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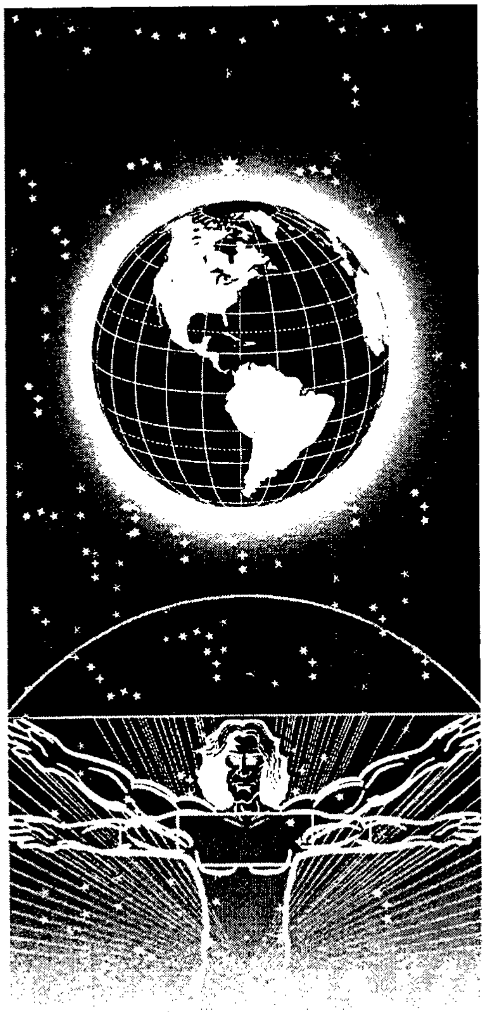

UNITED STATES AIR FORCE RESEARCH LABORATORY

RECIPROCITY OF INTENSITY AND DURATION ON THE DARK ADAPTATION EFFECTS OF LIGHT PULSES

William Kosnik

NORTHROP GRUMMAN INFORMATION TECHNOLOGY
4241 Woodcock Drive, Ste. B-100
San Antonio, Texas 78228

HUMAN EFFECTIVENESS DIRECTORATE
DIRECTED ENERGY BIOEFFECTS DIVISION
OPTICAL RADIATION BRANCH
2650 LOUIS BAUER DRIVE
Brooks AFB, Texas 78235-5214

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Cecilia O. Montes de Oca

CECILIA MONTES DE OCA, Capt, USAF
Contract Monitor

R Miller

RICHARD L. MILLER, Ph.D.
Chief, Directed Energy Bioeffects Division

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William Kosnik

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Northrop Grumman Information Technology
4241 Woodcock Drive, Suite B100
San Antonio, TX 78228

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14. ABSTRACT
This report addressed two questions. First, over what durations and intensities do light exposure of equal energy appear equally bright? Second, do light exposures of equal energy have equivalent effects on the course of dark adaptation? These questions were addressed to refine the AFRL/HEDO flashblindness model. These studies show that reciprocity between duration and intensity is the exception rather than the rule for dark adaptation. The evidence indicates that reciprocity can be expected from about 100 ms to about 10 ms. A study linking a range of short duration exposures from nanoseconds to milliseconds is lacking. During the initial stage of dark adaptation, different duration exposures have very different initial thresholds and recovery functions. From the standpoint of modeling, for exposure durations less than 10 ms, dark adaptation could be described by a single dark adaptation function. Modern lasers now make it possible to study very short duration exposures.

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Purpose

The purpose of this report is to answer two questions. First, over what durations and intensities do light exposures appear equally bright? That is, do two equal energy lights, but with different intensities and durations, look equally bright? Another way to ask this question is what is the temporal integration time of the visual system? The second question is do light exposures of equal energy have equivalent effects on the course of dark adaptation? That is, do two equal energy exposures, but different in duration and intensity, have the same effect on how the visual system recovers sensitivity after the exposure is terminated? The answers to these questions are needed to further refine the AFRL/HEDO flashblindness model.

Reciprocity in Brightness Perception

The answer to the first question is that the visual system does indeed sum the effects of light over time. This process is called temporal summation or temporal integration, but it is restricted to short time periods. Over brief periods of time temporal summation is complete. The perceived brightness of a light is determined by adding up all the quanta in an exposure. Lights of equal energy are equally detectable up to a critical duration. After the critical duration no further summation takes place and the brightness of a light depends on its intensity alone. So, lights that are equal in intensity are equally detectable. Below the critical duration, intensity and duration are reciprocal. This is what is meant by complete temporal summation. Although temporal summation occurs in both the rod and cone systems, this review will focus on the cone system.

The reciprocal relationship between duration and intensity is known as Bloch's Law and may be stated as

$$I \times T = C \text{ for } T \leq T_c, \tag{1}$$

and

$$I = C \text{ for } T > T_c. \tag{2}$$

where I = intensity, T = time, C is a constant, and T_c is the critical duration. This law is an extension of the Bunsen-Roscoe law of photochemistry. A schematic diagram of Bloch's law is illustrated in Figure 1. Equation (1) gives a function of log intensity vs log time as a straight line with a –1 slope. Any combination of intensity and duration that yields a constant product appears equal in brightness. The intensity must be above the critical intensity and the duration must be below the critical duration. Equation (2) gives a horizontal line. The horizontal line indicates that brightness is independent of duration. When experimental data is considered rarely do the two functions show such an abrupt shift from one slope to the other. Often a transition region is observed from complete reciprocity to no reciprocity. This region of partial summation is sometimes reported as having a –0.5 slope, and so follows the inverse-square law.

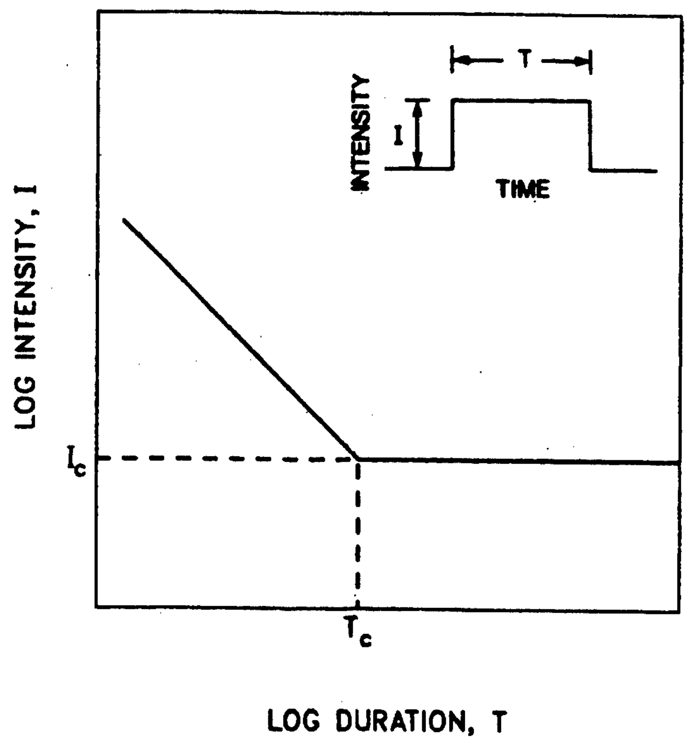

Figure 1. An idealized threshold-duration function. The function describes thresholds for rectangular light pulses as a function of duration. The left limb of the function has a slope of –1, which is Bloch's law and the right limb has a slope of 0. The transition between the two limbs occurs at the critical duration T_c and the critical intensity I_c. The inset shows the wave form of a rectangular pulse with duration T and intensity I. From Watson (1986).

Figure 2 shows how Bloch's law is influenced by light adaptation and stimulus size (Barlow, 1958). This figure shows the threshold of a rectangular pulse of light in the number of quanta/s/deg^2 as a function of pulse duration. These thresholds are shown as a function of background adapting level and stimulus size. The left panel uses a 0.118° diameter light and the right panel uses a 5.9° diameter light. The 0.118° diameter data reflect responses from cones only. All data points with the same symbol are at threshold and so look equally bright. The data points with lines through them have the same total energy, have a –1 slope, and so illustrate Bloch's law. In both panels Bloch's law is valid up to at least 0.1 s. The data for the 0.118° spot suggest that the critical duration increases up to 1.0 s for low intensity spots against dim backgrounds. The data in the 5.9° panel also shows that after 0.1 s, brightness threshold is independent of duration. The 0.118° panel shows that the transition to duration independence occurs gradually with increasing background luminance. Bloch's law has been demonstrated under a variety of stimulus conditions, background intensities, and for foveal and peripheral viewing (Watson, 1986).

Additional research has confirmed Barlow's (1958) finding of longer critical durations for smaller light spots (Hood and Finkelstein, 1986). Small diameter test lights in the range of 1-10' had critical durations of about 100 ms. For test lights 20' and larger the critical duration dropped to 50 ms (Karn, 1936). Sperling and Jolliffe (1965) found a similar relationship for 450 and 650 nm spots 4.5' and 45' in diameter. Reciprocity was valid up to 100 ms for the 4.5' test light. However, for the 45' light, reciprocity ended sooner for the 650 nm wavelength than the 450 nm wavelength. This data indicated that the short wavelength cone system had longer integration times than the long wavelength cone system. Thus, for estimating the critical duration of laser exposures it is important to take into consideration both wavelength and spot size.

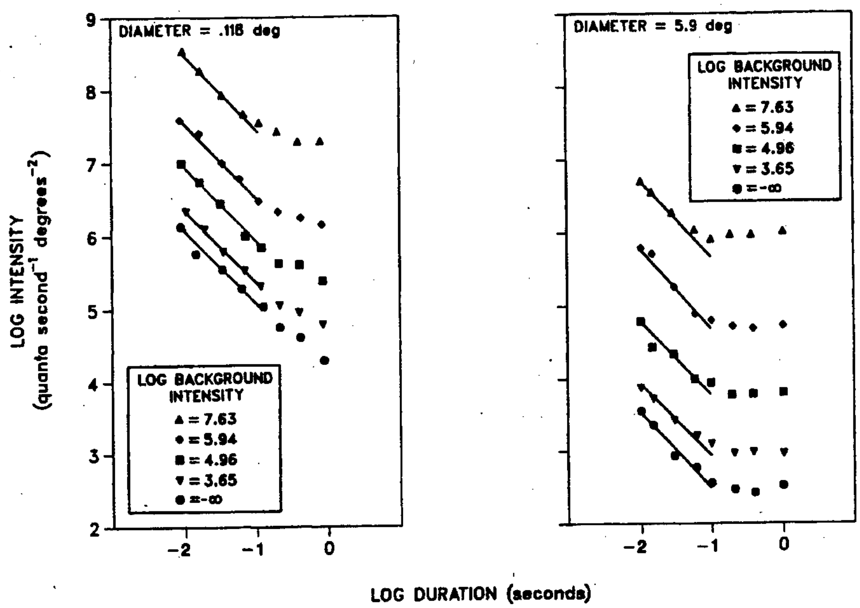

Figure 2. Threshold brightness of two light pulses. The 0.118° diameter pulse is shown in the left panel and the 5.9° pulse is shown in the right panel. Different symbols represent different adapting background intensities. Complete temporal summation is indicated by the straight lines with a -1 slope, which indicate Bloch's law. Bloch's law is valid for durations up to at least 100 ms. After 100 ms the data transition to partial or no reciprocity. From Barlow (1958).

The critical duration also changes during dark adaptation. The visual system integrates light over longer time periods as dark adaptation proceeds. The critical duration changes from about 30-40 ms early in dark adaptation to about 100-200 ms after complete dark adaptation for moderately intense exposures (Crawford, 1937; Stewart, 1972). Over half the change takes place within 10 s after the offset of the adapting field. As a rule, one may conclude reciprocity is valid up to a maximum time of about 100 ms in the cone system. Partial reciprocity occurs from 100-500 ms and no reciprocity is observed after 1 s.

The foregoing data applies to the cone system at threshold levels of sensitivity. Another question is does reciprocity hold for suprathreshold light intensities? Brindley (1952) investigated that question by testing pairs of light pulses in combinations of intensity and duration between 8.9 ms and 400 ns. This data is important for our purposes because we're not concerned with lights at threshold but with very bright lights. Table 1 shows the results for pairs of pulses judged to be equally bright. The first two columns show the durations of the two pulses. The first column shows the shorter duration of the pair. The third column shows the retinal illuminance of the shorter duration pulses (T1)

Table 1. Pairs of Light Exposures that Matched in Brightness.

T1	T2	I1 (td)	I1 (log td-s)	T2/T1
123 µ	1540 us	6 E5	1.87	12.5
		6 E4	0.87	
		6 E3	-0.13	
19.7 us	246 us	6 E5	1.07	12.5
		6 E4	0.07	
3.28 us	41.1 us	6 E5	0.29	12.5
411 ns	41100 ns	6.6 E3	-0.57	100
0.1 ms	8.6 ms	30 E4	3.41	86
0.1 ms	8.9 ms	3 E8	6.43	89

in td and the forth column shows the integrated retinal illuminance in log td-s. The last column shows the ratio of the durations of the pulse pair. Brindley found reciprocity for durations of 123 and 1540 µs, 20 and 246 µs, 3 and 41 µs, and 400 and 41100 ns. Thus, reciprocity spanned a range of about four orders of magnitude. Total energy ranged from a maximum of 2.7 E6 td-s for the longest duration pulse to 0.3 td-s for the 400 ns pulse. The low brightness levels of most of the exposures were due to the limited peak output of the available light sources, a tungsten filament lamp and a krypton discharge tube. With high peak powers and, therefore, higher integrated illuminances of modern lasers, the temporal integration properties of the visual system could be explored at heretofore untested durations and intensities.

So from Bloch, Brindley and others we may conclude that below about 100 ms, all equal energy light exposures look equally bright. The interpretation given to this data is that the eye is a perfect integrator over time periods less than 0.1 s. Although Watson (1986) warns that this is not exactly true, rather, Bloch's law is the inevitable consequence of any linear visual filter that passes only frequencies below some cutoff, we can assume so for our purposes. Therefore, the flashblindness model could adopt a duration between 30-100 ms as the upper limit over which 100% light integration would take place. The effect of duration on brightness perception would have to be combined in some other manner beyond 100 ms. Furthermore, although the brightness of a light may be independent of duration after about 1s, the course of dark adaptation is still dependent on exposure duration as we shall see below.

Reciprocity in Cone Dark Adaptation

Now that we have established the range of durations over which reciprocity is valid, we may ask the second question which is, do exposures reciprocal in intensity and duration have the same effect on dark adaptation? That is, do two lights of equal energy but different durations have the same effect on recovery of sensitivity? Crawford's

(1946) classic paper answered this question negatively for the most part. He measured dark adaptation recovery functions to constant energy exposures to a 30' circular test field on a 12° conditioning field. Both the test and the conditioning fields were white. Increment luminance thresholds were obtained from the author as a function of time in the dark. Adapting field durations ranged from 0.009-900 s and intensities from 0.03-5.03 log cd/m^2 to produce adapting energies from 3.33 to 6.86 log td-s. All stimuli were

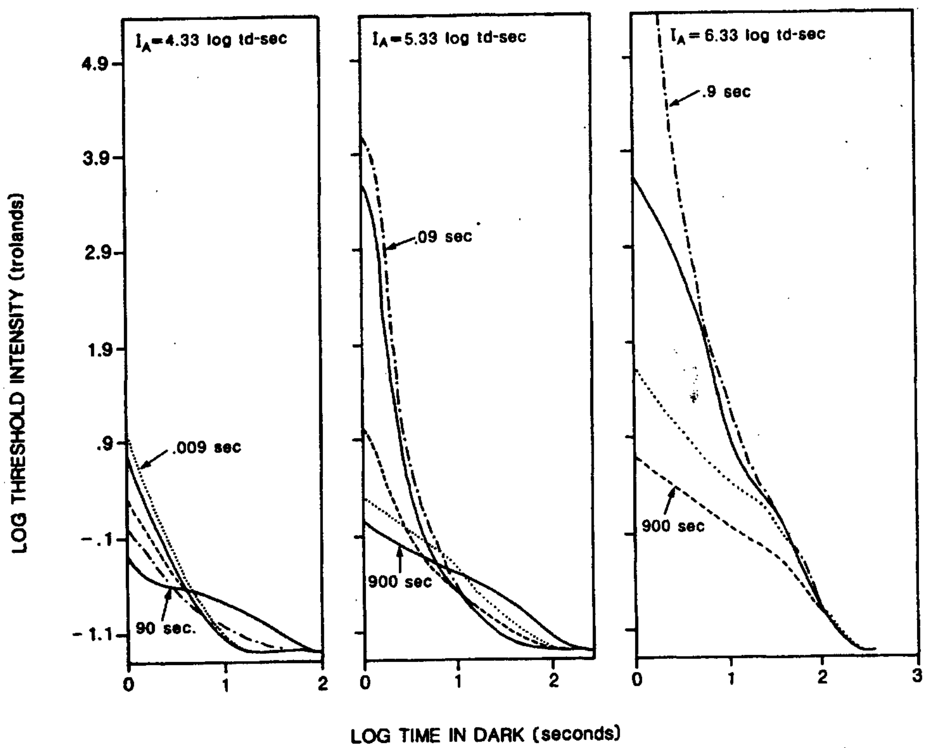

Figure 3. The effect of adapting field intensity and duration on foveal dark adaptation. Each panel contains dark adaptation curves following the offset of a constant energy adapting field. The duration of the field is increased by a factor of ten and the intensity is decreased by ten in each successive curve from top to bottom. In general equal energy adapting fields do not have equivalent effects on dark adaptation. Only later in the dark adaptation cycle do the curves tend to converge. From Crawford (1946.)

presented in Maxwellian view using a 3 mm diameter pupil. Some of Crawford's dark adaptation curves are illustrated in Figure 3. Reciprocity is indicated by overlapping curves. His results showed very little reciprocity between duration and intensity. In general, reciprocity was valid only for low adapting energies and short durations. As adapting energy increased initial thresholds diverged dramatically. However, 10-100 s into recovery the curves started to converge again.

Some other general observations can be made about the data. For constant energy exposures early in dark adaptation (less than 10 s), the more intense the adapting field the more the threshold is elevated. Similarly, as the duration increases the lower is the starting threshold, i.e., the lower the initial level of dark adaptation. Though longer duration lights are less effective at early times in the dark, they are sometimes more effective late in dark adaptation. This can be seen in Figure 3 where some of the longer exposure duration curves cross over the shorter duration curves. Crawford attributed the non-reciprocity of dark adaptation to the regeneration of photopigment that takes place at about the same rate as bleaching. For constant intensity exposures, the initial threshold increases as the duration increases. Also, as duration increases, the steepness of the slope increases up to about 3 s, then slope starts to decline. Finally, for constant duration exposures higher intensity lights produce higher initial thresholds and steeper recovery slopes.

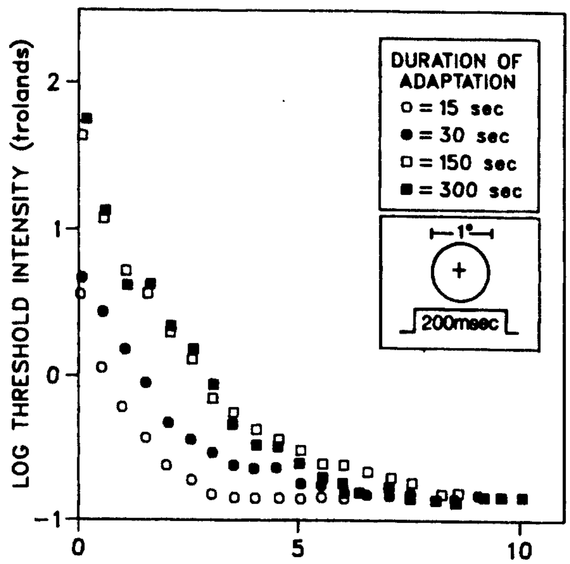

Figure 4. Foveal dark adaptation curves following exposure to a 5.0 log td white light. Increasing duration up to at least 150 s increases the effectiveness of the adapting field, i.e. the time course of adaptation is increasingly prolonged. From Mote and Riopelle (1951).

It might be expected from temporal integration theory that equal intensity exposures with durations longer than one second would have the same dark adaptation curves. Such a notion might follow from the observation that these exposures look equally bright. However, it can be appreciated in Figure 3 that equal intensity exposures do not have the same dark adaptation curves. For example, the top curve in each panel is 31,500 cd/ft^2 (338,940 cd/m^2) and the exposure durations are 0.009, 0.09, and 0.9 from left to right. As duration increases the initial threshold increases and dark adaptation has a slower course.

The point about equal intensity exposures having different dark adaptation curves with different durations is also demonstrated in a study by Mote and Riopelle (1951). In Figure 4 dark adaptation is shown for different durations of an exposure to a 5.0 log td white field. Increasing the exposure duration from 15 s to 300 s increased the effectiveness of the exposure, that is, the time course of recovery was prolonged. This indicates that even though equivalent intensity exposures look equally bright regardless of their duration, exposure duration still plays an important role in the time course of dark adaptation.

Although Crawford's 1947 study represents a *tour de force* in dark adaptation research some methodological shortcomings call into question the validity of his results. Crawford did not report any measurement error; nor did he report the number of trials on which each data point was based. Consequently, there is no record of the variability in his measurements. Variability surrounding dark adaptation threshold can be large, especially during the early phase of dark adaptation when sensitivity changes so rapidly. Without an estimate of the variability, it is impossible to tell how much of a difference between recovery curves constitutes a real difference and not a difference due to measurement error or observer variability.

Despite Crawford's findings, other studies have found that reciprocity is upheld under a variety of stimulus and test conditions, mostly for shorter durations than Crawford studied, though. Miller (1965) found reciprocity for durations of 0.56 and 1.4 ms for a 7.09 log td-s exposure, and for durations of 0.24 and 1.4 ms for an exposure of 6.72 log td-s. The recovery times ranged from 4 to 40 s for the former and 6 to 18 s for the latter exposure. A Sloan-Snellen letter target 28.7' in height (20/115 visual acuity) ranging in luminance between 131-0.07 mL (417-0.22 cd/m^2) was used. All letters were presented at one-second intervals for 0.8 s. Recovery times were measured after two successive correct letter identifications. Although reciprocity was demonstrated, the impact of this result is limited by the narrow range of durations studied. The largest ratio of durations studied was only 5.8. The short range of durations chosen was probably limited by the output of the light source, which was a Xenon flash tube.

Chisum (1973) found reciprocity, over a wider temporal range. Chisum examined exposure durations of 0.1, 0.25, 0.5, 1.0, and 8.5 ms, which overlapped Miller's durations at both ends of the scale. Exposures energies were in the range from 4.58 to 5.58 log td-s. The recovery target was a square wave grating 1.13° in diameter and centered 30' eccentric to fixation. This arrangement still placed the grating within the foveola, which is estimated to be 1.2° in diameter (Duane, 1987). The grating varied in luminance from 18.20 to 0.18 mL (57.3-0.6 cd/m^2). She found reciprocity over all test durations, although some small deviation from strict reciprocity was observed. These data agree very well with Miller's data.

Chisum's and Miller's exposures and short recovery times allow a direct comparison with Crawford's data. Over the range of common exposure energies Chisum and Miller found reciprocity where Crawford did not. However, Miller and Chisum used shorter exposure durations than Crawford. Their durations were 8.5 ms and less and Crawford's duration were not shorter than 9 ms. Therefore, Chisum's and Miller's results suggest that reciprocity could be expected at short duration exposures in the microsecond to millisecond range during the initial stages of recovery.

Bowie and Collyer (1973) also tested the reciprocity principle using a xenon arc lamp white light source. The adapting field was 10° in diameter and had a retinal illuminance of 6.59 log td-s delivered over durations of 0.5, 0.82, 1.5, 13.3 100 and 1000 ms. These durations are comparable to and extend beyond Chisum's (1973) and Miller's (1965) durations. Both the adapting field and target were centered on the fovea. The targets were 20/80 acuity Snellen letters. Target luminance ranged from 500-0.02 fL (1713-0.07 cd/m^2. As shown in Figure 5 reciprocity was initially observed for the 0.5, 0.82, and 1.5 ms exposures in the first seconds of recovery. Only small deviations in

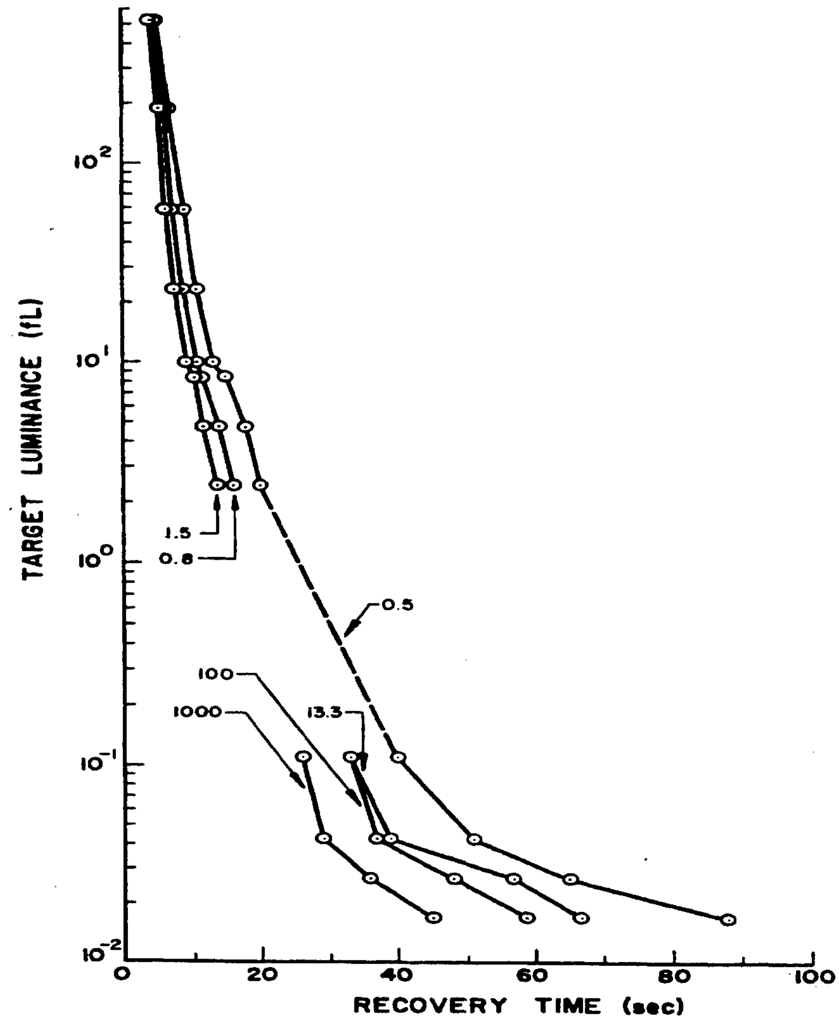

Figure 5. Dark adaptation functions following a 6.59 log td-s exposure of varying durations. Durations are shown in ms. The top three curves show reasonable reciprocity for millisecond exposures. The bottom four curves show later dark adaptation. Little reciprocity is observed for exposures greater than 1 ms. From Bowie and Collyer (1973).

reciprocity were noted through 20 s of recovery. These results confirm Chisum's and Miller's results. However, once again the range over which reciprocity was observed was small, only by a factor of three. Furthermore, as recovery continued the curves began to diverge. Reciprocity over a wider temporal span was not observed. This can be seen in the second set of curves in Figure 5. Recovery times for 0.5, 13.3, 100, and 1000 ms exposures are shown. These curves clearly diverge with continued recovery, showing evidence of reciprocity only for the 13.3 and 100 ms exposures at two target luminances. Dark adaptation thresholds for this set of durations were measured for luminance letters 0.1 fL (0.34 cd/m^2) and less. The use of low luminance targets delayed the measurement of recovery. Thus, recovery times were measured no earlier than 23 s. In general these data agree with the findings of Crawford, Miller, and Chisum in that reciprocity was found for durations less than 2 ms and not above 10 ms.

Miller, King, and Schoessler (1968) also examined the millisecond to second range of exposures and found no evidence of reciprocity. They measured recovery functions to equal energy exposures of 1.1 ms and 1.5 s. The adapting exposure energy was 6.41 log td-s after passing through an interference filter with a peak emission at 555 nm. The recovery targets were 20.4' (20/80 visual acuity) Sloan-Snellen letters 64.6 to 0.014 mL (205.6-0.04 cd/m^2) in luminance. Recovery times ranged from 3.7 to 72 s. They found that recovery times for the longer duration exposure were on the average 1.5 times longer than the shorter exposure. In another test Miller and coworkers compared recovery times for a 0.7 ms and a 1.0 s exposure. Both exposures were 6.23 log td-s. Recovery times ranged from 3-44 s. Again, the recovery times were 1.5 times longer for the longer duration exposure than for the shorter exposure.

These results were the opposite of the results obtained by Bowie and Collyer (1973) and Crawford (1946). These latter researchers found that the longer duration exposures had shorter recovery times. It is difficult to pinpoint the differences in Miller and co-workers' methods that could account for their results. One difference was that Miller used narrow passband sources, whereas Bowie and Collyer (1973) and Crawford (1946) used white light sources. Miller used a 555 nm filter to equate the spectral output of the two different light sources. The millisecond exposures were generated by a xenon flash lamp and the second exposures were produced by a tungsten source. The filter was used to equalize the spectral content of the two sources. One could point to the difference between the narrow band sources Miller used and the wide band sources used by other researchers as the basis for the reversal in recovery times, but this prospect was ruled out by Miller. In another experiment she used neutral density filters to equate the xenon and tungsten sources for total energy and still found longer recovery times for the longer duration exposures.

Another study provided support for Miller's results, but for a shorter range of exposure durations. Hill and Chisum (1962) investigated reciprocity for adapting light exposures of 0.165 and 9.8 ms. Recovery times were measured for gratings of 20/150 and 20/60 acuity. Although these researchers did not exactly equate exposure energies, the exposures were close enough to make meaningful comparisons. They found that for higher energy exposures (above 5.4 log td-s) recovery times were longer for the longer duration exposures compared to the shorter duration exposures. Below 5.4 log td-s similar energy exposures tended to have similar recovery times. The reason for these anomalous findings remains unknown.

Table 2 summarizes the reciprocity durations examined by the foregoing studies. Taken together the these studies suggest that reciprocity can be expected in the microsecond to millisecond range, but not above 10 ms. Above 10 ms, reciprocity may still hold for low energy exposures. Reciprocity may also hold in the later stages of recovery for some longer duration exposures after 10 s or more has elapsed.

It should also be noted that the above analysis applied only to foveal viewing of the adapting field and the test light. More evidence of reciprocity is seen when viewing is eccentric to the fovea (Crawford, 1946; Hayhoe, 1979).

One shortcoming common to all of the above studies is that no measures of response variability were reported. One would expect both intra- and inter-observer variability that would indicate the amount of variation around the mean response. Such measures, if reported, would have provided a much clearer picture of the existence of

Table 2. A Summary of Reciprocity Results from Selected Studies.

STUDY	DURATION[1,2]	ENERGY ([illegible])	SOURCE	SOURCE DIA (deg)	RECOVERY TIMES (s)
Crawford, 1946	**0.009, 0.09, 0.9, 9 s**	3.33	Tungsten (?) white	12	1-100
	0.03, 0.3, 3, 30 s	3.86			1-100
	0.009, 0.09, 0.9, 9, 90 s	4.33			1-100
	0.03, 0.3, 3, 30, 300 s	4.86			1-350 (5.8 min)
	0.09, 0.9, 9, 90, 900 s	5.33			1-450 (7.5 min)
	0.3, 3, 30, 300	5.86			1-450 (7.5 min)
	0.9, 9, 90, 900 s	6.33			1-650 (11 min)
	3, 30, 300 s	6.86			1-800 (13 min)
Miller, 1965	**0.56, 1.4 ms**	7.09	Xenon flash white	10	4-40
	0.24, 1.4 ms	6.72			6-18
Chisum, 1973	**0.1, 0.25, 0.5, 1.0, 8.5 ms**	4.58	Xenon flash white	8.7	1.1-12.5
	0.25, 0.5, 1.0, 8.5 ms	4.98			1.6-14.5
	0.5, 1.0, 8.5 ms	5.28			2.3-17.3
	1.0, 8.5 ms	5.58			3.5-26
Bowie & Collyer, 1973	**0.5, 0.82, 1.5 ms**	6.59	Xenon Arc white	10	1-20
	0.5, 13, 100, 1000 ms	6.59			23-88
Miller, King, & Schoessler, 1968	1.1 ms, 1.5 s	6.41	Xenon flash (1.1, 0.7 ms) green Tungsten (1.5, 1.0 s) green		4-72
	0.7 ms, 1.0 s	6.23			3-44
Hill & Chisum, 1962	0.165, 9.8 ms	5.31, 5.57, 3.89 4.89, 4.57, 3.57	Xenon flash	5	1-160

[1]Durations in **bold** durations indicate reciprocity.
[2]Durations underlined indicate reciprocity after 10 s of recovery.

reciprocity through the use of statistical tests. Only the Chisum study performed a statistical test on the reciprocity question. Without statistical analysis of the results it is impossible to determine whether the departures from reciprocity are real.

One final study deserves to be mentioned. This study, conducted by Hayhoe (1979), is important for our purposes because it applies to the dark adaptation conditions we are interested in, namely, small adapting fields and small recovery targets. Hayhoe found that the size of the adapting field greatly influenced the light adaptation level and the subsequent course of dark adaptation. Specifically, when the test and adapting fields were very small, dark adaptation was very much slower. She compared dark adaptation

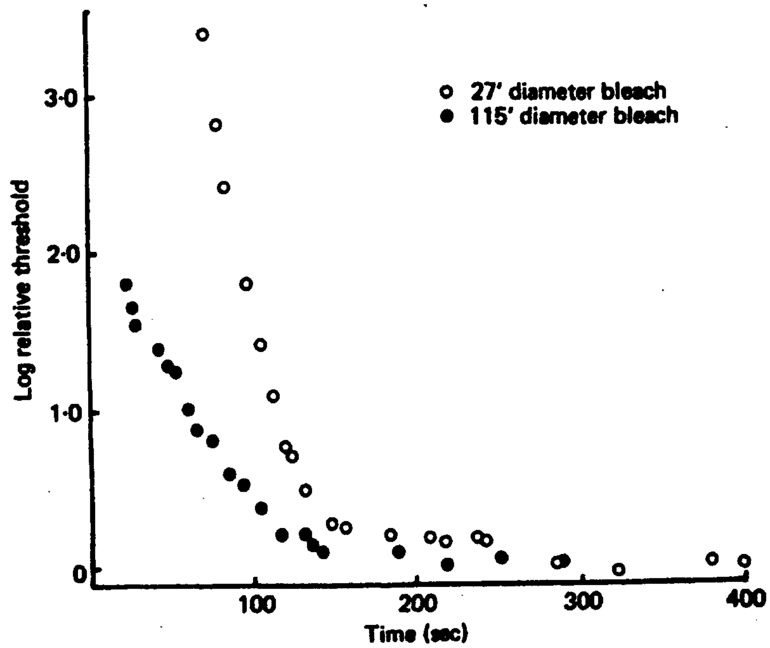

Figure 6. Cone dark adaptation data following a 100 ms exposure to a 7.7 log td bleaching exposure. Two different bleaching diameters were used: 27' and 15' fields. Decreasing the area of the bleaching field greatly elevated the threshold throughout most of dark adaptation. From Hayhoe (1979).

functions for a 3.0' circular red test light on a 27' and a 115' white adapting field. The bleaching field was 6.7 log td-s and 100 ms in duration. Such a spatial configuration well approximates a laser exposure on HUD symbology. As shown in Figure 6, Hayhoe found that the test light threshold was greatly elevated by the smaller adapting field. The first measurable threshold following the smaller adapting field (about 70 s) was more than 1700 times the threshold for the larger adapting field. The smaller field thresholds fell rapidly and approximated the larger adapting field at about 150 s. These data have implications for the effects of laser point sources. Most lasers have small output apertures, which make them point sources even from close viewing distances. Hayhoe's results suggest that point sources may have greatly prolonged recovery times compared to extended sources.

Conclusions

These studies show that reciprocity between duration and intensity is the exception rather than the rule for dark adaptation. Reciprocity appears to hold for short duration and low energy exposures. The evidence indicates that reciprocity can be expected from about 100 μs to about 10 ms. This time frame is also the range over which Bloch's law is valid. No data is available for durations less than 100 μs, but one could assume that if Bloch's law were valid in the 400 ns range, then reciprocity would also hold for nanosecond exposures in dark adaptation. It is clear that a study linking a range of short duration exposures from nanoseconds to milliseconds is lacking. Now that modern lasers have appeared on the scene, it would be possible to study the integrative and light adaptation effects of very short duration exposures.

In the range of durations from tens of milliseconds to seconds, reciprocity is sometimes found in the later stages of dark adaptation, that is, after 10-100 s have passed. During the initial stage of dark adaptation, though, different duration exposures have very different initial thresholds and recovery functions. It is significant to note that Bloch's law breaks down in the 30-100 ms range, the range in which reciprocity for dark adaptation finds its upper limit. Thus, a working hypothesis could be that complete reciprocity holds only for durations over which Bloch's law is valid. From the standpoint of modeling, for exposure durations less than 10 ms, dark adaptation could be described by a single dark adaptation function. The lack of reciprocity at longer durations indicates that different combinations of exposure intensity and duration will have different dark adaptation functions and, therefore, different time constants.

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