested the various conditions during one experimental session. The afterimage brightness was matched by the procedures described in the previous section following the first two flashes of the series. The recovery times for the 28.7' letter at various luminance levels were measured following the third and fourth flashes and the recovery times for the 16.3' letter following the fifth and sixth flashes. Three subjects

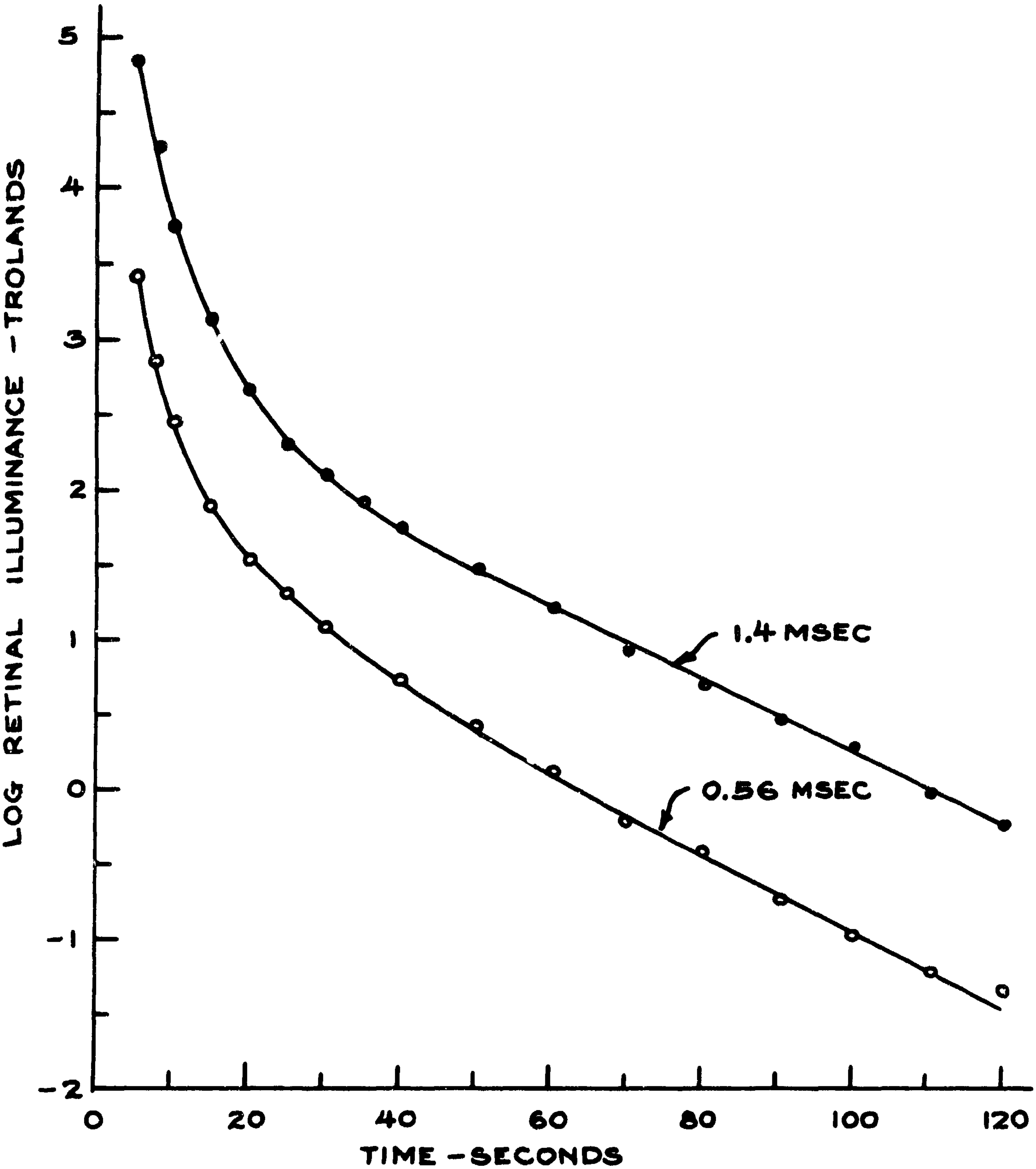


Figure 9. The group means for six subjects of the retinal illuminance from an external field required to match the afterimages following two different durations of flashes of 4×10^5 I.

received six additional flashes of 2×10^5 td·sec with the recovery times measured first and the brightness matching following the eleventh and twelfth flashes. All flashes were 1.4 msec duration with field luminances of 4×10^5 L and 2.5×10^4 L.

The individual recordings of wedge densities for maintaining a brightness match of the afterimages were read at 5 sec intervals for the first 40 sec following the flashes and at 10 sec intervals for the next 100 sec. The density readings were converted to retinal illuminance from the matching field by measuring the luminance of the unfiltered matching field and using the diameter of the Maxwellian beam at the subject's pupil. The results are shown in Table I for each subject for the high flash energy. The individual variation in the data is marked with a 2 log unit spread during part of the recovery period. The results for the three subjects who received the lower energy flashes are shown in Table I-A.

In the recovery time measurements, six different test letters of each size were used. A total of thirty letters of one size were randomly arranged around the circumference of a drum which was driven through a geneva gear system to bring a new letter into the field of view each second. The letters were transilluminated with a dark surrounding. The letters were presented at 140 mL immediately following the high energy flash, and as soon as the subject correctly identified two successive letters, a neutral filter was dropped in the illuminating beam. This was repeated to provide 10 luminance levels with the lowest at 0.007 mL. Six luminance levels

Table I. Log retinal illuminance to match the positive afterimage following 1.4 msec flashes of 4×10^5 L. The values are the means for two separate determinations by each subject.

t(sec) following flash	Subject J. N.	R. B.	D. P.	J. P.	J. A.	V. K.	Group Mean
5	5.30	4.70	5.00	5.50	4.35	5.04	4.981
7.5	4.95	4.20	4.30	5.00	3.69	4.15	4.381
10	4.60	3.70	3.58	4.40	3.21	3.54	3.838
15	4.25	3.10	3.08	3.60	2.57	2.59	3.198
20	3.80	2.60	3.00	2.60	2.27	1.91	2.696
25	3.45	2.30	2.90	2.00	2.04	1.68	2.395
30	3.20	2.25	2.78	1.60	1.82	1.35	2.166
35	3.10	2.05	2.68	1.48	1.66	1.18	2.025
40	2.85	1.85	2.62	1.42	1.51	1.01	1.877
50	2.40	1.40	2.45	1.02	1.20	0.79	1.543
60	2.05	1.25	2.32	0.85	0.80	0.54	1.302
70	1.70	1.10	2.25	0.72	0.29	0.36	1.070
80	1.45	1.05	2.25	0.58	0.20	0.16	0.948
90	1.22	1.00	2.00	0.39	0.17	-0.10	0.780
100	1.00	0.70	1.70	0.12	-0.17	-0.35	0.500
110	0.75	0.85	1.40	-0.28	-0.34	-0.50	0.313
120	0.48	0.80	1.05	-0.50	-0.19	-0.65	0.165
130	0.25	0.80	0.92	-0.75	-0.41	-0.66	0.025
140	0.00	0.55	0.25	-0.90	-0.63	-0.78	-0.343

I-A
Afterimage brightness following 1.4 msec flash at 2.5 x 10^4 L.

t-sec following flash	Subject J. N.	J. S.	D. P.	Group Mean
5.0	3.00	3.10	2.80	2.96
7.5	2.45	2.65	2.68	2.59
10	2.00	2.20	2.52	2.24
15	1.30	2.02	2.30	1.87
20	1.15	1.85	1.75	1.58
25	0.90	1.60	1.12	1.20
30	0.60	1.25	1.00	0.95
35	0.40	1.05	0.82	0.75
40	0.25	0.85	0.65	0.58
50	0.05	0.28	0.19	0.17
60	-0.30	-0.35	0.00	-0.21
70	-0.55	-0.95	-0.20	-0.56
80	-0.88	-1.35	--	-1.11
90	-1.15	-1.85	-0.70	-1.23
100	-1.55	-2.15	-1.93	-1.87

were used following the lower energy flash, ranging from 0.40 mL to 0.007 mL. The recovery times for each subject are listed in Table II and II-A with the group means. There was a large variation from subject to subject especially at the lower luminance levels. The group means of recovery times for the two letter sizes following the higher energy flashes are shown in the graph of Fig. 10. The mean recovery times for the two letter sizes are nearly identical from 140 mL to 5.4 mL but diverge rapidly for the lower luminance levels.

The equivalent background for threshold of the two letter sizes at the ten luminance levels was measured by each subject. A circular stop subtending 10° visual angle was inserted at S_2 in Fig. 6, and the subjects then saw the transilluminated letters superimposed on a bright background the same size as the afterimage from the flash. The luminance of the background was adjusted by means of the crossed neutral wedges until the letters were at threshold for each of the luminance levels used in the recovery time measurements. The data are recorded in Table III as the log retinal illuminance, in trolands, from the background for each subject and each recovery target condition. The group means of the data for each recovery target condition are plotted in Fig. 11 to show the relationship between the equivalent background retinal illuminance and the luminance of the test letters.

Table II. Recovery times for two letter sizes presented at various luminance levels following 1.4 msec flashes of 4×10^5 L.

Log B of Letter mL	28.7' Letter Subject J. N.	R. B.	D. P.	J. P.	J. A.	V. K.	Group Mean
2.15	8.0	4.5	7.5	7.5	8.5	4.0	6.66
1.45	13.5	7.5	11.0	13.0	13.0	8.0	11.00
0.73	22.5	12.0	14.0	19.5	17.0	13.0	16.33
0.29	25.0	16.5	18.0	23.0	20.5	17.0	20.00
-0.40	28.5	23.0	27.5	29.0	24.5	20.0	25.41
-0.83	31.5	27.5	44.5	33.5	35.5	25.0	32.91
-1.18	37.5	34.0	60.0	43.5	74.5	32.0	46.91
-1.53	43.5	37.5	95.0	61.0	94.0	41.0	62.00
-1.79	65.0	49.0	153.0	74.0	118.0	48.0	84.50
-2.14	101.0	62.5	198.5	107.5	226.0	57.0	125.41
	16.3' Letter						
2.15	4.0	5.0	10.0	6.5	5.0	6.0	6.08
1.45	12.0	10.0	18.0	10.5	8.5	10.0	11.50
0.73	19.0	13.5	25.5	14.5	13.0	15.0	16.75
0.29	27.0	18.0	38.0	21.5	18.5	19.0	23.66
-0.40	39.5	24.0	68.0	28.0	33.5	26.0	36.50
-0.83	52.0	36.0	92.5	32.0	47.5	47.0	51.16
-1.18	72.5	47.5	111.0	47.0	68.5	53.0	66.58
-1.53	81.0	73.5	178.0	69.0	124.0	73.0	99.75
-1.79	97.0	98.0	199.5	106.0	144.5	105.0	125.00
-2.14	137.0	119.0	308.0	164.5	--	160.0	177.70

II-A

Recovery times for two letter sizes presented at various luminance levels following 1.4 msec flashes of 2.5×10^4 L.

Log B Letter	Log td Equivalent Field	28.7' Letter Subject J. N.	J. S.	D. P.	Group Mean
-0.40	2.60	3.0	3.2	6.0	4.06
-0.83	2.23	8.0	7.5	12.0	9.16
-1.18	1.88	14.0	11.8	13.5	13.10
-1.53	1.37	22.0	17.5	22.0	20.50
-1.79	0.88	36.0	22.5	27.0	28.50
-2.14	0.23	42.0	28.5	28.5	33.00
		16.3' Letter			
-0.40	2.42	6.0	7.8	10.5	8.10
-0.83	2.03	11.0	13.2	15.5	13.23
-1.18	1.65	18.5	21.0	20.0	19.83
-1.53	0.99	26.0	28.8	24.5	26.43
-1.79	0.42	32.5	35.5	38.5	35.50
-2.14	-0.23	39.0	40.5	54.0	44.50

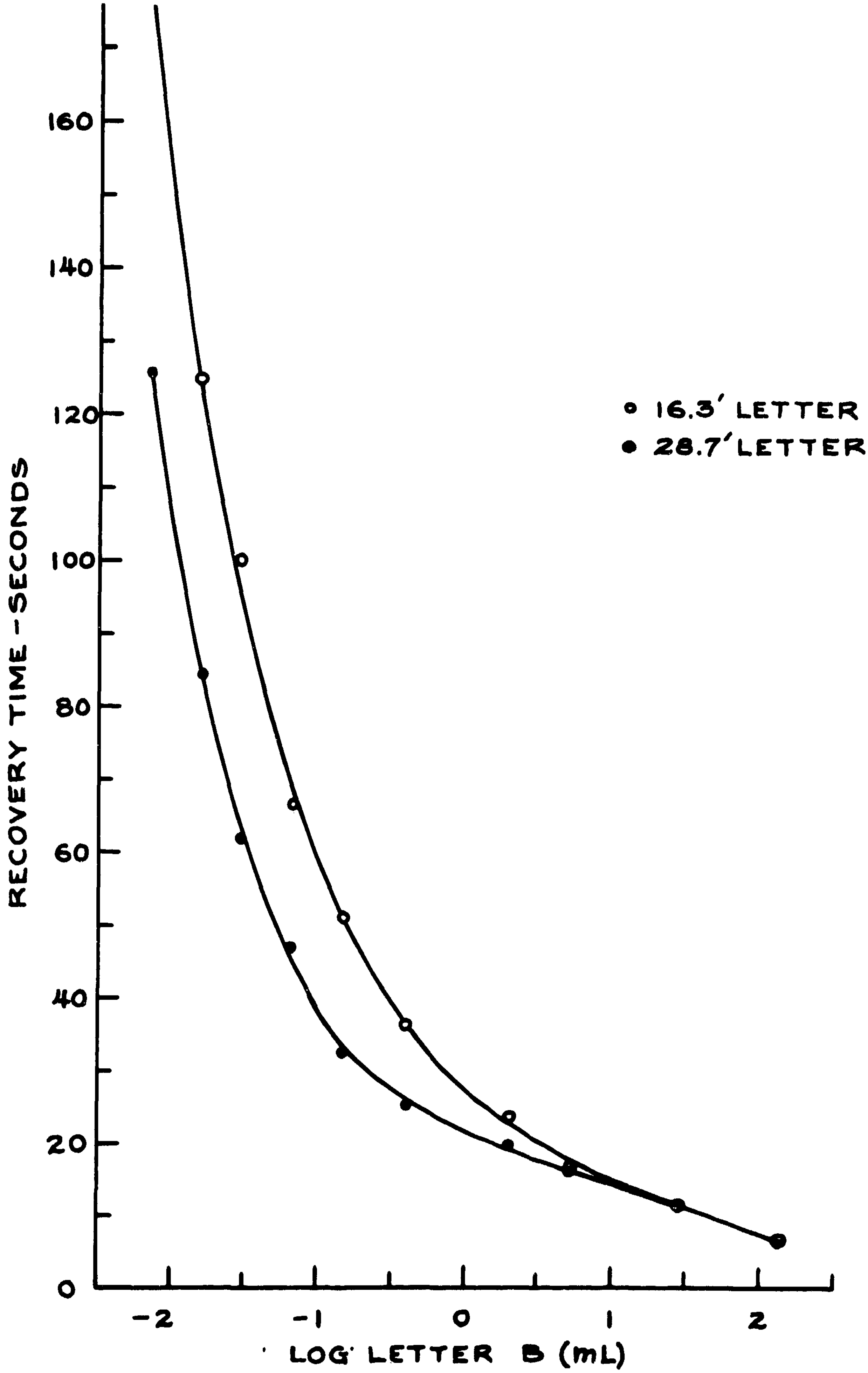


Figure 10. The group means for six subjects for the recovery times for 28.7' and 16.3' Sloan Snellen letters presented at ten luminance levels. The flashes were 1.4 msec in duration at 4×10^5 L (0.012 cal/cm^2 at the retina).

Table III. Retinal illuminance from a 10° external field adjusted for threshold detection of the recovery letters at various luminance levels (log trolands).

Log B Letter mL	28.7' Letter Subject J. N.	R. B.	D. P.	J. P.	J. A.	V. K.	Group Mean
2.15	4.63	4.70	5.00	4.55	4.63	4.75	4.710
1.45	3.87	4.13	4.29	3.73	3.85	4.09	3.993
0.73	3.15	3.73	3.69	3.20	3.50	3.33	3.433
0.29	2.94	3.20	3.28	2.87	2.90	2.98	3.028
-0.40	2.36	2.62	2.55	2.34	2.39	2.50	2.460
-0.83	2.07	2.32	1.97	1.91	1.93	1.82	2.003
-1.18	1.76	2.06	1.80	1.33	1.52	1.51	1.663
-1.53	1.38	1.64	1.09	1.31	1.23	0.90	1.258
-1.79	0.89	0.82	0.49	0.87	0.54	0.87	0.746
-2.14	0.38	0.57	-0.20	0.42	-1.18	0.37	0.060

	16.3' Letter						
2.15	4.50	4.50	4.70	4.30	4.45	4.60	4.508
1.45	3.85	3.98	4.02	3.85	3.75	3.92	3.895
0.73	3.28	3.38	3.45	3.00	3.67	3.33	3.351
0.29	2.92	3.07	3.00	2.64	2.79	2.74	2.860
-0.40	2.22	2.37	2.30	1.96	2.21	2.19	2.208
-0.83	1.97	2.13	1.93	1.66	1.67	1.73	1.848
-1.18	1.60	1.74	1.48	1.31	1.09	1.42	1.440
-1.53	1.17	1.41	0.41	0.65	0.99	0.97	0.966
-1.79	0.44	0.65	-0.12	0.40	-0.38	0.73	0.286
-2.14	0.10	0.07	-0.87	-0.33	-1.53	0.10	-0.041

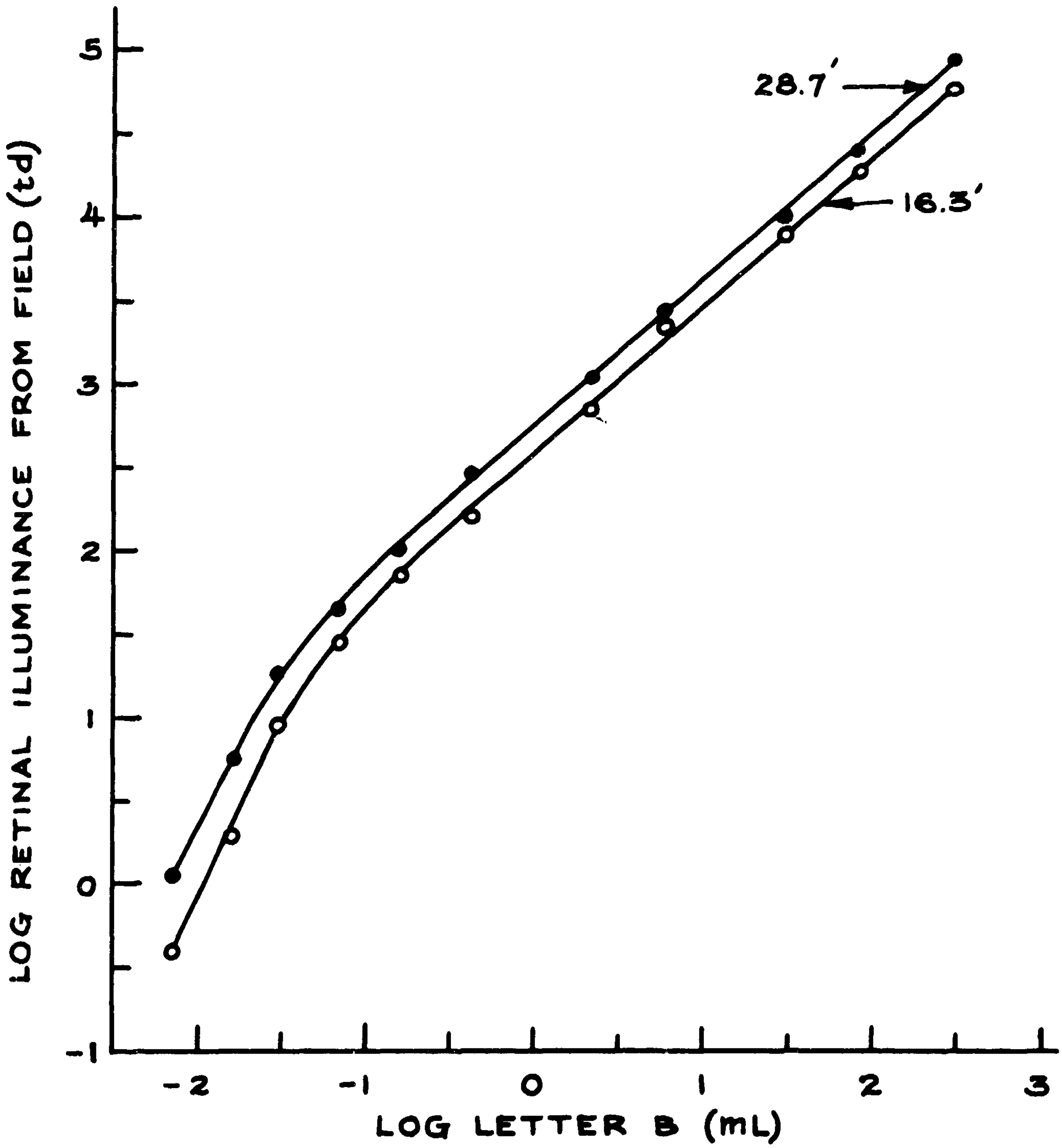


Figure 11. The group means for six subjects of the retinal illuminance from a 10° external field when adjusted for threshold recognition of test letters superimposed on the field.

The data from the afterimage brightness matching and the recovery time measurements are shown in the graphs of Fig. 12 for each subject. The recovery time measurements have been plotted in terms of the equivalent background retinal illuminance for each of the letter conditions. The agreement between the two sets of measurements is reasonably good and suggests that even closer agreement would exist if there were more than two measurements at each point.

If one accepts the hypothesis that the afterimage acts in the same way as a subjectively equally bright external field in raising the threshold, it should be possible to predict the individual recovery times for the different targets from the data obtained. The procedure followed in testing the hypothesis is shown graphically in Fig. 13. The curve on the left is the best visual fit through the data points for the afterimage brightness matching for subject R. B. The curves on the right are the best fit through the data for the field luminance values for threshold recognition of the two letters at the various luminance levels for the same subjects. The broken lines show the procedure for finding the predicted recovery time for the 16.3' letter at 2 mL. This procedure was followed for each letter condition for each subject, and the results are shown in Table IV for group means of the predicted and measured recovery times for target luminance levels from 140 mL to 0.007 mL. The agreement between the predicted and measured recovery times is within 10% for each of the seven luminance levels.

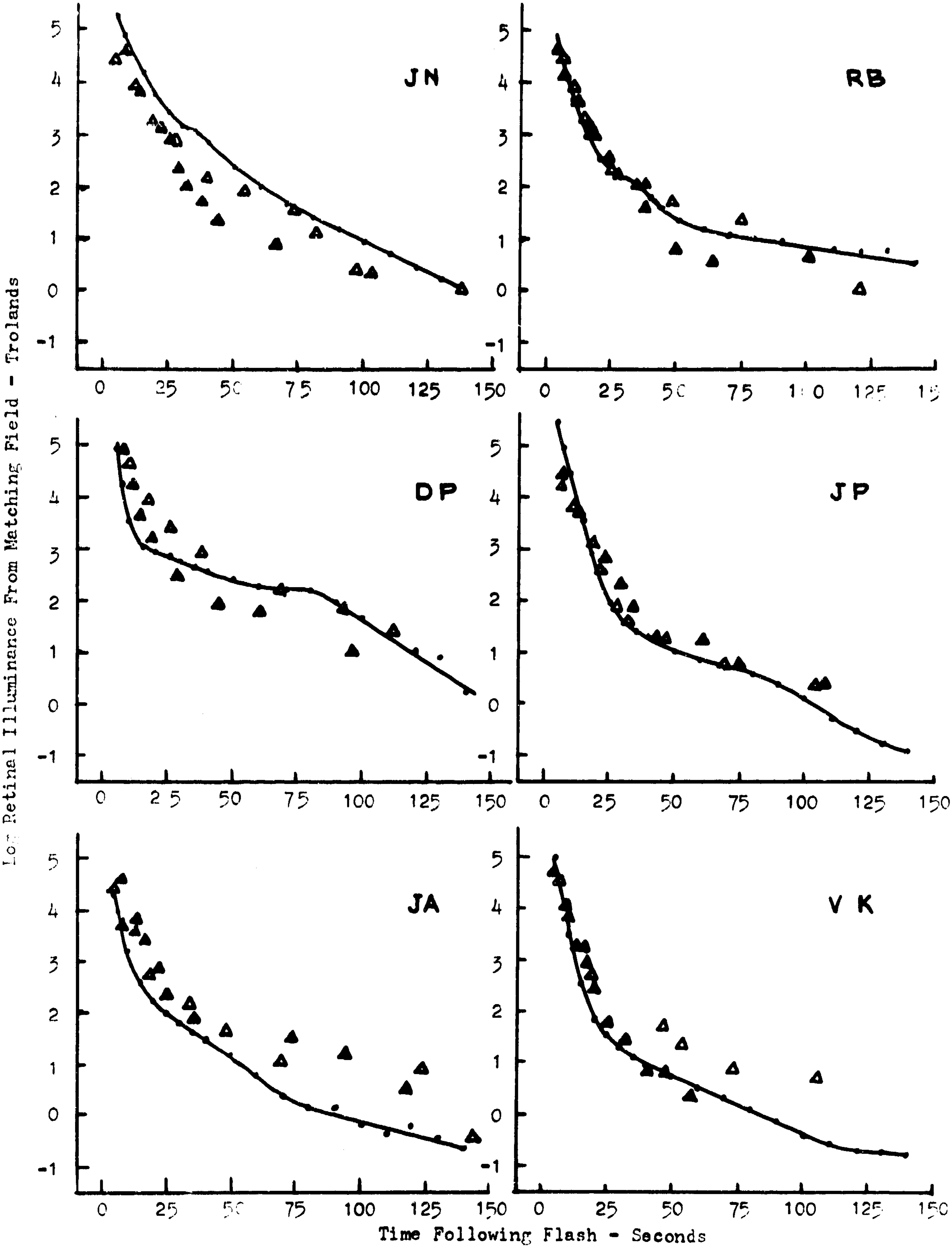


Figure 12. Comparison of afterimage brightness matching and recovery time data for six subjects. The solid symbols are the data for 28.7' letter and the open symbols for the 16.3' letter.

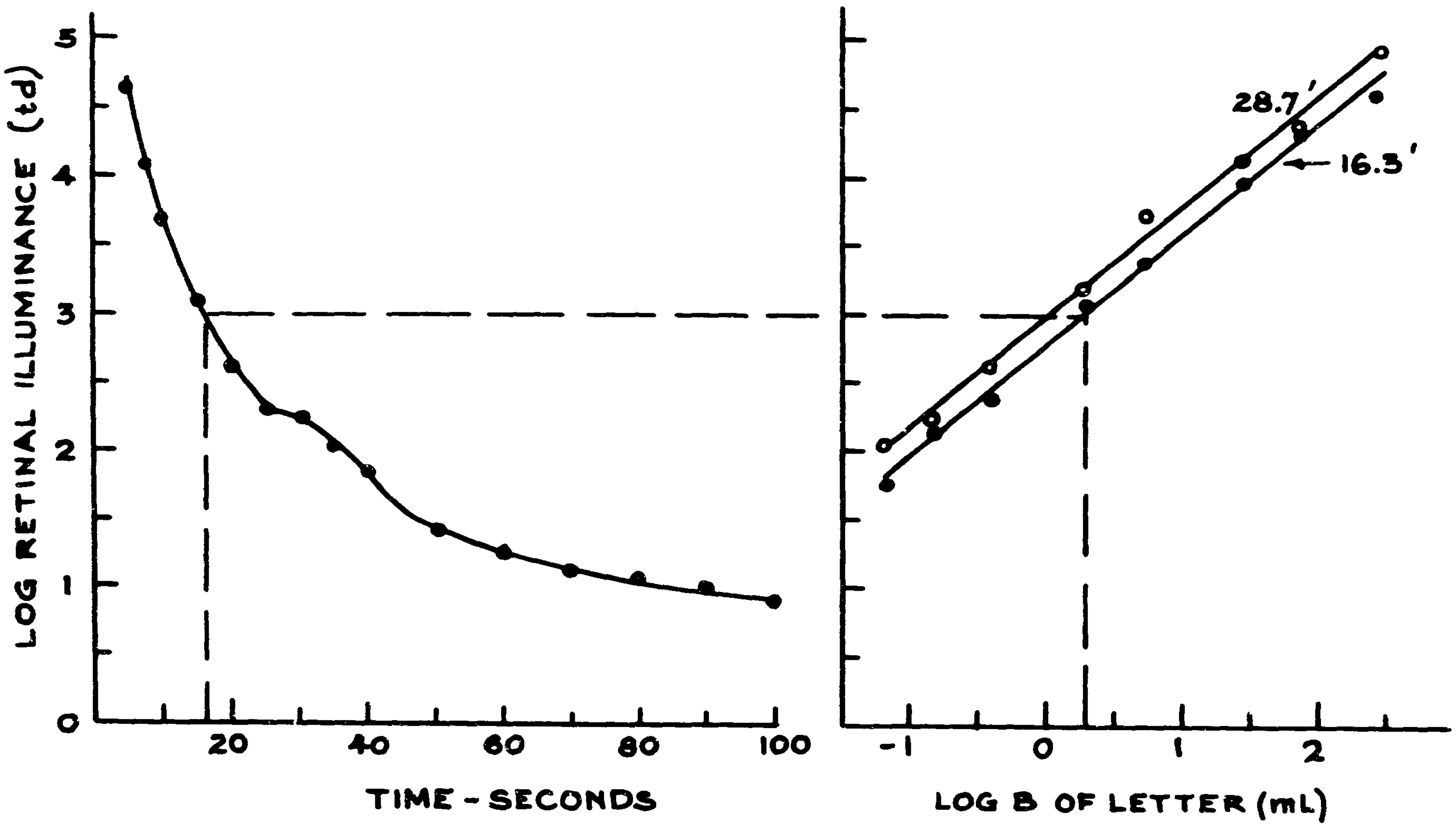


Figure 13. Graphical representation of the procedure used in predicting the recovery time for a 16.3' letter presented at 2 mL following a 3×10^7 td·sec flash. The curve on the left is the measured decay of the afterimage brightness for subject R. B. The graph on the right is the relationship between the luminance of the target letters and the retinal illuminance from an external 10° field adjusted for threshold recognition of the letters.

Table IV. Comparison of the predicted and measured recovery times for the 28.7' and 16.3' Sloan-Snellen letters at seven luminance levels following 3×10^7 td·sec flashes. The values are the group means for six subjects for the two letters.

Log B Letter (mL)	Recovery Time in Seconds Predicted	Measured
2.15	6.93	6.37
1.45	10.60	11.25
0.73	14.55	16.54
0.29	19.71	21.83
-0.40	31.23	30.95
-0.83	43.37	42.03
-1.18	54.29	56.74

4. Binocular Matching of Afterimage Brightness

It was found necessary to change the configuration of the photometric field for binocular measurements of the afterimage. When the afterimage was in one eye, and the matching field viewed with the other eye, the convergence problems caused by the afterimage moving with the eye were too disturbing for the subjects to make consistent judgements of the equality of the two fields. The flash field was modified by inserting an annular stop at S_1 in Fig. 6. The outside diameter of the stop subtended 10°, and the inside diameter 6° visual angle. The flash produced an annular afterimage in the right eye, and a 2° circular stop at S_2 provided a matching field for the left eye. It was reasonably easy to keep the two fields concentric by fixating on the center of the matching field. During one session, each of seven subjects received twelve flashes of 4×10^5 L at three durations: 1.4 msec, 0.24 msec, and 0.04 msec. The subjects made binocular brightness matches for two flashes fo each duration and monocular matches with the same photometric field configuration for two flashes of each duration.

The group means of the data are shown in Fig. 14 for the three flash energies and the two matching conditions. There was no apparent difference in the luminance of the matching field at any instant following the flash between the monocular end binocular matches. The luminance for matching the afterimage for 15 sec following the 1.4 msec flash was approximately 1 log unit less than in monocular bipartite matches.

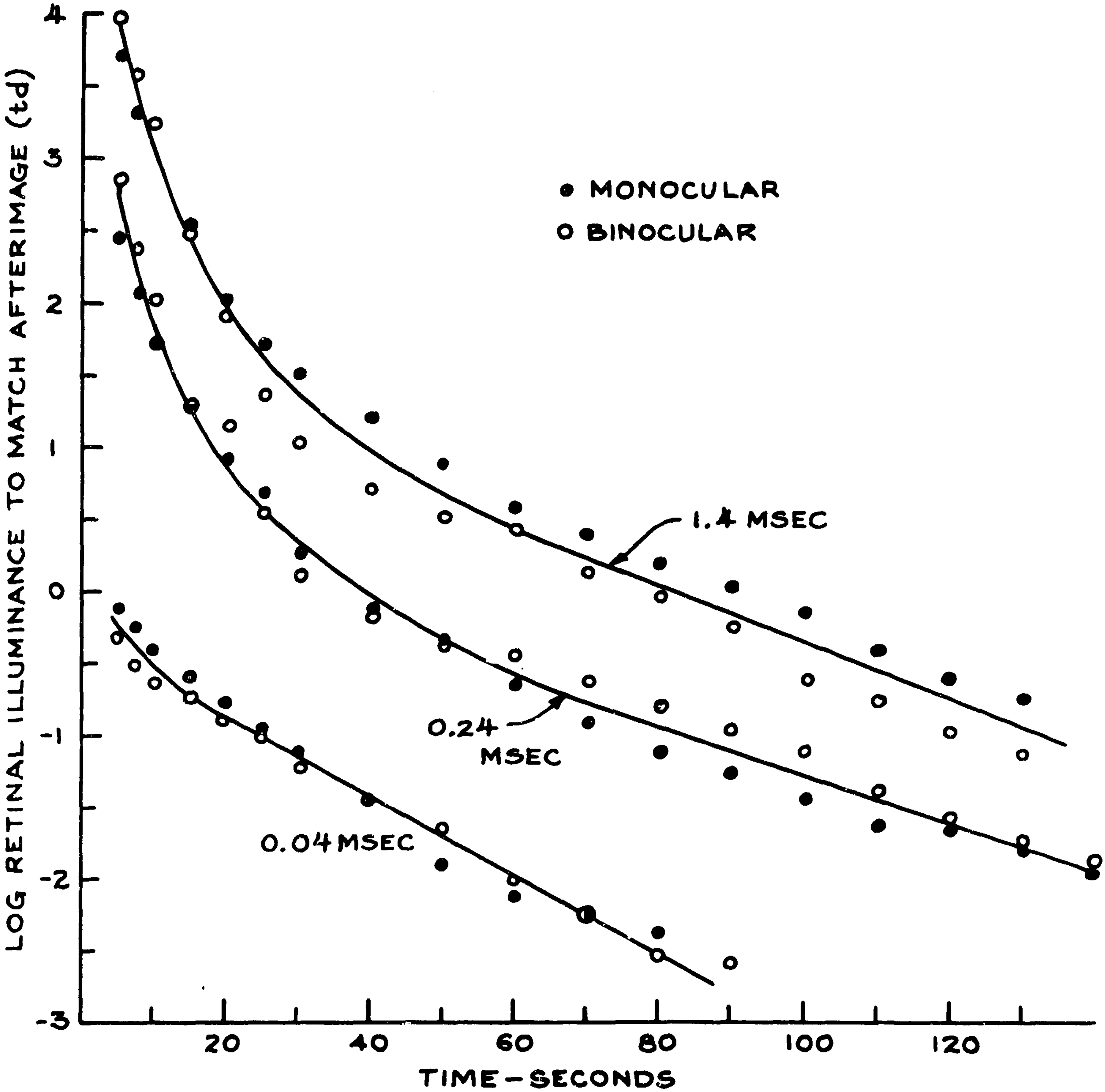


Figure 14. Comparison of results of afterimage brightness matching for an annular afterimage concentric with a centrally fixated 2° matching field. In the monocular case, both the afterimage and matching field were in the right eye, and in the binocular case, the afterimage was in the right eye and the matching field in the left.

5. Peripheral and Foveal Afterimage Matching

The discrepancy between the measured afterimage brightness for the monocular bipartite field and the monocular matching with an annular afterimage was found for each subject during the early course of the afterimage decay. One possible explanation of the discrepancy is that the foveal photopigments regenerate faster than rhodopsin, and the afterimage seems to be related to the kinetics of the photoreceptor pigments. The afterimage appears as a bright area with a darker central portion after a minute or two following the flashes. It was felt that with a photometric field divided across the fovea, the subjects might match the foveal portion during the earlier stage of the decay and the peripheral portion later, whereas with the annular afterimage, only the peripheral portion would be available. Two conditions of monocular matching were set up for flashes of 4×10^5 L at durations of 1.4 msec, 0.24 msec, and 0.04 msec. In the first condition, the annular afterimage was matched with the foveal standard field, and in the second, a 2° foveal afterimage was matched with an annular standard field. Each subject made two determinations of the afterimage brightness decay for each condition at each flash energy during one session. The group means of the data are shown in Fig. 15.

There seems to be no significant difference in the results for the two conditions of matching for the two minute period shown in the graphs. The amount of light required to match the afterimage remains constant whether it falls on the central portion of the retina with the afterimage surrounding it or on the peripheral region of the retina surrounding a central afterimage.

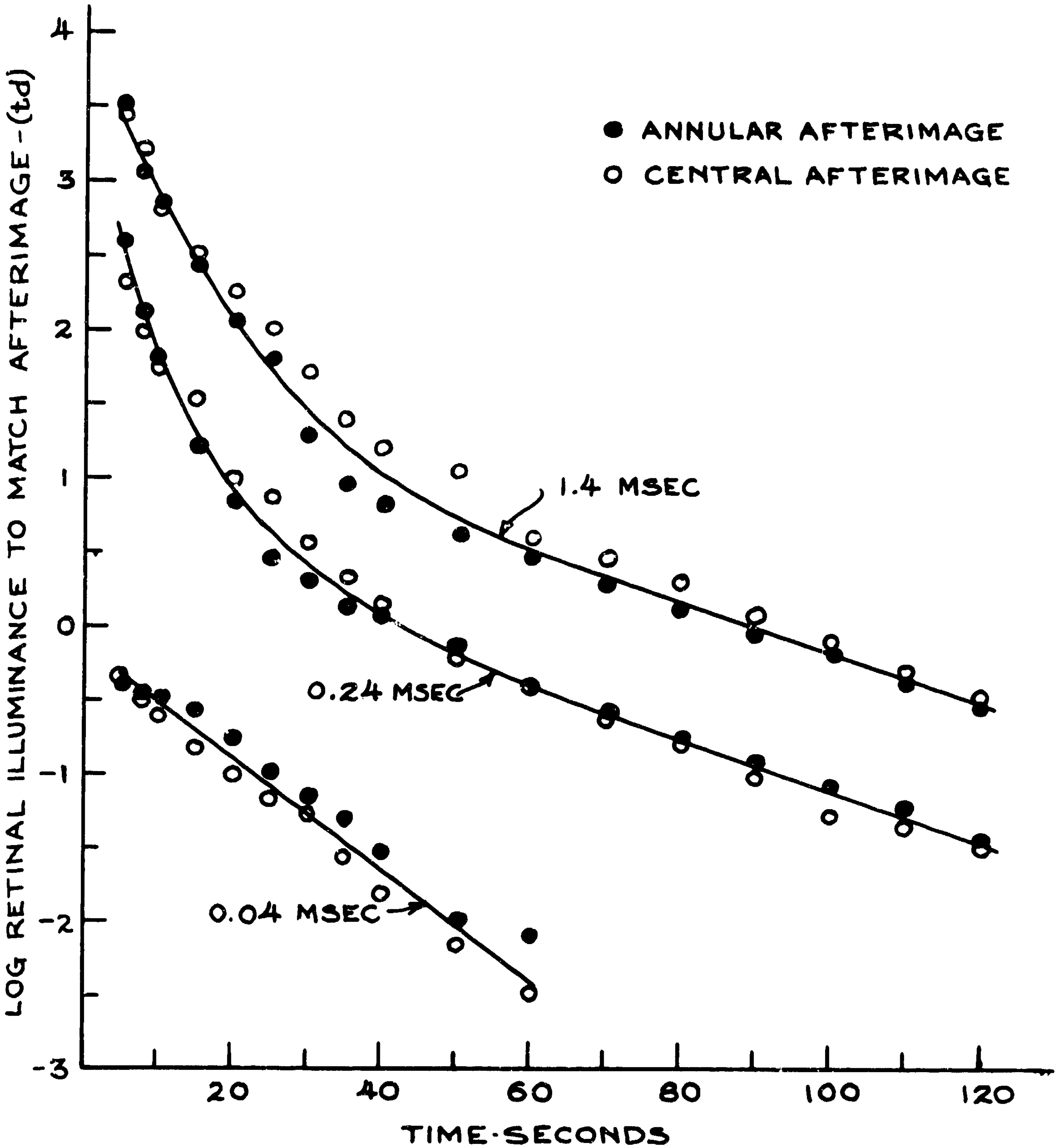


Figure 15. Comparison of results of monocular afterimage brightness matching with an annular photometric field configuration. The solid dots are the data points for a 2° centrally fixated standard field and a concentric annular afterimage. The open circles are the data for a 2° central afterimage with a concentric annular matching field.

6. Summary of Afterimage Matching and Recovery Time Measurements

The monocular bipartite field matching of the afterimage brightness was significantly different from the other conditions of brightness matching with a space separating the afterimage and standard field. There was close agreement, however, between the recovery time measurements expressed in terms of the equivalent background fields for recognition of the Sloan-Snellen target letters and the bipartite afterimage matching. With the bipartite field, the subjects felt that they made more sensitive changes during the periods when the afterimage overlapped the standard field. This would mean that the standard field fell on the same retinal area that had been exposed to the flash, and a ΔI threshold criterion was used. The individual differences in the light from an external field required to match the afterimage show a consistent trend that is related to the differences in recovery time. A correlation study of the predicted and measured recovery times for the two letters at various luminance levels for six subjects showed a correlation coefficient of 0.82.

The brightness matching with the standard field separated from the afterimage by at least 1°, required consistently less light in the standard field than was required in the bipartite matching. The data are tabulated in Table V. for each of the flash energies used. As long as the standard field falls on fresh retina in the same or the opposite eye, the luminance required for a brightness match is constant.

Table V. Log retinal illuminance in trolands from an external field required for matching the afterimages following flashes of 0.04, 0.24, and 1.40 msec duration at 4×10^5 L. The values are the group means for six subjects. The binocular and monocular matches with an annular afterimage and a 2° central matching field were made during one session by each subject. The monocular matches with the annular afterimage and with the central afterimage were made during a different session by each subject.

0.04 msec Flash

It = 8×10^5 td·sec or 0.0003 cal/cm² at the retina

t-sec following flash	Annular afterimage: Binocular Matching	Annular afterimage: Monocular Matching	Monocular matching: Annular Afterimage	Monocular matching: Central Afterimage
5	-0.32	-0.12	-0.38	-0.37
7.5	-0.53	-0.24	-0.44	-0.53
10.	-0.64	-0.41	-0.51	-0.62
15	-0.75	-0.59	-0.57	-0.83
20	-0.88	-0.77	-0.76	-1.01
25	-1.03	-0.95	-0.99	-1.18
30	-1.23	-1.12	-1.15	-1.28
35	-1.47	-1.30	-1.31	-1.58
40	-1.65	-1.50	-1.53	-1.83
50	-2.03	-1.91	-2.00	-2.17
60	-2.27	-2.26	-2.11	-2.51

Table V. continued.

0.24 msec Flash

It = 4.8×10^6 td·sec or 0.002 cal/cm^2 at the retina

t-sec following flash	Annular afterimage: Binocular Matching	Annular afterimage: Monocular Matching	Monocular matching: Annular Afterimage	Monocular matching: Central Afterimage
5	2.85	2.45	2.61	2.32
7.5	2.38	2.07	2.13	1.97
10	2.05	1.74	1.83	1.73
15	1.27	1.32	1.20	1.53
20	1.15	0.92	0.83	0.99
25	0.53	0.68	0.46	0.87
30	0.10	0.26	0.33	0.55
35	-0.10	0.00	0.13	0.33
40	-0.20	-0.14	0.07	0.12
50	-0.34	-0.40	-0.13	-0.23
60	-0.45	-0.66	-0.42	-0.43
70	-0.62	-0.91	-0.60	-0.65
80	-0.79	-1.12	-0.76	-0.80
90	-0.94	-1.29	-0.92	-1.05
100	-1.11	-1.44	-1.09	-1.30
110	-1.38	-1.65	-1.22	-1.37
120	-1.59	-1.67	-1.43	-1.45

Table V. continued

1.40 msec Flash

It = 2.8 x 10^7 td·sec or 0.012 cal/cm^2 at the retina

t-sec following flash	Annular Afterimage: Binocular Matching	Annular Afterimage: Monocular Matching	Monocular Matching: Annular Afterimage	Monocular Matching: Central Afterimage	Monocular Matching: Bipartite Field
5	3.97	3.69	3.50	3.44	4.98
7.5	3.57	3.36	3.06	3.20	4.44
10	3.24	3.05	2.84	2.81	3.94
15	2.47	2.55	2.42	2.50	3.34
20	1.90	2.02	2.05	2.25	2.88
25	1.35	1.73	1.81	2.00	2.59
30	1.02	1.50	1.28	1.73	2.36
35	0.88	1.39	0.96	1.39	2.23
40	0.70	1.20	0.83	1.20	2.12
50	0.51	0.88	0.61	1.06	1.85
60	0.43	0.59	0.47	0.60	1.63
70	0.13	0.39	0.27	0.49	1.44
80	-0.05	0.19	0.13	0.31	1.25
90	-0.26	0.03	-0.05	0.07	1.02
100	-0.63	-0.15	-0.21	-0.10	0.70
110	-0.77	-0.42	-0.38	-0.31	0.50
120	-0.99	-0.61	-0.53	-0.48	0.25

The brightness matching for any individual in one session is surprisingly consistent for successive flashes. The composite curves for subjects V. K. and R. B., shown in Fig. 8a and 8b, suggest an exponential decay of the afterimage with time. The mean data for each subject are shown plotted in Fig. 16 on a log time basis. There is some systematic variation from a straight line for each subject that may correspond to the periods of saturated color in the afterimage, making matching difficult. It is interesting that the slopes of the lines over the first 150 sec for the two subjects are the same, and that R. B.'s data finally coincides with that of the other subject over the range from four to six minutes.

V. RECIPROCITY BETWEEN INTENSITY AND DURATION FOR CONSTANT INTEGRATED FLASH ENERGY

There is considerable evidence to suggest that the afterimage brightness is directly connected with the quantity of photopigment bleached by flashes of light. If the same type of reciprocity failure between intensity and duration for very brief flashes occurs in the photopigment in the intact eye as has been found in rhodopsin solutions, the effect should be discernable in the afterimage brightness. The work reported in the previous section showed the high correlation existing between afterimage brightness measurements and recovery time measurements for acuity targets. In order to test for a reciprocity failure in the intact eye, it was felt necessary to provide flashes over the range from 0.5 to 5.0 msec duration with constant integrated energies sufficient to provide a high percentage of bleached molecules.

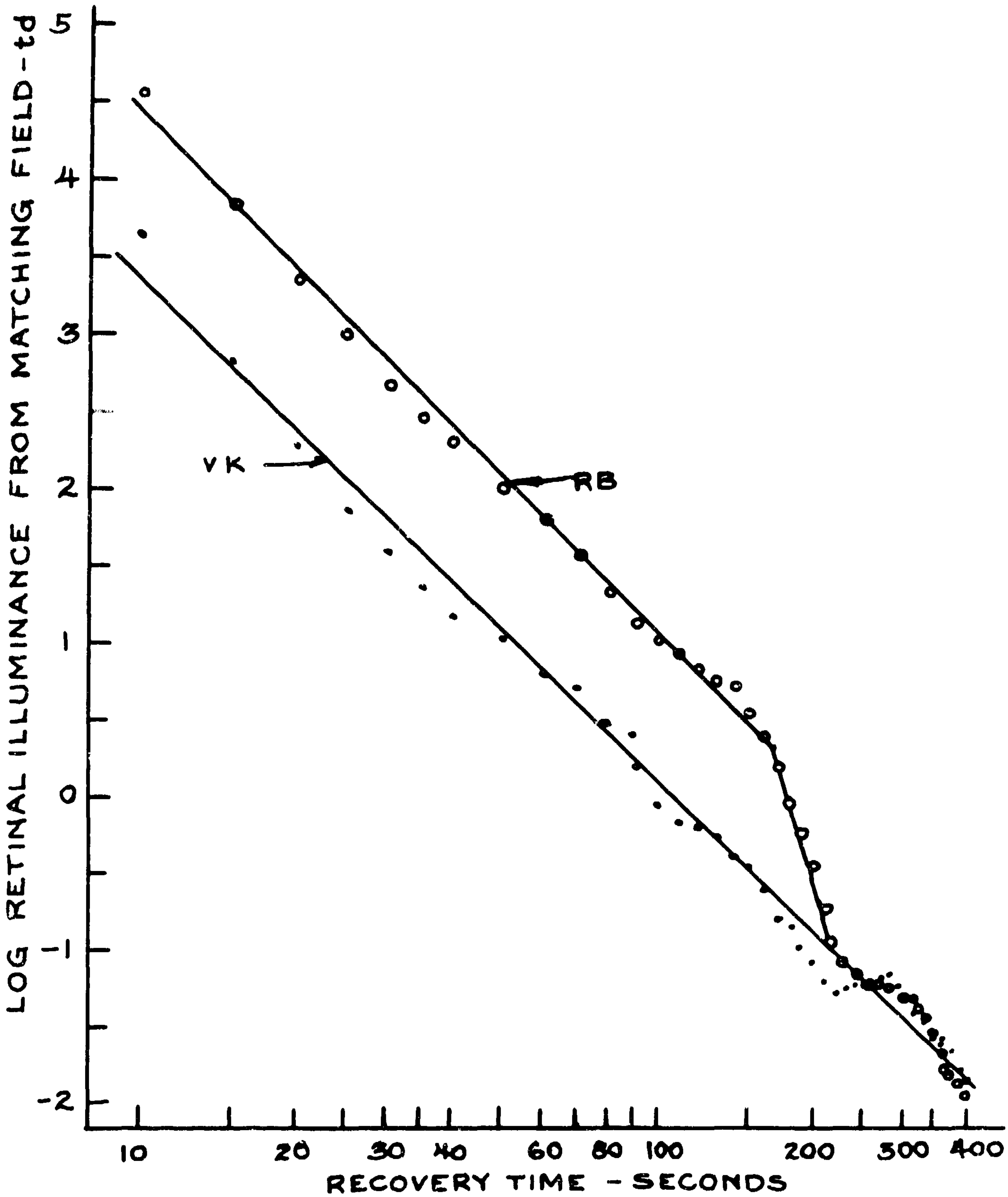


Figure 1(. Mean data for three separate determinations of afterimage brightness for each of two subjects following flashes of 3×10^7 td·sec (0.012 cal/cm^2).

1. Apparatus

The transmission of the optical system used in the previous work was 22%. A major portion of the loss through the system occured at the beamsplitter in front of the subject's eye. By removing the beamsplitter and substituting a lantern slide cover glass to divert a portion of the flash into the monitoring phototube, the transmission was increased to 84%. The increased transmission provided as much integrated energy in a 0.38 msec flash as had formerly been in the 1.4 msec flashes. The time course of radiance of the flash tube is shown in Fig. 17a which is a photograph of the oscilloscope trace from a phototube. The sweep rate was 1 msec/cm, and the ordinate is the relative radiance of the tube. The trace indicates that at the peak of the discharge, the radiance remains constant within 10% over approximately 1.5 msec. The earlier work with 1.4 msec flashes chopped from the peak of the discharge produced bleaching close to the theoretical maximum, so the increased transmission permitted flashes from 0.4 msec to 1.5 msec to be tested with proper filtering of the longer flashes to maintain constant energy.

The trace in Fig. 17a shows that the tube radiance diminishes to 1/10 of its peak value about 5 msec after reaching the peak. The form of the decrease in radiance is nearly exponential as shown in Fig. 17b which is an oscilloscope trace from the phototube signal after passing through a logarithmic adapter circuit of the operational amplifier. By attenuating the light from the earlier portion of the flash to maintain a constant

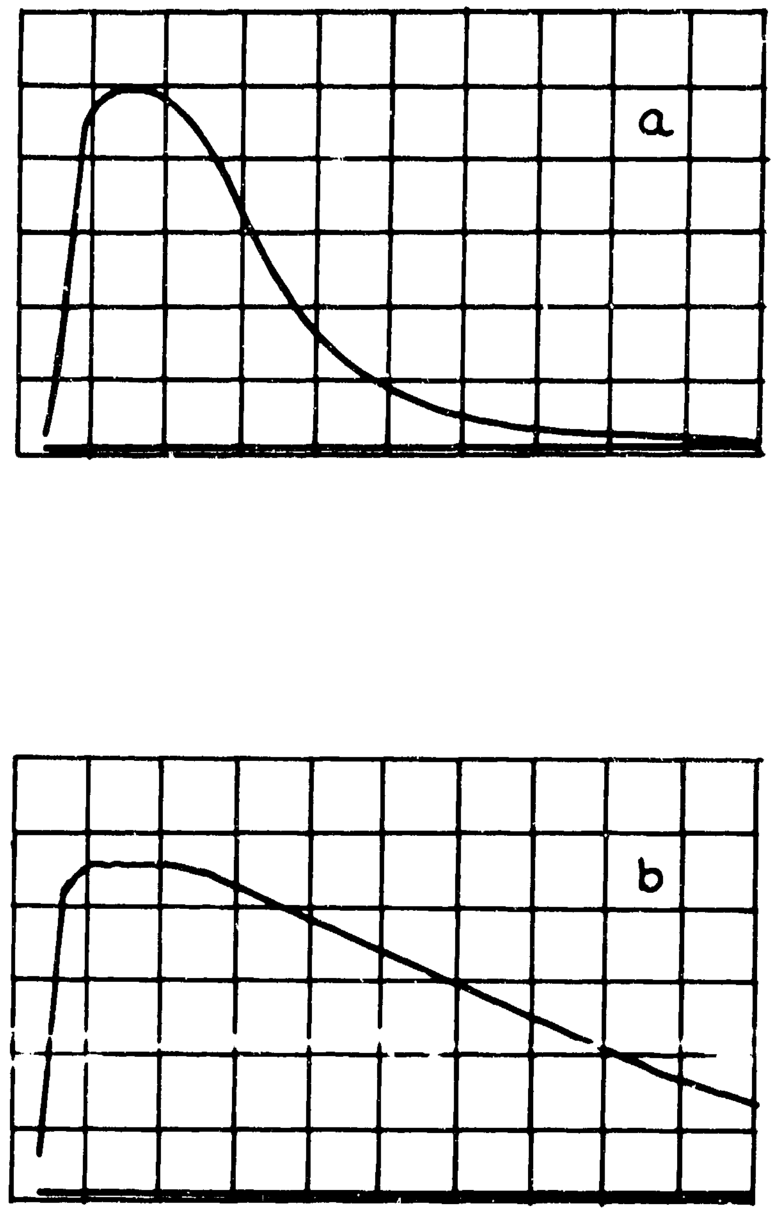


Figure 17. (a) The time course of the flash tube radiance. The ordinates are the relative radiance, and the sweep rate was 1 msec per grid division. (b) The crt trace of the signal shown in (a) after passing through a log adapter circuit of the oscilloscope operational amplifier. The log of the tube radiance is linear with time during the decay portion.

radiance over 5 msec, the integrated flash energy could be made equal to a 0.5 msec flash taken from the peak of the discharge. This was accomplished by locking the rotating mirror of the shutter system in the 45° position to admit the total flash through the aperture conjugate to the subject's pupil and substituting a sector disc shutter near the aperture. Seven sector discs, 10 inches in diameter, were prepared and driven at 1725 rpm. The seven sector openings produced flash durations of 0.5, 0.78, 1.10, 1.54, 2.4, 3.4, and 5.0 msec. The flash tube was triggered by a light switch so the various sector openings were synchronized with the flash to insure that the peak radiance of the discharge was reached at the instant that the sector opening started its sweep across the aperture. The trace in Fig. 18a shows the form of the 1.5 msec flash through the sector shutter.

Graded neutral density strips were made by exposing film through a logarithmic spiral sector shutter to match the exponential decay of the flash radiance. They were fastened over the sector openings for the 2.4, 3.4, and 5.0 msec flashes. The resulting oscilloscope traces for the 3.4 and 5.0 msec flashes are reproduced in Fig. 18b. The neutral density strips did not match the decay perfectly, and especially in the 3.4 msec case, there is some variation in the radiance over the flash duration. However, if the lower trace in Fig. 18b for the 5.0 msec sector is compared with the unfiltered trace in Fig. 17a, taken at a lower gain on the oscilloscope, the degree of compensation afforded by the neutral wedge is apparent.

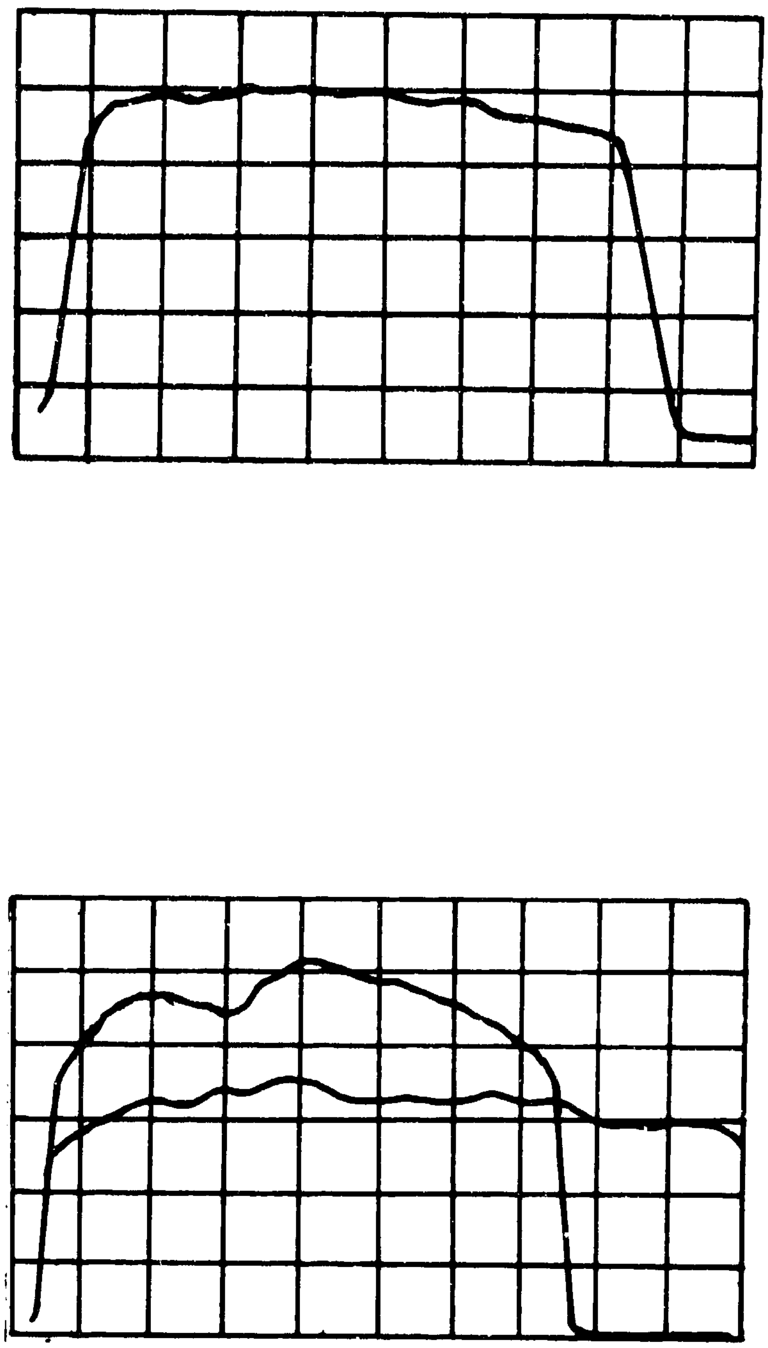
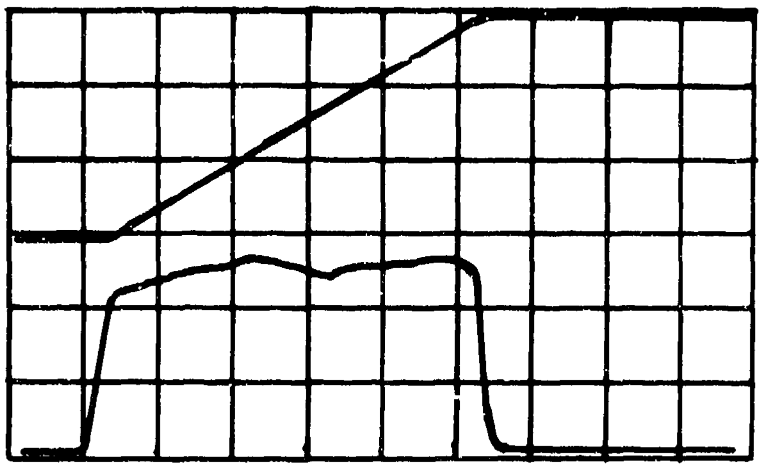


Figure 18. (a) The crt trace from a 1.54 msec flash produced by synchronizing the flash tube discharge with a rotating sector shutter. (b) The wave forms of the 3.4 msec and 5.0 msec flashes from the flash tube synchronized with sectors covered by compensating neutral density wedges.

To facilitate maintainance of a constant It product for the various flash durations, the phototube signal was put through an integrating circuit of the operational amplifier before being displayed on the oscilloscope. The crt traces in Fig. 19a show the radiance as a function of time in the lower curve for the 2.4 msec flash and the integrated wave form in the upper trace. Figure 19b shows four integrated flashes from photographs of the crt taken during a regular experimental session. The constancy of the integrated energies for the 0.5, 1.1, 2.4, and 5.0 msec flashes is immediately apparent. If any integrated trace varied by more than $\pm 5\%$ from the established value for a given experimental session, the visual data for that flash were discarded and a corrected flash substituted at the end of the session. The corrections were made by inserting or removing neutral filters in the flash beam, and the smallest increment of filtering was a piece of cellophane.

2. Experimental Procedure and Results

An experiment was designed to test the effect of flash duration on the recovery times for the Sloan-Snellen letters presented at various luminance levels. Seven flash durations from 0.5 msec to 5.0 msec were used, and the flash energies were maintained at 3×10^7 td·sec or 0.012 cal/cm^2 at the retina, neglecting losses in the ocular media. In one experimental session, each subject measured the recovery times for the 16.3' and 28.7' letters presented at eight luminance levels from 280 mL to 0.007 mL following each of the flash durations. One letter size was tested at each of the



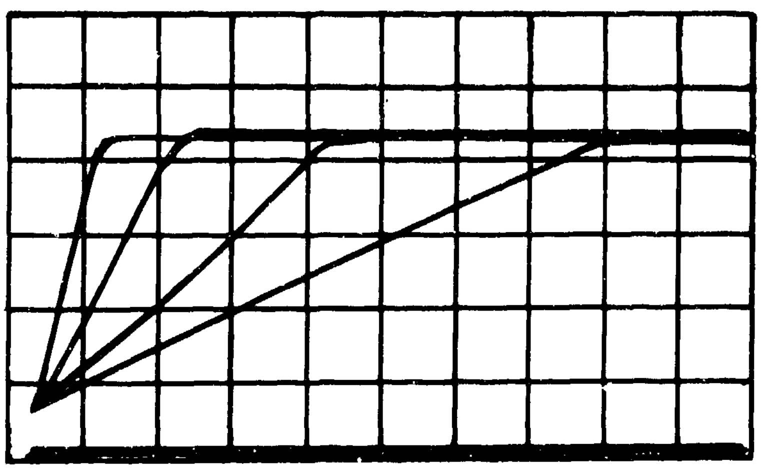


Figure 19. (a) The lower trace is the wave form from the 2.4 msec flash from the flash tube through the compensating neutral wedge, and the upper trace is the integrated flash. (b) Four integrated flashes from a regular experimental run showing the constant It product for the 0.5, 1.1, 2.4, and 5.0 msec durations.

luminance levels following a flash, and the fourteen combinations of letter sizes and flash durations were independently randomized for each subject. The complete experiment was replicated on a different day by each of the four subjects participating.

The means of the two recovery times for every condition for the four subjects are tabulated in Table VI. The recovery times for the two lowest luminance levels showed such high variability that only the range from 280 mL to 0.07 mL are recorded. The mean data for the 28.7' letter at 280, 5.4, 0.40, and 0.07 mL are plotted in Fig. 20 on a logarithmic scale. The graphs indicate a definite reciprocity failure, with increasing recovery times for constant energy flashes from 0.5 to 1.5 msec durations. The recovery times level off and remain constant for durations greater than 1.5 msec. There is an approximately constant percentage increase in recovery times for the different target luminances as shown by the nearly constant slopes of the graphs for the different target conditions. The increase in recovery times from 0.5 to 1.5 msec flashes is about 30%.

The individual differences in the magnitude of the reciprocity failure were marked. For most subjects the data for the 16.3' letter showed less of an effect than for the 28.7' letter, especially at lower target luminances. The recovery times for all conditions for each of the subjects are recorded in Table IX~~/~~ in the appendix. The data are shown in Fig. 21, by subject, for five luminance levels of the 28.7' letter. One subject, R. B., showed no reciprocity effect for the highest luminance level and a nearly 50%

Table VI. Means for four subjects of recovery times for Sloan-Snellen letters presented at various luminance levels following 3×10^7 td·sec flashes of different durations. The energy at the retina was 0.012 cal/cm^2, neglecting losses in the ocular media.

28.7' Letter

Letter Luminance mL	Flash Durations (msec) 0.54	0.78	1.10	1.54	2.4	3.4	5.0
280.2	5.75	6.25	6.69	7.06	6.75	7.19	7.13
5.37	10.56	11.50	12.44	12.63	13.06	13.13	14.00
1.95	14.25	15.56	17.00	17.31	17.75	17.50	19.06
0.40	21.00	24.44	25.94	27.88	27.94	29.13	28.00
0.15	28.50	33.06	36.94	40.81	36.88	36.57	37.75
0.07	38.13	46.13	51.69	56.13	56.38	54.94	54.00

16.3' Letter

Letter Luminance mL	0.54	0.78	1.10	1.54	2.4	3.4	5.0
280.2	6.75	6.88	6.69	7.06	6.81	7.31	7.69
5.37	12.38	12.88	13.06	14.94	13.81	15.31	15.38
1.95	17.06	18.00	18.88	20.13	19.75	22.44	23.63
0.40	32.75	34.94	38.56	36.88	37.25	34.63	37.38
0.15	45.94	46.94	50.75	54.26	52.68	50.44	57.25
0.07	68.13	74.50	71.69	76.88	75.56	74.94	74.00

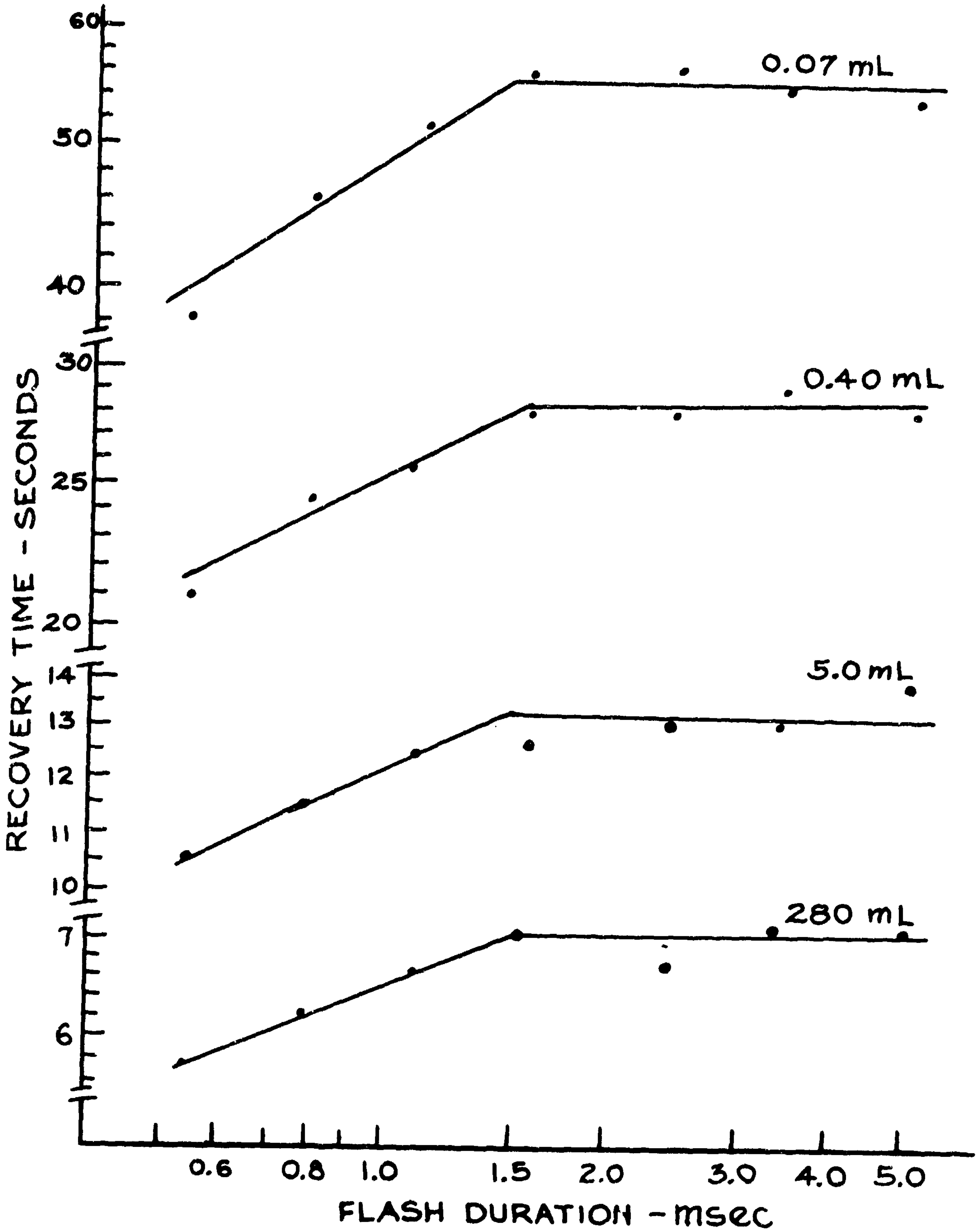


Figure 20. The mean recovery times for four subjects for the 28.7' letter presented at the indicated luminance levels. The flashes were 3×10^7 td·sec (0.012 cal/cm^2 at the retina) with durations ranging from 0.5 to 5.0 msec.

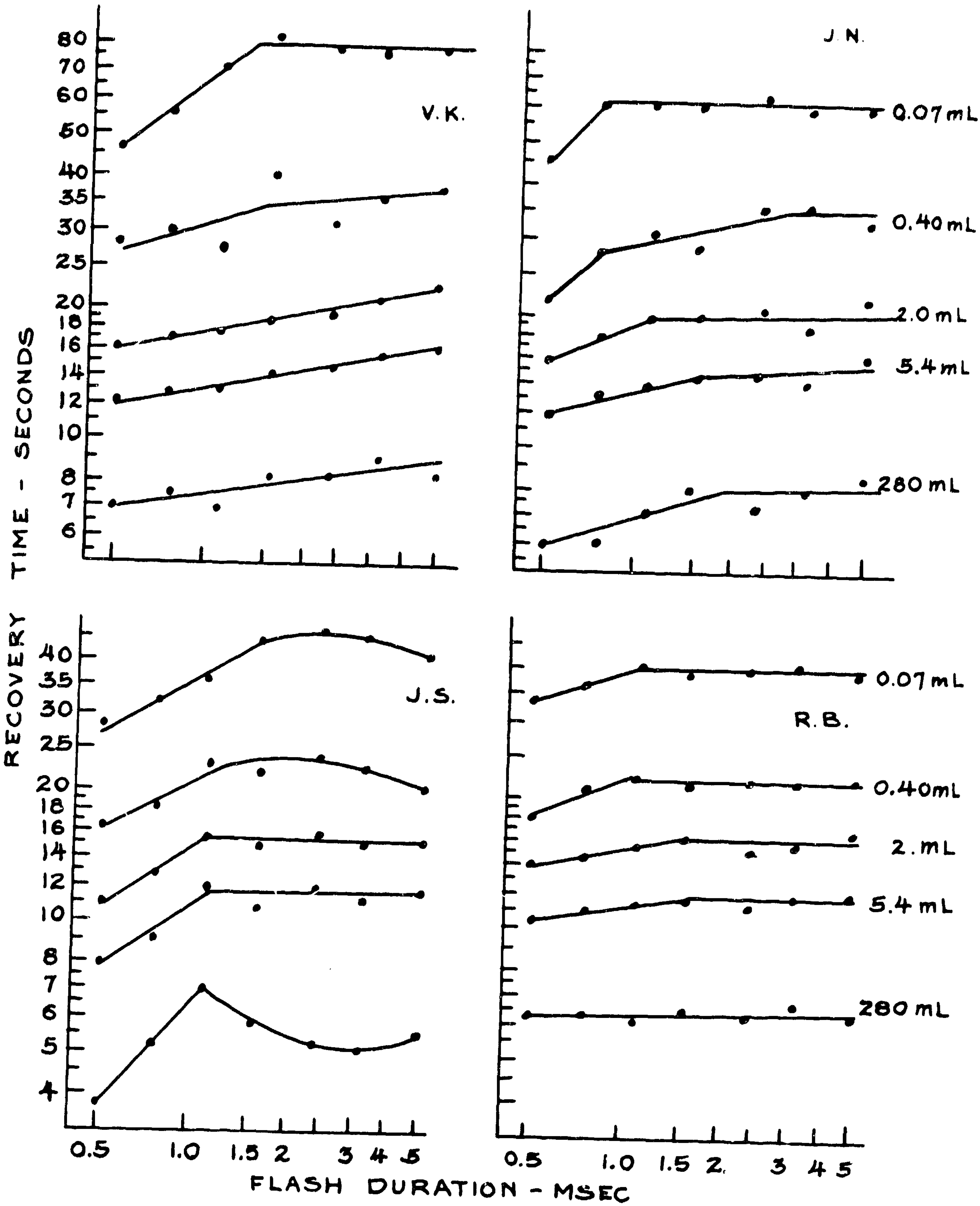


Figure 21. The recovery times for each of the four subjects for the 28.7' letter at various luminance levels. All flashes were 3×10^7 td·sec (0.012 cal/cm^2) with the indicated durations.

increase from the 0.5 to 1.5 msec flashes for the 0.07 mL target. Subject J. S. showed a strong reciprocity failure for all luminance levels of recovery targets. The increase in recovery times from 0.5 to 1.5 msec flashes were all of the order of 50%. Subject V. K. showed continuously increasing recovery times over the full range of durations for the three highest luminance levels.

In the previous study in this laboratory, no reciprocity failure was found for flashes of 40 μsec compared with 1.4 msec. The flash energy was 8×10^5 td·sec, and the recovery targets were the small Sloan-Snellen letters at 0.07 mL. The data in the last line of Table VI. for the same target conditions show very little reciprocity failure for the 0.54 msec flash and none for the other durations. It is very probable, therefore, that the flash energy in the previous work was too low to produce sufficient bleaching of the photopigments for a reciprocity failure to show and that the recovery target chosen for the measurements was insensitive to small changes in bleaching.

3. Change in Recovery Times with Decreased Flash Luminance

Hagins[8] showed, with objective densitometry on rabbit retinas, that very brief flashes would produce a bleach of not more than 50% no matter how much the flash energy was increased after the maximum bleach was produced. It seemed desirable to replicate his work, using the intact retinas of human subjects to see if the reciprocity failure indicated a true maximum of bleaching potential for the various flash durations. This portion of the work was approached with caution because of the high energy densities required. There were practical limitations on the flash energies available with our present source, also. The rather nice feature of the xenon flash sources is that they are capable of flashes producing nearly maximum photopigment bleach levels over the range of flash durations from 0.5 to 5.0 msec and yet are below the energy levels required for threshold of permanent damage.

From Fig. 20, it appears that the mean recovery times for the four subjects are constant for flash durations from 1.5 msec to 5.0 msec. In order to determine if we had reached the maximum possible bleaching level for the flash durations used, an experiment was designed to test the effect on recovery times by varying the flash luminance for the 1.5 msec and 5.0 msec durations. The maximum flash energy obtainable with the graded neutral density in the 5.0 msec sector was 3×10^7 td·sec or 0.012 cal/cm^2 at the retina. Each subject measured, during one experimental session, the recovery times for the 14.3' and 28.7' letters at eight luminance levels following 5.0 msec flashes of seven field luminances, differing by $\sqrt{2}$. The highest luminance, corresponding to the 3×10^7 td·sec flash was 1.1×10^5 L. The field luminance was decreased by neutral density filters in 0.15 density steps to the lowest value of 1.4×10^4 L. The usual techinque was employed of testing one letter size at each of the luminance levels following a flash. The fourteen combinations of letter sizes and flash luminances were independently randomized for each subject.

The mean recovery times for six letter luminances, ranging from 280 mL to 0.07 mL for the four subjects are recorded in Table VII in order of decreasing flash energy. The recovery times for the various luminance levels of the two letter sizes decreased by about 10% for a reduction in flash luminance of 0.15 log units, from 1.1×10^5 L to 7.8×10^4 L. There was some individual variation between the subjects with one showing little change in recovery times for the higher luminance flashes. The data for the different subjects are recorded in Table X in the appendix.

The maximum flash energy obtainable with the 1.54 msec sector synchronized with the flash discharge was 9×10^7 td·sec or 0.036 cal/cm^2 at the retina. The field luminance corresponding to the 9×10^7 td·sec flash was 1.1×10^6 L. The luminance was decreased by $\sqrt{2}$ steps to 1.35×10^5 L, and each subject measured, during one session, the recovery times for the two letter sizes at eight luminance levels. The mean data for the four subjects are recorded in Table VIII. The individual recovery times for each of the subjects are recorded in Table XI of the appendix.

The results of the recovery time measurements for the various flash energies at the two durations are plotted together in Fig. 22 for four target conditions. The graphs show continuously increasing recovery times for the 5.0 msec flashes with increased flash luminance. The 1.54 msec flashes show increasing recovery times to a flash energy of 3×10^7 td·sec corresponding to 3.8 x 10^5 L. Increasing the flash luminance beyond this

Table VII. Means for four subjects of recovery times for Sloan-Snellen letters presented at various luminance levels following 5.0 msec flashes of different intensity. The highest flash energy was 3×10^7 td·sec or 0.012 cal/cm^2 at the retina, neglecting losses in the ocular media.

28.7' Letter

Letter Luminance mL	Log Flash Energy - td·sec						
	7.5	7.35	7.20	7.05	6.90	6.75	6.60
280.2	6.50	5.75	5.50	5.25	--	--	--
5.37	13.00	11.38	12.75	9.63	7.88	7.13	6.38
1.95	17.50	16.00	16.75	13.00	12.13	12.35	7.63
0.40	27.75	22.50	22.50	17.88	13.88	15.13	12.50
0.15	36.38	32.50	30.00	22.00	20.88	19.00	14.50
0.07	50.50	44.00	42.00	29.63	26.63	24.88	19.38

16.3' Letter

280.2	7.37	6.88	6.25	5.75	--	--	--
5.37	15.25	13.63	10.75	10.63	8.88	7.13	6.75
1.95	22.50	20.00	15.88	15.50	13.00	11.00	10.00
0.40	38.38	34.50	26.50	23.00	17.63	16.13	13.00
0.15	48.00	43.88	37.75	29.38	27.63	19.75	16.75
0.07	65.00	58.75	50.13	45.38	41.25	23.25	19.88

Table VIII. Means for four subjects of recovery times for Sloan-Snellen letters presented at various luminance levels following 1.54 msec flashes of different intensity. The highest flash energy was 9×10^7 td·sec or 0.036 cal/cm^2 at the retina, neglecting losses in the ocular media.

28.7' Letter

Log Flash Energy - td·sec

Letter Luminance mL	7.95	7.80	7.65	7.50	7.35	7.20	7.05
280.2	7.13	6.50	6.13	6.50	--	--	--
5.37	13.25	13.25	12.25	12.13	12.13	10.25	9.75
1.95	18.38	17.75	16.50	16.63	16.50	14.25	13.75
0.40	29.13	26.13	25.50	26.38	23.38	19.00	19.13
0.15	36.86	36.38	34.88	32.25	31.75	27.88	23.25
0.07	55.00	55.63	52.75	48.38	44.50	37.50	34.63

16.3' Letter

280.2	7.50	7.00	6.88	6.63	--	--	--
5.37	16.00	15.13	15.00	14.63	11.38	12.88	10.75
1.95	20.75	20.88	20.75	19.75	19.13	16.63	15.00
0.40	33.25	35.50	38.38	33.75	30.13	24.13	22.88
0.15	47.75	56.38	53.75	53.88	44.75	36.75	36.00
0.07	70.13	76.75	76.25	78.75	63.25	51.63	45.50

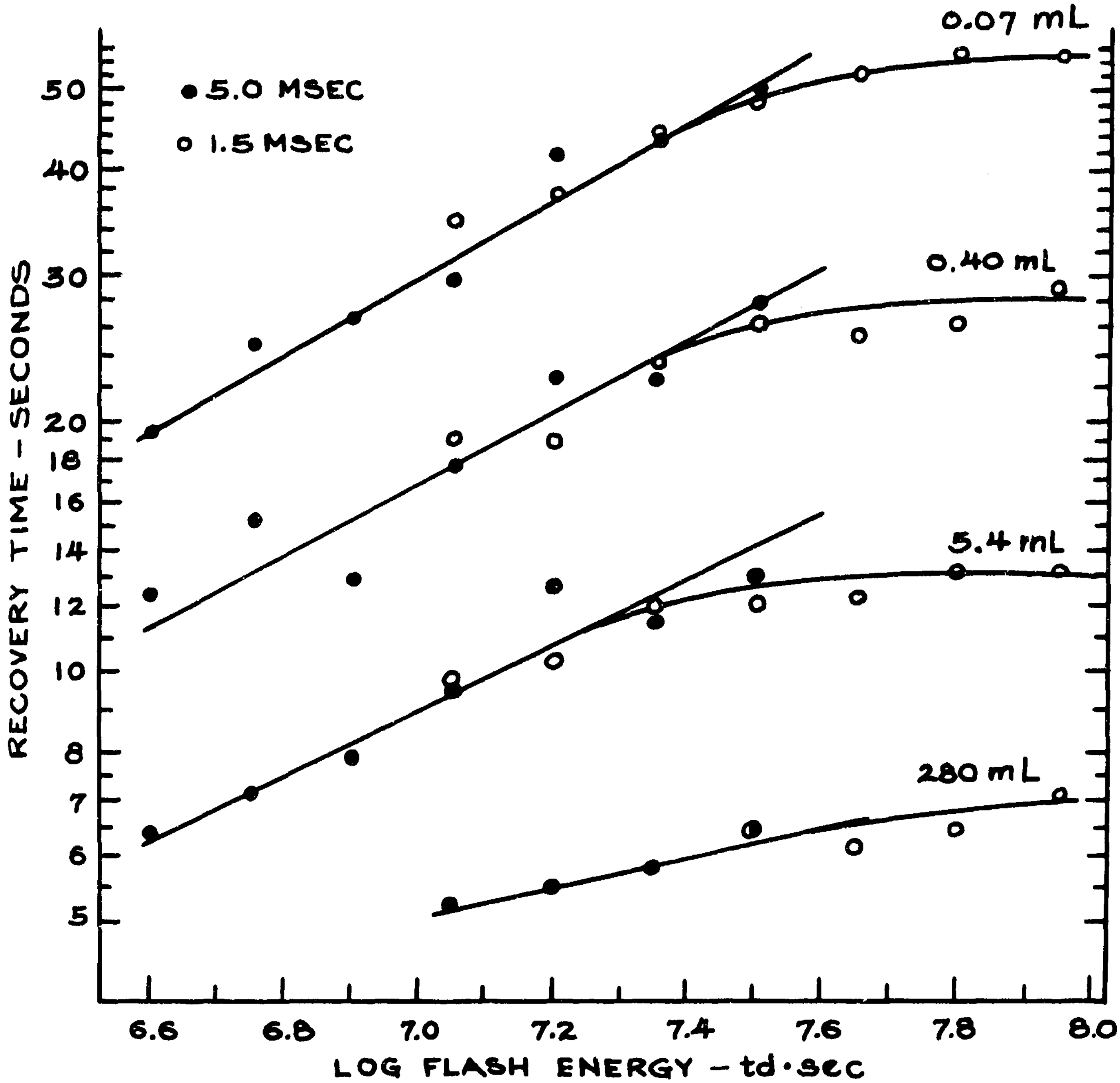


Figure 22. The mean recovery times for four subjects for a 28.7' letter presented at various luminance levels following flashes of 1.5 msec and 5.0 msec duration. The flash energies were varied by reducing the field luminance by neutral density filters.

level produces no change in the mean recovery times for the four subjects. It may be inferred that the 3.8×10^5 L field with a 1.54 msec flash bleaches the maximum amount of photopigment that can be bleached at that duration and that higher energies simply provide a correspondingly higher probability of photoreversal with no additional effective bleaching.

The problem should be investigated more thoroughly, and plans for future work in this area are being made in this laboratory. The effect of decreasing the flash luminance at each of the durations used in the reciprocity failure experiment will be investigated. An attempt will be made to increase the available light in the 5.0 msec flash to determine if there is an upper limit to the recovery times with increasing flash luminance similar to that found for the 1.54 msec flash.

REFERENCES

1. Williams, T. P., "Photoreversal of Rhodopsin Bleaching," J. Gen. Physiol., 47, (1964), 578-579.

2. Hill, J. H. and Chisum, G. T., "Flash Blindness Protection," Aerospace Medicine, August, 1962, 958-964.

3. Miller, N. D., "Visual Recovery," SAM-TR-65-12, April 1965, Final Report Contract No. AF33(657)-9229. DDC AD 450 072.

4. Crawford, B. H., "Visual Adaptation in Relation to Brief Conditioning Stimuli," Proc. Roy. Soc., Series B, 134, (1947), 283-302.

5. Fry, G. A., "The Positive Afterimage and Measurements of Light and Dark Adaptation," Contract No. AF 33(657)-9615, Now in press.

6. Padgham, C. A., "Further Studies of the Positive Visual Afterimage," Opt. Acta, 4, (1957), 102.

7. Barlow, H. B. and Sparrock, J. M. B., "The Role of Afterimages in Dark Adaptation," Science, 144, (1964), 1309-1314.

8. Hagins, W. A., "The Quantum Efficiency of Bleaching of Rhodopsin in situ," J. Physiol., 129, (1955), 22-23.

APPENDIX

The recovery times by individual subjects for various flash conditions and target conditions are recorded in the following tables.

Table IX. Individual data on recovery times for Sloan-Snellen letters presented at various luminance levels following 3×10^7 td·sec flashes of different durations. The energy at the retina was 0.012 cal/cm^2, neglecting losses in the ocular media.

Subject V. K.
28.7' Letter

Log Letter Luminance mL	Log Equiv. Field td	Flash Duration in msec 0.54	0.78	1.10	1.54	2.4	3.4	5.0
2.45	5.05	7.0	7.5	6.75	8.0	8.25	9.0	8.25
0.73	3.40	12.25	12.75	12.75	14.0	14.5	15.5	16.0
0.29	3.00	16.25	17.0	17.25	18.5	19.25	21.0	22.5
-0.40	2.30	28.0	30.25	27.75	40.5	31.0	36.0	37.25
-0.83	1.87	38.75	40.0	48.0	58.0	47.0	47.75	47.25
-1.18	1.54	47.25	55.75	71.0	82.5	77.0	75.5	77.5
-1.79	0.87	118.25	71.5	128.5	109.0	95.0	110.5	131.75
-2.14	0.55	142.0	130.25	138.75	123.25	138.5	150.5	158.25

14.3' Letter

Log Letter Luminance mL	Log Equiv. Field td	Flash Duration in msec 0.54	0.78	1.10	1.54	2.4	3.4	5.0
2.45	4.90	9.25	8.5	8.25	8.5	7.75	8.75	9.25
0.73	3.25	14.75	14.5	15.25	17.0	14.5	18.25	17.25
0.29	2.85	19.25	20.0	21.5	24.0	22.75	24.0	33.0
-0.40	2.20	53.25	48.25	47.25	50.25	49.75	48.25	53.5
-0.83	1.75	64.0	61.75	54.0	84.25	69.75	74.25	86.5
-1.18	1.40	105.5	117.0	91.5	125.75	100.5	100.5	100.25
-1.79	0.70	179.0	194.0	133.5	157.0	157.0	147.5	132.5
-2.14	0.10	144.5	228.5	209.75	202.5	186.0	186.0	206.15

Table IX. continued

Subject J. N.
28.7' Letter

Log Letter Luminance mL	Log Equiv. Field td	Flash Duration in msec 0.54	0.78	1.10	1.54	2.4	3.4	5.0
2.45	4.90	6.0	6.0	7.0	8.0	7.25	8.0	8.5
0.73	3.40	11.75	13.25	13.75	14.25	14.5	14.0	16.25
0.29	3.05	15.75	18.0	19.75	19.75	20.75	18.75	22.0
-0.40	2.40	21.5	28.25	31.0	28.25	35.75	36.5	33.0
-0.83	2.05	30.0	38.75	41.25	46.5	40.25	42.25	46.25
-1.18	1.75	44.5	61.0	60.25	60.0	63.25	59.5	59.75
-1.79	0.95	79.0	99.0	78.0	89.75	96.0	87.25	78.0
-2.14	0.35	101.0	118.0	97.75	117.0	112.5	104.0	100.25

16.3' Letter

Log Letter Luminance mL	Log Equiv. Field td	0.54	0.78	1.10	1.54	2.4	3.4	5.0
2.45	4.75	7.25	7.0	7.25	7.0	6.5	7.25	8.75
0.73	3.25	14.50	14.00	16.0	17.5	16.5	17.75	18.75
0.29	2.94	20.5	20.5	23.0	21.5	23.75	29.0	25.5
-0.40	2.30	35.75	35.75	43.25	39.5	45.25	36.25	42.5
-0.83	1.95	60.25	54.0	71.5	58.5	60.5	57.0	58.5
-1.18	1.55	79.75	71.75	87.75	74.5	77.75	89.5	78.25
-1.79	0.65	134.0	117.25	132.0	121.75	104.25	123.5	108.0
-2.14	0.12	184.5	176.5	165.25	165.0	137.75	144.25	152.25

Table IX continued.

Subject J. S.
28.7' Letter

Log Letter Luminance mL	Log Equiv. Field td	Flash Durations in msec 0.54	0.78	1.10	1.54	2.4	3.4	5.0
2.45	5.16	3.75	5.25	7.0	5.75	5.25	5.0	5.5
0.73	3.56	8.0	9.0	12.0	10.75	12.0	11.25	11.75
0.29	3.17	11.0	12.75	15.5	14.75	1[illegible].0	15.0	15.25
-0.40	2.54	13.5	18.0	23.0	21.75	23.25	22.5	20.0
-0.83	2.14	19.75	24.5	28.0	30.25	30.25	27.0	30.5
-1.18	1.80	28.25	32.0	35.5	43.75	46.25	44.5	40.75
-1.79	1.15	50.5	62.0	58.25	52.0	71.5	67.5	65.75
-2.14	0.76	60.5	77.0	80.0	69.0	91.75	82.75	98.25

14.3' Letter

Log Letter Luminance mL	Log Equiv. Field td	0.54	0.78	1.10	1.54	2.4	3.4	5.0
2.45	4.92	4.5	[illegible].25	5.0	5.75	5.25	5.5	6.0
0.73	3.33	9.25	10.25	9.5	12.5	11.5	12.0	12.5
0.29	2.92	13.0	14.5	15.0	17.25	15.75	18.75	18.25
-0.40	2.2[illegible]	18.5	22.75	2[illegible].0	2[illegible].25	2[illegible].5	25.5	25.75
-0.85	1.88	24.75	30.5	32.75	35.5	40.0	33.0	38.5
-1.18	1.52	35.75	38.0	44.75	53.25	59.75	43.75	53.5
-1.79	0.85	64.5	80.0	79.5	80.5	83.0	89.5	83.25
-2.14	0.43	99.5	93.25	104.75	108.75	113.0	114.75	103.5

Table IX. continued.

Subject R. B.
28.7' Letter

Log Letter Luminance mL	Log Equiv. Field td	Flash Durations in msec 0.54	0.78	1.10	1.54	2.4	3.4	5.0
2.45	4.95	6.25	6.25	6.0	6.5	6.25	6.75	6.25
0.73	3.55	10.25	11.0	11.25	11.5	11.25	11.75	12.0
0.29	3.22	14.0	14.5	15.5	16.25	15.0	15.25	16.5
-0.40	2.65	18.0	21.25	22.0	21.0	21.75	21.50	21.75
-0.83	2.30	25.5	29.0	30.5	28.5	30.0	29.25	27.0
-1.18	2.05	33.5	35.75	40.0	38.25	39.0	40.25	38.0
-1.79	1.05	57.25	65.0	69.75	62.75	73.5	66.25	68.5
-2.14	0.40	77.5	90.75	90.25	80.5	88.5	89.5	89.0

16.3' Letter

Log Letter Luminance mL	Log Equiv. Field td	0.54	0.78	1.10	1.54	2.4	3.4	5.0
2.45	4.75	6.0	7.75	6.25	7.0	7.75	7.75	6.75
0.73	3.35	11.0	12.75	11.75	12.75	12.75	13.25	13.0
0.29	3.02	15.5	17.0	16.0	17.75	16.75	18.0	17.75
-0.40	2.45	23.5	33.0	37.75	31.5	27.5	28.50	27.75
-0.83	2.10	34.75	41.5	44.75	39.0	41.25	37.5	45.5
-1.18	1.78	51.5	71.25	62.75	54.0	64.25	66.0	64.0
-1.79	0.70	83.5	98.0	90.0	88.25	94.75	99.25	84.0
-2.14	0.05	111.25	122.5	133.25	128.5	124.5	140.0	102.5

Table X. Individual data on recovery times for Sloan-Snellen letters presented at various luminance levels following 5.0 msec flashes of different intensity. The highest flash energy was 3 x 10^7 td·sec or 0.012 cal/cm^2 at the retina, neglecting losses in the ocular media.

Subject V. K.
28.7' Letter

Log Letter Luminance mL	Log Flash Energy - td·sec 7.5	7.35	7.20	7.05	6.90	7.75	6.60
2.45	7.0	7.0	7.0	5.5	--	--	--
0.73	14.0	14.0	13.0	10.0	9.0	8.0	6.5
0.29	18.0	18.0	16.5	13.5	13.0	14.0	9.5
-0.40	30.5	25.0	26.5	17.5	17.0	17.5	13.0
-0.83	36.5	34.0	39.0	23.0	21.0	20.5	16.5
-1.18	54.5	56.5	61.0	35.5	25.0	24.5	20.0
-1.79	72.5	77.5	75.5	77.0	44.0	40.0	26.0
-2.14	99.0	92.5	87.5	88.0	55.5	43.5	30.5

16.3' Letter

2.45	8.0	7.5	6.5	6.5	--	--	--
0.73	17.5	16.5	11.0	11.5	9.0	8.5	7.0
0.29	26.0	20.5	18.0	17.5	13.5	12.5	10.5
-0.40	44.5	41.5	32.5	26.0	18.5	19.0	14.5
-0.83	60.0	52.5	45.0	34.0	32.5	22.5	19.0
-1.18	69.5	67.5	59.5	60.5	53.5	26.0	22.5
-1.79	164.5	129.0	72.0	102.5	89.0	44.5	31.5
-2.14	--	148.0	108.0	144.0	139.5	64.5	51.0

Table X continued.

Subject J. N.
28.7' Letter

Log Letter Luminance mL	Log Flash Energy - td·sec 7.5	7.35	7.20	7.05	6.90	6.75	6.60
2.45	6.0	5.0	4.5	5.5	--	--	--
0.73	13.0	12.5	13.0	10.5	9.0	7.5	7.5
0.29	19.0	18.5	17.5	14.0	13.0	11.0	11.0
-0.40	28.5	26.5	22.5	20.5	19.5	14.5	14.5
-0.83	40.0	37.0	31.5	24.5	23.5	18.0	18.0
-1.18	54.5	52.5	36.0	34.0	32.5	29.0	20.5
-1.79	91.0	83.0	67.0	57.5	56.5	53.5	23.5
-2.14	101.0	111.5	76.0	64.0	61.5	64.0	29.5

16.3' Letter

2.45	6.5		7.0	6.0	--	--	--
0.73	15.0		14.0	17.0	11.5	9.0	8.5
0.29	21.5		19.5	20.0	15.5	12.5	12.0
-0.40	38.5		31.5	29.5	24.5	16.0	16.0
-0.83	59.0		41.0	35.5	31.5	22.0	20.0
-1.18	79.0		48.0	42.5	39.5	27.0	23.0
-1.79	99.0		97.0	89.0	75.5	56.0	36.5
-2.14	150.0		128.5	105.0	82.5	66.0	51.0

Table X continued.

Subject J. S.
28.7' Letter

Log Letter Luminance mL	Log Flash Energy - td·sec 7.5	7.35	7.20	7.05	6.90	6.75	6.60
2.45	5.5	4.0	4.5	4.0	--	--	--
0.73	11.5	9.0	15.0	8.0	6.5	5.0	5.0
0.29	16.0	13.5	19.0	11.5	10.5	--	--
-0.40	24.0	17.5	22.5	17.0	14.0	10.5	8.5
-0.83	33.0	32.0	26.0	20.5	18.0	15.0	12.0
-1.18	48.0	35.0	39.0	25.0	22.0	19.0	16.0
-1.79	62.0	58.5	46.0	34.0	25.5	24.0	19.0
-2.14	70.0	82.5	51.5	44.5	31.5	29.5	22.5

16.3' Letter

2.45	6.5	5.0	5.5	4.0	--	--	--
0.73	12.5	17.5	9.0	7.5	8.5	5.5	6.0
0.29	20.5	21.0	12.5	11.5	12.0	9.0	--
-0.40	37.5	29.0	18.0	16.0	16.5	12.0	10.0
-0.83	41.0	40.0	31.0	21.0	21.0	15.0	13.0
-1.18	64.0	55.0	37.0	23.5	28.0	18.5	15.5
-1.79	76.0	90.0	46.5	41.0	42.5	22.0	22.5
-2.14	108.5	101.5	80.5	51.5	56.5	45.0	29.0

Table X continued.

Subject R. B.
28.7' Letter

Log Letter Luminance mL	Log Flash Energy - td·sec 7.5	7.35	7.20	7.05	6.90	6.75	6.60
2.45	7.5	7.0	6.0	6.0	--	--	--
0.73	13.5	10.0	10.0	10.0	7.0	8.0	6.5
0.29	17.0	14.0	14.0	13.0	12.0	12.0	10.0
-0.40	28.0	21.0	18.5	16.5	15.0	18.0	14.0
-0.83	36.0	27.0	23.5	20.0	21.0	22.5	11.5
-1.18	45.0	32.0	32.0	24.0	27.0	27.0	21.0
-1.79	55.0	48.0	53.0	35.5	38.0	31.0	27.0
-2.14	74.5	80.5	58.0	51.0	45.0	35.0	31.0

16.3' Letter

2.45	7.0	7.5	6.5	6.0	--	--	--
0.73	13.5	14.0	12.0	12.0	9.0	6.0	7.0
0.29	17.5	18.0	15.0	15.5	13.0	10.0	9.0
-0.40	27.0	26.0	23.0	24.0	17.0	14.5	13.0
-0.83	31.0	30.5	30.0	28.5	24.5	19.0	16.0
-1.18	57.0	45.0	44.5	37.0	30.0	22.5	19.0
-1.79	78.0	74.0	65.0	49.0	33.5	33.0	25.0
-2.14	112.0	100.0	91.0	60.0	48.5	42.0	48.0

Table XI. Individual data on recovery times for Sloan-Snellen letters presented at various luminance levels following 1.54 msec flashes of different intensity. The highest flash energy was 9 x 10^7 td·sec or 0.036 cal/cm^2 at the retina, neglecting losses in the ocular media.

Subject V. K.
28.7' Letter

Log Letter Luminance mL	Log Flash Energy - td·sec 7.95	7.80	7.65	7.50	7.35	7.20	7.05
2.45	9.5	7.5	8.0	8.0	--	--	--
0.73	16.0	14.0	14.5	15.5	14.0	11.5	10.0
0.29	22.0	17.5	19.5	22.0	20.0	15.0	15.0
-0.40	36.0	28.5	31.0	35.0	28.0	21.0	19.5
-0.83	40.5	44.5	43.5	46.5	44.0	34.0	24.5
-1.18	76.5	74.0	72.0	76.5	57.5	47.0	34.5
-1.79	109.5	80.0	91.5	109.5	98.5	82.0	61.0
-2.14	201.5	98.0	132.0	122.5	139.5	99.0	83.0

16.3' Letter

Log Letter Luminance mL	7.95	7.80	7.65	7.50	7.35	7.20	7.05
2.45	10.0	8.5	8.5	8.5	--	7.5	--
0.73	18.0	17.5	18.0	19.0	9.0	15.0	12.5
0.29	24.0	24.0	23.0	25.0	23.0	19.5	16.0
-0.40	43.0	48.0	43.5	39.0	36.5	30.5	25.0
-0.83	50.5	82.5	55.0	75.5	57.0	42.5	46.0
-1.18	78.5	103.5	100.0	103.5	84.0	62.5	56.5
-1.79	163.5	197.0	178.0	183.5	97.5	117.5	86.5
-2.14	158.0	--	196.0	202.0	166.5	129.5	102.50

Table XI. continued.

Subject J. N.
28.7' Letter

Log Letter Luminance mL	Log Flash Energy - td·sec						
	7.95	7.80	7.65	7.50	7.35	7.20	7.05
2.45	8.0	6.5	6.0	6.0	--	--	--
0.73	15.0	13.5	13.0	12.0	13.0	12.0	13.0
0.29	20.0	20.0	17.0	16.5	17.0	15.5	17.0
-0.40	32.5	32.0	27.0	24.0	23.0	19.0	25.0
-0.83	43.0	37.0	38.0	32.0	33.0	29.0	29.5
-1.18	63.0	66.0	51.0	45.0	46.0	42.0	45.0
-1.79	96.5	85.0	80.0	72.0	66.0	57.0	65.0
-2.14	110.5	105.0	122.0	104.0	104.0	92.0	98.5

16.5' Letter

2.45	7.0	--	7.0	6.0	--	--	--
0.73	19.0	16.5	13.0	15.0	12.0	15.0	11.0
0.29	23.5	22.0	23.0	23.0	21.0	19.0	15.0
-0.40	42.0	38.0	42.5	37.0	31.0	26.0	29.0
-0.83	53.0	52.0	58.0	49.0	45.0	43.0	40.0
-1.18	83.0	76.0	80.0	86.0	66.0	62.0	48.0
-1.79	173.0	134.0	139	141	154	88.0	70.0
-2.14	--	164.0	151	198	180.5	123.0	105.5

Table XI continued.

Subject J. S.
28.7' Letter

Log Letter Luminance mL	Log Flash Energy - td·sec						
	7.95	7.80	7.65	7.5	7.35	7.20	7.05
2.45	5.0	5.0	4.5	5.5	--	--	--
0.73	11.0	13.5	10.5	10.0	9.5	7.5	7.0
0.29	16.0	18.5	14.5	14.0	14.0	11.5	10.0
-0.40	25.0	25.0	25.5	23.0	23.5	16.0	14.5
-0.83	35.5	31.0	31.0	30.0	27.5	21.0	18.0
-1.18	44.0	41.0	53.0	34.0	41.5	26.0	25.0
-1.79	78.0	99.0	75.0	67.5	46.5	30.0	46.0
-2.14	82.5	107.5	87.5	88.5	80.0	62.5	51.5

16.3' Letter

2.45	6.0	5.5	5.5	6.0	--	--	--
0.73	14.0	14.0	16.0	12.5	12.5	11.5	8.5
0.29	19.0	18.5	19.5	16.0	16.5	14.5	12.0
-0.40	22.5	28.0	39.0	29.0	26.5	19.5	15.5
-0.83	37.5	51.0	56.0	51.5	34.0	26.5	24.0
-1.18	52.5	67.5	67.5	58.5	44.5	36.0	33.5
-1.79	129.5	82.5	108.0	87.5	87.0	57.5	64.5
-2.14	142.5	117.5	126.0	105.5	138.5	66.5	76.5

Table XI continued.

Subject R. B.
28.7' Letter

Log Letter Luminance mL	Log Flash Energy - td·sec						
	7.95	7.80	7.65	7.50	7.35	7.20	7.05
2.45	6.0	7.0	6.0	6.5	--	--	--
0.73	11.0	12.0	11.0	11.0	12.0	10.0	9.0
0.29	15.5	15.0	15.0	14.0	15.0	15.0	13.0
-0.40	23.0	19.0	18.5	23.5	19.0	20.0	17.5
-0.83	28.5	33.0	27.0	27.5	22.5	27.5	21.0
-1.18	36.5	41.5	35.0	38.0	33.0	35.0	34.0
-1.79	64.5	78.5	54.0	59.5	50.5	51.0	49.5
-2.14	71.0	85.0	75.5	78.0	60.0	88.0	61.5

16.3' Letter

2.45	7.0	7.0	6.5	6.0	--	--	--
0.73	13.0	12.5	13.0	12.0	12.0	10.0	11.0
0.29	16.5	19.0	17.5	17.0	16.0	13.5	17.0
-0.40	25.5	28.0	28.5	30.0	26.5	20.5	22.0
-0.83	40.0	40.0	46.0	39.5	43.0	35.0	34.0
-1.18	66.5	60.0	57.5	67.0	58.5	46.0	44.0
-1.79	105.0	96.0	90.0	113.0	92.0	72.0	62.0
-2.14	137.0	109.0	106.0	122.0	127.0	81.0	89.0

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High intensity flashes of 0.04 msec to 1.4 msec duration were used to determine the afterimage brightness as a function of time following the flash. Six human subjects made continuous matches of the afterimage for periods up to six minutes following the flashes. The flash energies ranged from 3×10^7 to 8×10^5 td·sec or from 0.012 to 0.0003 cal/cm^2 at the retina, neglecting losses in the ocular media. The mean afterimage brightness, 5 sec following the highest intensity flashes, was 10^5 td. The afterimage brightness data were correlated with recovery time measurements for Sloan-Snellen letters presented at luminance levels from 280 mL to 0.07 mL.

The reciprocity relationship between the duration and luminance of flashes subtending 7.5° visual angle was investigated for constant flash energy of 3×10^7 td·sec. Seven flash durations from 0.5 to 5.0 msec were tested. The recovery times for the Sloan-Snellen letters at various luminance levels increased approximately 30% following 1.5 msec flashes compared with the 0.5 msec flashes. There was no apparent change for the mean recovery times for four subjects following flashes from 1.5 msec to 5.0 msec in duration.

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Flashblindness, recovery time						
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