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Dark Adaptation with Interposed White Adapting Fields *

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Abstract. It is proposed that dark adaptation following a moderate pigment bleach may nearly as well be carried out (and more conveniently) under low room lighting conditions as in complete darkness. To test this idea, dark adaptation curves were determined either immediately after the termination of a 3 min, 4.1 log td white pre-exposure field, or following 10 or 15 min of additional exposure to one of three low-level photopic (2.9, 2.4, 1.8 log td) backgrounds of *white* light. Dark thresholds measured after the additional exposure fell rapidly and reached the rod plateau of the normal dark adaptation curve with a maximal *delay* of 1.5 min (for the 10 min backgrounds) or 6.5 min (for the 15 min backgrounds). For the time to be spent in the dark, this meant a *savings* of 8.5 min. At smaller delays savings were even greater. The difference between savings and delay indicates whether or not an interposed background is feasible.

Zusammenfassung. Wir untersuchten, ob die Dunkeladaptation nach einer mittelstarken Pigmentbleichung nicht fast ebenso gut (und bequemer) bei niedriger Raumbeleuchtung erfolgen kann wie in völliger Dunkelheit. Um dies zu testen, wurden Dunkeladaptationskurven auf zweierlei Weise bestimmt: Sofort nach dem Erlöschen einer weißen Vorbelichtung von 3 min Dauer und 4.1 log td retinaler Beleuchtungsstärke; oder nach zusätzlicher Belichtung durch einen von drei *weißen* Hintergründen von 2.9, 2.4, oder 1.8 log td für 10 oder 15 min. Dunkelschwellen, die nach der zusätzlichen Adaptation an die Hintergründe gemessen wurden, fielen schnell ab und erreichten den Endwert der normalen Dunkeladaptationskurve mit einer *Verzögerung* von höchstens 1.5 min (bei den 10 min Hintergründen) oder 6.5 min (bei den 15 min Hintergründen). Bezogen auf die Zeit, die in völliger Dunkelheit zugebracht werden mußte, bedeutet dies eine *Einsparung* von 8.5 min. Bei geringeren Verzögerungen war die Einsparung entsprechend größer. An dem Unterschied zwischen der Einsparung und der Verzögerung läßt sich ablesen, ob ein zusätzlicher Hintergrund angebracht ist.

Introduction

In order to speed up adaptation to low levels of luminance, photographers, X-ray-technicians and military personell have long been using red goggles or red room lighting peaking between 600 and 650 nm. This allows stimulation of the cones but minimally affects the sensitivity of rods, thus permitting a quick changeover from photopic to scotopic vision (Rowland and Sloan 1944; Hecht and Hsia 1945; Hulburt 1951; Smith et al. 1955; Connors 1966; Cavonius and Hilz 1970).

When white light is used instead of red, dark adaptation is delayed behind its optimal rate because of the greater bleaching power of such light (Brown 1956, 1971). However, if adaptation is stepped down by interposing one or several intermediate backgrounds, the remaining recovery occurs fast (Sloan 1950; Zigler et al. 1951; Hattwick 1954; Rushton 1961; Blakemore and Rushton 1965; Spillmann et al. 1972). This is comparable to what is found when the fully dark adapted eye is briefly exposed to any of these backgrounds (Crawford 1937, 1947; Baker et al. 1959). Both kinds of results may be attributed to the fast time course of neural adaptation which governs recovery of sensitivity when the bleaching power of a background is too weak to affect photopigment (Rushton 1961; Dowling 1967).

In this study, we investigated how much can be gained from interposing white backgrounds of practical luminance and duration when adaptation followed a 4.1 log td, 3 min bleach. As a measure we used the difference between the *savings of time spent in the dark* and *the delay incurred in reaching a given threshold.*

Method

Apparatus

A three-channel visual discriminometer (Crozier and Holway 1939) was employed for threshold determination. Channel 1 presented the test field, a 1° white square located at 10° from center on the nasal horizontal meridian and exposed for 0.04 sec. Channel 2 provided a 30° white circular background. Channel 3 contained a dim red fixation point centered relative to the background. The entire stimulus display was seen in Maxwellian view using the right eye only. All thresholds were taken with the observer in a light-proof wooden booth, built around the head of the discriminometer. To facilitate positioning and fixation, a chin-forehead rest was used.

The eye was pre-exposed by looking at a 60° × 60° translucent plate that was transilluminated by a 500 W tungsten projector bulb operated at 110 V. Pre-exposure luminance (with

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* Dedicated to Dr. E. Wolf on his 80th birthday

a 2 mm artificial pupil) corresponded to 4.1 log td and lasted for 3 min. Immediately after this period, the observer moved to the eye-piece of the discriminometer and quickly aligned himself for testing. Because of this arrangement, no thresholds could be recorded on the steady preexposure field or during the very early part of dark adaptation.

Subject

One of the authors, VD, served as observer.

Procedure

The experiment was conducted in two steps. In step 1, a series of five *normal* dark adaptation curves was obtained in complete darkness using the method of limits. The data were pooled within half-min periods and mean threshold values were calculated. A curve was then fitted by eye.

In step 2, the course of recovery from pre-exposure was determined in the presence, and after the extinction, of three intermediate background levels of white (tungsten) light: 2.9, 2.4, and 1.8 log td. By following immediately after the 4.1 log td pre-exposure, these backgrounds served as additional low-level adapting fields with durations of either 10 or 15 min. All three luminances were in the lower photopic range and had been chosen (from a ΔI vs I curve, not shown here) to halt the normal dark adaptation curve before the cone break at threshold plateaus separated by approximately 0.5 log unit. After extinguishing the background light, threshold measurements were continued up to 30 min by which time the final threshold value had always been reached. The recorded values also were pooled, in half-minute intervals, and averaged. The resulting curves are henceforth called the *experimental* dark adaptation curves.

Results

The experimental curves, measured against the three background levels of 10 min duration each, are presented in Fig. 1. The curves obtained with the same backgrounds lasting 15 min are given in Fig. 2. As a reference, the normal dark adaptation curve (step 1) is shown as a thick line in both figures.

The normal curve descends rapidly to its cone plateau at a threshold value of $\bar{1}.85$ log td. It breaks shortly after 7 min into dark adaptation, reflecting the cone-rod transition, and then continues for another 15 min to its final value. In comparison, the experimental curves stop at a level corresponding to the increment threshold for each given background luminance measured under steady state conditions. This threshold is maintained, with a small but steady increase (due to massed stimulation), until the background is turned off at 10 or at 15 min.

Immediately after offset of the backgrounds, the experimental curves decrease steeply. In the case of the 10 min backgrounds (Fig. 1), the dark threshold for the 2.9 log td curve abruptly falls about 1.4 log unit, the 2.4 log td curve 1.0 log unit, and the 1.8 log td curve 0.6 log unit. Hereafter, curves continue along the same time course joining the normal dark adaptation curve at about 22 min.

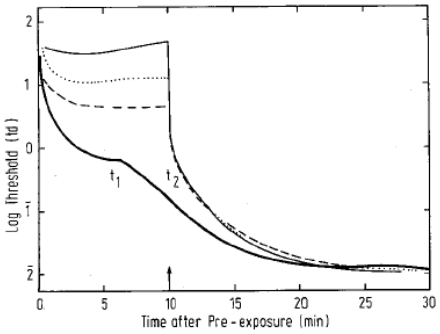

Fig. 1. Experimental dark adaptation curves obtained during and after exposure to one of three intermediate background luminances: 2.9 (——), 2.4 (······) and 1.8 (---) log td. Backgrounds followed 3 min of pre-exposure to 4.1 log td and lasted 10 min (arrow). A normal dark adaptation curve obtained in the absence of background illumination is shown for reference (heavy black line). Curves were fitted to mean values computed from 1 and 5 runs, respectively, using half-minute intervals. Original data points were omitted for the sake of clarity. t_1 and t_2 refer to the times at which the normal dark adaptation curve and the experimental curves arrive at any given threshold.

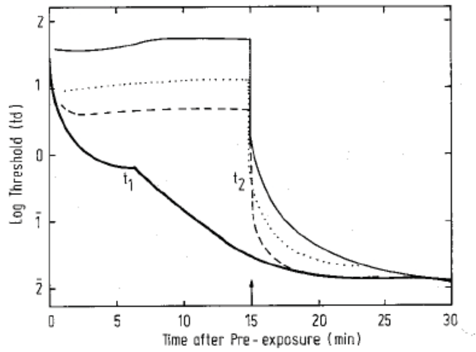

Fig. 2. Same as for Fig. 1. Backgrounds lasted 15 min.

For background durations of 15 min (Fig. 2), the instantaneous threshold changes are even greater. The three curves decrease by about 1.4, 1.5, and 1.6 log unit, respectively, and although following different slopes proceed towards a common end plateau. Thresholds measured after exposure to the lowest background luminance catch up fastest. They arrive at the normal dark adaptation curve only 3 min after this background is extinguished. The curves for the medium and higher backgrounds initially fall short of the normal dark threshold by 0.8 and 1.3 log unit, respectively, and require about 12 more min to reach the absolute threshold. None of the six experimental curves shows a cone break.

Figure 3 quantifies the threshold elevation of each of the 6 experimental curves relative to the normal dark adaptation curve. Differences of log threshold are plotted as a function of time after pre-exposure. They were derived by subtracting (in Figs. 1 and 2) the normal dark threshold from the experimental threshold, in one minute intervals. The threshold elevation increases from the moment the preexposure light is extinguished (0 min) up to the inflection point of the normal dark adaptation curve (7 min); it then increases further to the point where the background luminance is terminated at 10 or 15 min (arrows on axis of abscissas). Here, curves fall sharp-

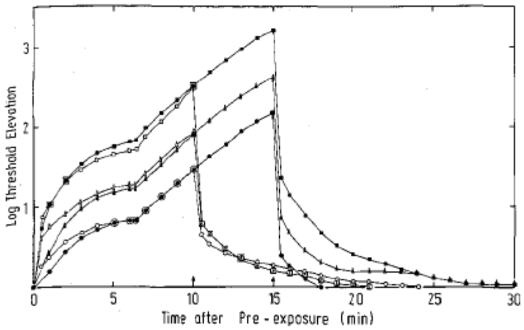

Fig. 3. Threshold elevation as a function of time after pre-exposure. Curves were derived from Figs. 1 and 2 by subtracting log threshold values of the normal dark adaptation curve from corresponding values of the six experimental curves, using 1 min intervals. Arrows indicate when backgrounds lasting 10 min (empty symbols) or 15 min (filled symbols) were extinguished. Symbols denote background luminances of 2.9 log td (□), 2.4 log td (Δ), and 1.8 log td (○).

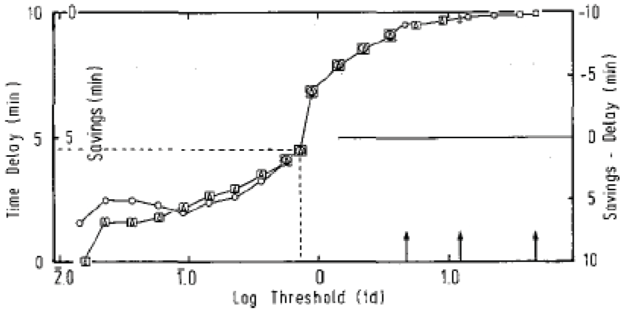

Fig. 4. Left outer axis of ordinates: *Time delay* as a function of threshold. Arrows indicate the threshold at the time of background extinction, and curves should be read from right to left to conform with the time course of dark adaptation. Curves were derived from Fig. 1 by subtracting time values of the normal dark adaptation curve from corresponding values of the 3 experimental curves, using 0.2 log unit steps. Symbols denote background luminances of 2.9 log td (□), 2.4 log td (Δ), and 1.8 log td (○). Left inner axis of ordinates (from top to bottom): *Savings,* or the reduction of time actually spent in the dark to attain a given threshold, was computed by subtracting the delay from the background duration. Right axis of ordinates: *Difference between savings and delay.* Only in rod vision (delineated by dashed lines) is the savings worth the delay. For thresholds above the cone plateau, the difference between savings and delay becomes negative

ly in accordance with Figs. 1 and 2, and then more slowly until they approach an asymptote.

Figures 4 and 5 give the relative time delay (left outer axes of ordinates) as a function of threshold. Delays were derived in analogy to threshold elevation, by subtracting (in Figs. 1 and 2) the times for the normal from those of the experimental dark adaptation curves; this was done in 0.2 log unit steps. Values specify the extra time needed to attain any given threshold if backgrounds of 10 min (Fig. 4) and 15 min (Fig. 5) were interposed after pre-exposure.

Curves for both background durations are S-shaped. After offset of the backgrounds (arrows on abscissa), the delays of the experimental curves relative to the normal dark adaptation curve are 10 and 15 min, respectively. Over more than 1 log unit (read from right to left), delays first decrease slowly, then steeply until the cone plateau ($\bar{1}.85$ log td), and thereafter more gradually again. By the time the absolute threshold is reached, the maximal delay is 1.5 min for the 10 min backgrounds and 6.5 min for the 15 min backgrounds. Three of the curves, notably the 1.8 log td, 15 min condition in Fig. 5, even show zero delay.

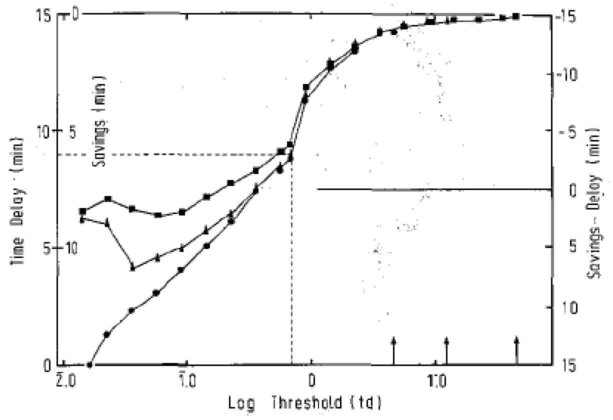

Fig. 5. Same as for Fig. 4. Backgrounds lasted 15 min. Curves were derived from Fig. 2. Symbols denote background luminances of 2.9 log td (□), 2.4 log td (Δ), and 1.8 log td (○).

The *delay* by which an experimental curve, at time t_2 (see Fig. 1), lags behind the time course of normal dark adaptation, at time t_1, is given by Equation 1 (below). Equation 2a specifies, for each threshold obtained, the difference between *time spent in the dark* under the normal (t_1) as opposed to the experimental condition (t_2 – background duration). This difference indicates the amount of *savings* resulting from introducing a background after preexposure. Savings may be conveniently calculated by subtracting the delay from the background duration (Eq. 2c); it can be read off the inner left axes of ordinates of Figs. 4 and 5 (read from top to bottom). At the absolute threshold, values range from 8.5 to 10 min for the 10 min backgrounds and from 8.5 to 15 min for the 15 min backgrounds.

The formulas used are as follows:

$$t_{\text{delay}} = t_2 - t_1 \qquad \text{(Eq. 1)}$$

$$t_{\text{savings}} = t_1 - (t_2 - t_{\text{background}}) \qquad \text{(Eq. 2a)}$$

$$= t_{\text{background}} - (t_2 - t_1) \qquad \text{(Eq. 2b)}$$

$$= t_{\text{background}} - t_{\text{delay}} \qquad \text{(Eq. 2c)}$$

$$t_{\text{savings}} - t_{\text{delay}} = t_{\text{background}} - 2t_{\text{delay}} \qquad \text{(Eq. 3)}$$

If one wants to save time in the dark without incurring too long a delay in reaching threshold, the *difference between savings and delay* is a useful index. It may be calculated according to Eq. (3) and can be read off the *right* axes of ordinates of Figs. 4 and 5. This index yields, in the above examples, values of 7 and 10 min for the 10 min backgrounds and values of 2 and 15 min for the 15 min backgrounds. Note that positive differences occur only for rod thresholds. In cone vision, the expense of the delay exceeds the benefit from the savings.

Discussion

The time course of visual recovery from a pre-exposure bleach was determined either in the usual manner (while in the dark), or following the interposition of low photopic backgrounds maintained for 10 or 15 min. Typically, dark adaptation curves recorded after the additional exposure to the backgrounds are steeper than the normal dark adaptation curve and have no cone-rod break.

A comparison of results shows that in spite of larger relative threshold elevations and time delays for the 15 min backgrounds, recovery here occurs as fast or faster than for the 10 min backgrounds. If the curves in Figs. 1 and 2 are aligned at the point in time at which the backgrounds are terminated (arrows), the 2.9 log td, 15 min curve (thin continuous line) matches with its counterpart for the 10 min duration, whereas for the 2.4 and 1.8 log td background levels curves at 15 min descend faster than at 10 min.

The similarity between the two normalized 2.9 log td curves suggests that the time course of recovery in both cases has to be attributed mainly to the illumination by the interposed backgrounds. In contrast, the difference between the curves for the two lower levels is likely to be attributable to the aftereffect of the initial 4.1 log td preexposure. This would add onto the aftereffect from the background and, thus, slow down the 10 min curves, but not the 15 min curves for which such an effect would no longer be expected. A quantitative check for additivity of the two effects would require obtaining recovery curves for the backgrounds alone.

The abrupt threshold reduction observed when the backgrounds were turned off, agrees with findings by Blakemore and Rushton (1965) and Rushton and Spitzer Powell (1972) who showed that photochemical recovery from preexposure in the presence of low photopic white backgrounds is not halted, but proceeds at rates close to normal, past the cone break and into rod vision. The reason for this lies in the low bleaching power of such backgrounds which normally does not exceed 5% (Alpern 1971; Alpern et al. 1971; Rushton and Spitzer Powell 1972). Similar results were obtained with waning backgrounds where thresholds were found to drop momentarily, although not completely, when the background light was temporarily extinguished (Spillmann et al. 1972).

Our observations also extend previous results by Crawford (1947), Baker *et al.* (1959), and Lingelbach and Haberich (1976), according to which, in the fully or partially dark-adapted eye, short periods of light adaptation to moderate luminance levels are followed by a rapid recovery, with sudden threshold decreases of 2 log units or more from the level of equilibrium. These data may be attributed to fast neural processes governing field adaptation as opposed to bleaching adaptation (Blakemore and Rushton 1965; Dowling 1967).

Practical Considerations

Our systematic measurements of relative threshold elevation (Fig. 3) and time delay (Figs. 4 and 5) at various points after background extinction permit, for the first time, to assess the benefits and disadvantages of interposing white backgrounds during dark adaptation. In all cases, the final rod threshold maximally was reached 1.5 and 6.5 min later than in normal dark adaptation for the 10 and 15 min backgrounds, respectively. However, the amount of time to be spent in darkness generally was much shorter with a background than without it, thus providing savings of 8.5 min or more. For this reason, a white background of practical duration and luminance can be advantageous whenever some delay in reaching a given dark threshold can be tolerated.

In order to remain economical, the background luminance should be neither too high, nor too long in duration. Once the time course of recovery from a given background level no longer changes, delay will continue to increase uniformly with background duration, whereas savings will remain the same. As a consequence, the difference between the two measures (t_{savings} minus t_{delay}) will approach zero and even become negative, indicating that the delay is no longer offset by the savings. This can already be seen for the 2.9 log td, 15 min curve in Fig. 5 (filled squares), which is merely displaced upward relative to its 10 min counterpart in Fig. 4 (empty squares).

In comparison, the 1.8 log td, 15 min condition (Fig. 2, dashed line) would seem quite suitable if white light were to be employed in a stepped-down dark adaptation. It affords the benefit of a practical background illumination and reaches the final threshold without any delay, thus saving 15 min in the dark (Fig. 5, filled circles).

This study may be extended to include other pre-exposure conditions, lower as well as higher ones. The following may serve as an example. In Switzerland, where road driving often requires repeated changes from glaring light (sun, snow) to the dark of a long tunnel, interior illumination conforms with the principle of "dark adapting in the light" as outlined in this paper. To avoid the initial "blackout," such tunnels provide many relatively bright lights as one enters and then progressively reduce the number of lit fictures towards the middle. In this way, they keep the sensitivity of the eye abreast of the prevailing illumination, not unlike a series of intermediate backgrounds as used in our experiments.

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