DARK ADAPTATION FOLLOWING EXPOSURE TO HIGH-LUMINANCE FLASHES*

BY

C. D. B. BRIDGES

Visual Research Division, Ophthalmological Research Unit (Medical Research Council), Institute of Ophthalmology, University of London

CRAWFORD (1946) has found that the course of peripheral dark adaptation following exposure to flashes of light depended only upon the quantity of light entering the eye, and not upon its actual luminance (provided the flash duration does not exceed 1 sec.). The purpose of the present study was to find out whether this rule was applicable to high-luminance flashes. Apparatus is described for exposing the eyes of dark-adapted subjects to flashes of luminance greater than 10^6 ft. L., and for measuring their effects on the peripheral visual threshold.

Apparatus

(1) **Light Source.**—The source of light was a xenon-filled, tungsten-electrode arc (Neron XBO 162). This arc had a luminance of 2.6×10^7 ft. L., and could be operated on 20 v. A.C. or D.C. In practice, it was ignited with A.C., then switched over to 24 v. 80 amp. hr lead-acid accumulators. Under these conditions the arc was found to be extremely stable throughout the course of the experiments.

(2) Optical System

(a) *Production of Light-Adapting Flash.*—Light from source S (Fig. 1, opposite) was focused by a lens L_1 in the plane of the adjustable slit s_1 . L_2 then focused the source at the Compur shutter t_1 , L_3 collimated the beam, which then passed through the 4-in. mixing cube C, and the source was finally brought to focus in the pupillary plane of the observer's right eye by the lens L_4 .

The luminance of the flash was controlled by the neutral wedge W_1 and by neutral filters at F_1 .

(b) *Measurement of Dark Adaptation.*—The source S was focused by L_5 in the plane of the adjustable slit s_2 ; the beam was then collimated by L_6 and deflected through successive right-angles by the silvered prisms P_1 and P_2 . The beam was stopped down to the required width by s_3 , focused by L_7 in the plane of the Compur shutter t_2 , collimated by L_8 , deflected through the mixing cube C, and finally focused by L_4 in the pupillary plane of the observer's right eye. L_9 served simply as a spectacle lens.

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FIG. 1.—Diagrammatic scheme of apparatus.

The luminance of this beam was controlled by the neutral wedge W_2 and a wheel F_2 carrying neutral filters ranging from density 0.25 to 9.75 in 0.25 log unit steps.

The images of S formed by both optical systems coincided at the centre of the observer's pupil, and since these images were small no artificial pupil was required.

(3) Calibration

(a) *Neutral Wedges and Filters.*—These were calibrated in the usual manner with a rotating sector and photomultiplier. The neutral filters of high optical density were made by combining low optical density filters.

(b) *Flash Luminance.*—With the test field switched off, the luminance of the flash field (suitably reduced by means of filters) was photometrically compared with that of a magnesium oxide screen illuminated with a tungsten-filament source. A method of "forced-choice" was used, in which the observer was required to state whether the flash field was brighter or dimmer than the reference field. A rough match point was first obtained, and then twelve luminances, six brighter and six dimmer than this point, were each presented twelve times in random succession. The difference between each luminance level was 0.1 log unit, corresponding to the setting of W_1 .

Percentage "brighter" responses were plotted versus optical density. A sigmoid curve ranging from 0–100 per cent. "brighter" was obtained, and the 50 per cent. point was determined. This corresponded to the match point.

In this manner, the maximum luminance of the flash field was found to be 1.23×10^6 ft. L. (with a standard deviation of ± 0.04 log unit).

(c) *Test Field Luminance*.—The central 3° area of the flash field was stopped out, and the test field size increased to 3° . The two fields were then matched directly.

(d) *Shutter Speeds*.—Shutter t_1 was fitted with a pointer and graduated scale. Times of opening for various shutter settings were recorded with a photo-multiplier and cathode ray tube. Times were found to be reproducible within 0.1 m.sec. Shutter t_2 was always used at the same setting, viz. 21.3 m.sec.

(4) *Observers*.—The ages of the observers were respectively 22 yrs (A), 24 yrs (B), and 25 yrs (C). One female subject (D, aged 33 yrs) was also available, but except for one experiment proved to be unsuitable. None of the observers had previous experience of this type of work, and in each case it was necessary to carry out three or four familiarizing experiments.

Observer D was a myope requiring +8 D sph. correction; this was allowed for in the selection of L_9 .

(5) *Field Sizes*.—The diameter of the flash field subtended an angle of 8.5° at the observers' eyes; the test field appeared in the centre of this and subtended an angle of 0.5° . A small red fixation cross (0.4° diameter) ensured that the coincident centres of these fields were 15° temporal from the visual axis. The luminance of this cross was maintained at a comfortable level by the observer.

Procedure

The observer was made to bite on his own dental impression carried on a metal plate attached to a three-dimensional adjustment.

The experimental procedure was designed to measure the observer's dark-adapted threshold for a 10-min. period, to expose the eye to the adapting flash, and then to measure the subsequent progress of dark adaptation until the threshold had dropped to the pre-flash level.

Each threshold measurement was carried out in the following steps:

- (1) Operator rang warning bell.
- (2) Observer fixed red cross.
- (3) Three very dim 0.5° diameter, 21.3 m.sec. duration flashes were sent through the testing side.
- (4) Observer indicated how many flashes were seen by none, one, two, or three rings of his signal bell.

If the observer saw all three flashes, their luminance was reduced and steps 1 to 4 were repeated. Reduction of luminance and testing continued until the flashes were no longer visible. The luminance was finally adjusted until two flashes out of the three were reported as "seen". The flash luminance at this point was taken as the threshold.

Between groups of flashes the observer rested. The warning bell ensured the observer's full attention and careful fixation during the 5-sec. period occupied by the flashes.

In a typical experiment, the observer was dark adapted for 30 min., then his absolute threshold was measured at 1 min. intervals for 10 mins. After a warning, the flash shutter was released. Thresholds were then determined as

described, although the rapidity of adaptation in the few minutes following the flash made it necessary to preset the filters and wait until the testing flashes were reported as "seen".

No adapting flash lasted longer than 91.2 m.sec., consequently the possibility of an observer's involuntary blinking during a flash was excluded.

Results

(1) **Fully Dark-adapted Threshold.**—During each 10 min. pre-flash period, measured thresholds showed only a standard deviation ranging from 0.014 to 0.060 log unit. Day-to-day variation was found to be somewhat greater, the threshold of Observer B having the largest day-to-day-standard deviation of 0.074 log unit. The observers' mean thresholds and corresponding standard deviations are listed in Table I.

TABLE I
MEAN THRESHOLDS

Observer	Mean Dark-adapted Threshold (log ft. L.)	Standard Deviation (log ft. L.)	No. of Measurements
A	3.316	0.060	14
C	4.935	0.047	14
B	3.180	0.074	12
D	3.037	—	2

(2) **Dark-adaptation Curves.**—In this study each dark-adaptation curve is expressed in terms of the observer's pre-flash threshold. In this way, results obtained on different days and with different observers are more easily compared. Furthermore, recovery times can be referred to certain multiples of the observer's threshold rather than to units of luminance. Such recovery times then relate to the observer's own visual capacity at low luminance levels. Fig. 2 (overleaf) shows a pair of dark-adaptation curves obtained with Observer A after exposure to 91.2-m.sec. duration flashes. As the luminance of the adapting flash is raised, *ceteris paribus*, the dark-adaptation curve takes longer to reach the pre-flash level. Fig. 2 shows the emergence of the rod-cone break at the higher luminance level.

(3) **Effect of Varying Luminance (L) and Duration (T) of Adapting Flash, keeping (LT) Constant.**—Four typical dark-adaptation curves obtained with Observer C are shown in Fig. 3 (overleaf). Two of these were for an adapting flash of 8.24×10^5 ft. L. and 5.9-m.sec. duration, the other two were for a luminance of 5.35×10^4 ft. L. and 91.2-m.sec. duration. In each case, the value of LT was 4.86×10^3 ft. L. sec.

The pair of dark-adaptation curves shown in Fig. 4 (opposite) were similarly obtained with Observer A. These correspond to an LT of 4.86×10^4 ft. L. sec., for durations of 39.8 and 91.2 m.sec., and luminances of 1.23×10^6 and 5.35×10^5 ft. L. respectively.

Similar results were obtained with all observers for values of LT ranging from 9.97×10^2 ft. L. sec. to 1.12×10^5 ft. L. sec. Mean dark-adaptation curves for Observer A following exposure to flashes of various LT values are shown in Fig. 5 (overleaf). Luminances ranged from 1.09×10^4 ft. L. to 1.23×10^5 ft. L.

The dark-adaptation curves following exposure to flashes of constant LT showed quite a large threshold variation during the first 5 min. (± 0.05 to 0.09 log unit), but at about 30 min. this variation diminished (± 0.02 to 0.03 log unit). The reverse, of course, holds true if one considers the times required to reach a given multiple of the mean pre-flash threshold. Thus the standard deviation of the time required to reach 2.5 log units above threshold was ± 0.1 min., and increased to ± 0.4 to 0.5 min. for times required to reach 0.5 log unit above threshold.

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FIG. 5.—Mean dark-adaptation curves for one observer following exposure to flashes with various LT values.

(4) **Relationship between Light-quantity (LT) in a Flash and the Time Course of Subsequent Dark Adaptation.**—The times required to reach 1.5, 1.0, and 0.5 log units above the mean pre-flash threshold are plotted against LT in Fig. 6*a, b, c* (opposite). For a given observer, it may be seen that the relationship between these two quantities is of the form:

$$\log t_{\alpha} = x \log LT + y \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where t_{α} = time in seconds required to reach α log units above the mean pre-flash threshold,

LT = luminance multiplied by the time of the flash,
and x and y are constants.

The constants x and y have fixed values for a given observer and a given value of α . Their values are listed in Table II (opposite).

Discussion and Conclusions

In the work of Crawford (1946), durations of exposure to the adapting light ranged from 0.009 to 900 sec. The parafoveal recovery process

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FIG. 6.—Relationship between the light-quantity LT in a flash and the time-course of subsequent dark adaptation. The ordinates are log (time required to reach α log units above the mean pre-flash threshold). Crawford's data have been calculated from the published dark-adaptation curves (Crawford, 1946).

TABLE II
CONSTANTS IN EQUATION $\log t_{\alpha} = x \log LT + y$ FOR DIFFERENT OBSERVERS

Observer	$\alpha = 0.5$		$\alpha = 1.0$		$\alpha = 1.5$	
	x	y	x	y	x	y
A	0.470	+0.675	0.571	-0.014	0.683	-0.689
C	0.384	+1.153	0.563	+0.141	0.677	-0.536
B	0.467	+0.721	0.589	-0.016	0.696	-0.673
Crawford	0.455	+0.999	0.546	+0.298	0.639	-0.328

depended on the quantity of light entering the eye, provided the duration did not exceed 1 sec. In the present work, brighter adapting luminances were used, but the durations did not exceed 0.0912 sec. (*i.e.* somewhat less than the latent period of the blink reflex). In consequence, the validity of this conclusion was not tested over the same wide range of luminances and durations. However, for exposures lasting for from 0.0059 to 0.0912 sec and for luminances of from 9.97×10^2 to 1.23×10^6 ft. L., the results of the present work confirm those of Crawford.

If the log times required to reach given multiples of the fully dark-adapted threshold were plotted against log luminance multiplied by duration of adapting flash, Crawford's results are found to lie on a series of straight lines, as shown in Fig. 6(*d*). In the present study the results for each observer demonstrated a similar linear relationship between these quantities. The general form of this relationship was $\log t\alpha = x \log LT + y$. For each subject the slope x was found to increase from $\alpha = 0.5$ to $\alpha = 1.5$ (α represents the log multiple of threshold to which the recovery time is measured). This merely means that the earlier phases of the adaptation curve are influenced more by the adapting flash than are the later ones.

The values of x and y vary slightly from observer to observer, although the differences in $\log t_\alpha$ between Observer C (the slowest adapter) and Observer A (the most rapid adapter) range only from 0.048 to 0.220 log unit (see Table II). Crawford's results lie slightly but consistently above those of Observer C, although again the differences in $\log t_\alpha$ are quite small, ranging from 0.018 to 0.201 log unit.

It is interesting to speculate on what might happen if still higher luminance flashes were used. Exposure of the eye to light of luminance and duration insufficient to cause appreciable rhodopsin bleaching nevertheless causes profound changes in the visual threshold, and it has been suggested that light and subsequent dark adaptation are bound up with intraretinal neural events (*cf.* Granit, Holmberg, and Zewi, 1938; Lythgoe, 1940; Pirenne and Denton, 1952; Rushton and Cohen, 1954; Arden and Weale, 1954). At higher levels of retinal illumination, the bleaching and regeneration of rhodopsin must have an increasingly important role to play in determining changes in the visual threshold.

Prolonged, high-intensity light adaptation can probably bleach a considerable proportion of the retinal rhodopsin. The situation when brief flashes of light are used is somewhat different. Thus, when high-intensity photoflashes were used to irradiate the living rabbit eye, it was found that apparently no more than about 50 per cent. of the retinal rhodopsin could be bleached (Hagins, 1954; 1955). The failure to bleach all the rhodopsin is not due to an insufficiency of light quanta for this purpose. Bridges (1960), working with solutions of frog rhodopsin, has shown that, when the intensity of 0.004-sec. duration irradiating flashes is raised, there is at first a progressively increasing proportion of rhodopsin bleached, as might be

expected. When the intensity is raised above a certain point, however, the quantity of photosensitive material remaining after the flash-irradiation starts to increase.

It might therefore be concluded that with short-duration flashes of any intensity it would be impossible to bleach photochemically all the visual pigment in a retina. From this point of view, vision could never be totally incapacitated by lack of visual pigments in the photoreceptors. At very high intensities the limiting factor is likely to be thermal destruction of the retinal tissues. Light absorbed in the pigment epithelium and choroid is degraded into heat, and if the rate of heat loss by conduction and blood cooling does not balance the rate of heat production the resulting rise of temperature will lead to a retinal lesion.

Summary

(1) Apparatus is described for investigating the visual effects of bright flashes on the periphery of the dark adapted human eye.

(2) For three observers (aged 21 to 25 yrs) it was found that the course of peripheral dark adaptation following exposure to a flash depended only on the quantity of light in the flash, and not on its actual luminance. This finding holds for exposure times ranging from 0.0912 to 0.0059 sec. and for luminances ranging from 1.23×10^6 to 9.997×10^2 ft. L., thus confirming the work of Crawford (1946) at lower luminances.

(3) The time for a given observer to reach a given multiple of his mean pre-flash threshold may be expressed by the equation:

$$\log t_{\alpha} = x \log LT + y \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where t_{α} = time in seconds required to reach α log units
above the mean pre-flash threshold,

LT = product of luminance and time (in ft. L. sec.),

and x and y are constants for a given subject and a given value of α .

The values of x and y vary from observer to observer and according to the value of α .

(4) The possible effect of still higher luminance flashes is discussed.

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