Dark Adaptation Threshold, Rate, and Individual Prediction

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● THE PURPOSE of this paper is to make a detailed study and interpretation of the relationship between dark adaptation and age. Other studies (1, 3, 4, 9, 11, 12, 17, 19, 20, 21, 27, 30) have demonstrated an association between age and the process of dark adaptation, but an attempt to estimate the extent of the change in the general population from the existing data has proved almost impossible. This is true partly because the experimental conditions, degree and time of presentation, intensity, and color of light under which this phenomenon has been studied have varied widely from one age sample to another and partly because those studies that have shown a relationship have depended on highly select samples that did not represent the general population (19). Such experimental groups have also varied in both composition and size. Furthermore, in some studies an artificial pupil (21) or a mydriatic (23) was used, and in others they were not (27).

The indications are that the range of individual differences in the dark adaptation process as a function of age is considerably greater than has been supposed, and greater than any one study has demonstrated. Therefore, to obtain a better estimate of the influence of age on the dark adaptation process the present study was conducted using a much larger and more representative age sample of the population.

Among those variables which influence rate and the ultimate degree to which the viewer will be able to adapt at low levels of luminance are duration and intensity of pre-exposure illumination (26) and wave length (33).

The variables taken into consideration in the present study were (a) age, (b) dark adaptation thresholds for 21 time intervals, and (c) the intersection of the cone and rod curves.

In an alternative statistical study of the relationship of dark adaptation and age, McFarland and Fisher (21) stated that the dark adaptation curve itself could be described as inversely logarithmic and therefore represented by the general equation

$$y = 10^{a + bx} + C \tag{1}$$

in which

- y = $\mu\mu$l luminance;
- a = initial level of dark adaptation;
- b = drop time (drop time is generally taken to mean the amount of time required to reach some predetermined level of dark adaptation);
- x = time; and
- C = the asymptote of the curve.

However, it is also possible to compute C (8, 21) by the formula

$$C = \frac{P_1 \times P_2 - P_3^2}{P_1 + P_2 - 2(P_3)} \tag{2}$$

in which

- P_1 = a given value of the curve early in time, for example, the 6th minute;
- P_2 = a value on the curve late in time, for example, the 30th minute;
- P_3 = a value on the curve midway between P_1 and P_2; and
- C = the asymptote of the curve.

This method of calculating C, the asymptote of the rod curve, is generally applicable to calculating the asymptote of the cone curve as well.

Hammond and Lee (12) stated that the dark adaptation curve can be represented by

$$\text{Log } I = a + b/t^2 \qquad (3)$$

in which

a = a constant, the general level of the curve at the asymptote;
b = a constant, the rate of adaptation; and
t = the time in minutes from the cessation of the pre-adaptation light stimulus.

In previous investigations the general procedure was to fit curves individually by using various formulas, and then identifying such parameters as the curve intercept, cone-rod curve intersection, drop rate, asymptote of the cone curve, and the asymptote of the rod curve. But dark adaptation is a phenomenon known to vary, relative to a number of conditions of which age is one. It is now certain that as age increases the curve is displaced upward on the y axis. At the same time the cone and rod segments of the curve seem to pivot around their individual focal points near the intercept. The pattern of displacement is extremely orderly.

It is evident that, if the age variable is related to the dark adaptation curve in some lawful manner, then this function could be described mathematically. If this is so, then it should be possible to describe the age curve family. However, this has not been done.

Instead, at this time in the investigation of dark adaptation as a function of age, conventional statistical methods in the study of the age factor were substituted for a more mathematical resolution of the dark adaptation time and age interaction. This approach established beyond a reasonable doubt that dark adaptation becomes a function of age. For example, in 1955 McFarland and Fisher (21) used Eq. 2 for obtaining C and found a correlation of 0.895 between age and C. Inasmuch as the sample of subjects used was composed largely of aircraft pilots who were, by the nature of their occupation, highly selected with respect to visual efficiency, a correlation of this magnitude would not ordinarily have been expected. This is because restricted range of samples tends to lower the magnitude of the conventional product moment, r. The results, r = 0.895, failed to support their inference, because this correlation was one of the highest ever discovered among physiological and psychological relationships.

However, the statistical approach did not fulfill the need for a mathematical model of the dark adaptation, time, and age relationships. Consequently, a search for a general equation was initiated. A model was constructed which made possible the accurate prediction of the mean level of adaptation for any point on the time continuum as a function of age.

METHOD

Subjects

There were 240 male subjects. Thirty subjects were drawn from each decade ranging from the teen-age level through 89 years. The total sample was composed of persons taken from YMCA groups, college-age students, university faculty, taxi drivers, unemployed persons obtained from the USES Agency, and retired men living at home or in private institutions for the aged. All subjects were paid for their services, and after obtaining the data, over one-half the subjects in each decade were then offered and given a complete eye examination free of charge.

Apparatus

The instrument (16) used throughout this study was the Hecht-Schlaer adaptometer which had been rebuilt and recalibrated by the manufacturer. The research was conducted in three different cities to accommodate aged persons for whom traveling was difficult.

Procedure

After each subject was seated in the experimental room, his left eye was covered by a patch, and his head was held steady in a head-chin rest. Vision was uncorrected. The lights in the dark-room were turned off, and after a lapse of approximately 1 min, the retina of the right eye was bleached by exposure to a standard 1,600-millilamberts

TABLE 1

MEAN DARK ADAPTATION AS A FUNCTION OF AGE AND TIME LOG_{10} μμl LUMINANCE[1]

Age (Years)	16-19		20-29		30-39		40-49		50-59		60-69		70-79		80-89	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
0-59 Sec	6.93	0.30	6.78	0.41	6.95	0.32	7.03	0.26	7.06	0.26	7.21	0.24	7.49	0.58	7.67	0.13
Min																
2	6.42	0.32	6.16	0.46	6.37	0.34	6.62	0.27	6.78	0.27	6.94	0.25	7.16	0.57	7.43	0.14
3	5.93	0.39	5.65	0.48	6.05	0.35	6.29	0.32	6.49	0.31	6.73	0.31	7.06	0.17	7.25	0.15
4	5.66	0.39	5.43	0.51	5.85	0.40	5.98	0.35	6.25	0.40	6.59	0.34	6.95	0.22	7.12	0.16
5	5.58	0.40	5.26	0.60	5.67	0.47	5.86	0.37	6.17	0.42	6.50	0.43	6.94	0.23	7.08	0.17
6	5.36	0.41	5.05	0.67	5.45	0.48	5.61	0.33	5.94	0.46	6.27	0.38	6.70	0.29	6.90	0.21
7	5.08	0.45	4.83	0.71	5.17	0.46	5.36	0.34	5.63	0.44	6.02	0.38	6.48	0.29	6.71	0.26
8	4.82	0.46	4.61	0.66	4.86	0.47	5.10	0.38	5.41	0.45	5.76	0.44	6.25	0.32	6.52	0.29
9	4.55	0.52	4.38	0.66	4.84	0.38	4.80	0.38	5.14	0.50	5.51	0.51	5.98	0.43	6.33	0.43
10	4.17	0.48	3.95	0.63	4.17	0.36	4.51	0.39	4.77	0.60	5.24	0.65	5.71	0.44	6.10	0.45
12	3.80	0.40	3.50	0.46	3.87	0.38	4.22	0.34	4.48	0.64	4.99	0.61	5.48	0.46	5.91	0.50
14	3.48	0.43	3.28	0.47	3.62	0.37	3.96	0.35	4.25	0.61	4.78	0.61	5.26	0.45	5.74	0.55
16	3.24	0.41	3.14	0.47	3.44	0.37	3.76	0.31	4.02	0.57	4.50	0.59	5.00	0.48	5.55	0.59
19	3.02	0.35	2.98	0.45	3.23	0.37	3.54	0.31	3.85	0.57	4.27	0.59	4.74	0.48	5.54	0.59
22	2.86	0.35	2.85	0.45	3.04	0.29	3.34	0.29	3.70	0.58	4.05	0.55	4.54	0.47	5.16	0.62
25	2.74	0.32	2.78	0.45	2.93	0.30	3.22	0.29	3.55	0.53	3.88	0.53	4.36	0.46	5.01	0.66
28	2.64	0.30	2.72	0.46	2.87	0.27	3.13	0.30	3.43	0.51	3.74	0.52	4.22	0.46	4.90	0.68
31	2.52	0.30	2.65	0.47	2.81	0.28	3.07	0.31	3.36	0.48	3.67	0.50	4.14	0.47	4.83	0.71
34	2.45	0.23	2.64	0.47	2.77	0.26	3.02	0.29	3.32	0.47	3.63	0.49	4.11	0.47	4.81	0.72
37	2.43	0.17	2.60	0.46	2.76	0.25	3.02	0.29	3.32	0.47	3.62	0.48	4.11	0.48	4.81	0.73
40	2.43	0.17	2.60	0.44	2.76	0.26	3.02	0.29	3.32	0.47	3.62	0.48	4.11	0.48	4.81	0.72

[1]The data for 0-59 seconds were not used in the statistical analysis since they were considered the least reliable.

incandescent light source for 3 min. At the end of the pre-test period, the subject was exposed to a red fixation point 7 deg right of center. The violet light test stimulus of 1 deg (53.0 percent transmission at 405 μ) was then presented. The duration of each flash of light was ⅕ sec. All of the experimental measurements were made by the same person.

The first observation was made within the first 59 sec after the termination of the pre-exposure light. Then, beginning with the second observation, one reading was taken every minute for the next 9 min, every 2 min for the next 6 min, and every 3 min for the following 24 min.

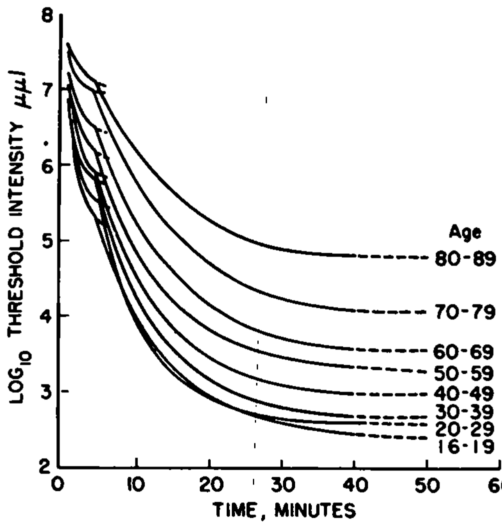

Figure 1. Dark adaptation as a function of age. Age range 16-89 years, N = 240.

RESULTS

Table 1 and Figure 1 show that the family of mean dark adaptation curves obtained as a function of age rises in an orderly manner, suggesting that the differences between their terminal points increases geometrically from one age level to the next. Table 1 also shows the standard deviation for each threshold to be exceedingly small. The intercorrelations among age and thresholds are unusually high (Table 2).

Inasmuch as the curves for the 16- to 19-year old group and the 20- to 29-year old group seemed to be nearly alike, they have been combined for the purpose of simplify-

TABLE 2

INTERCORRELATION OF DARK ADAPTATION THRESHOLD FOR EACH TIME INTERVAL AND DARK ADAPTATION THRESHOLDS WITH AGE[1]

	N 240—Age Range 16-89 Years																				
Min	2	3	4	5	6	7	8	9	10	12	14	16	19	22	25	28	31	34	37	40	Age
2		0 87	0 83	0 83	0 81	0 79	0 77	0 76	0 76	0 75	0 75	0 74	0 73	0 73	0 71	0 70	0 69	0 69	0 70	0 70	0.71
3			0 96	0 96	0 94	0 92	0 90	0 88	0 87	0 86	0 85	0 84	0 82	0 82	0 81	0 79	0 79	0 79	0 79	0 79	0 82
4				0 98	0 97	0 94	0 92	0 90	0 89	0 88	0.87	0 85	0 84	0 83	0 82	0 80	0 79	0.79	0 80	0.80	0 80
5					0 98	0 95	0 93	0 91	0 89	0 88	0 86	0 85	0 83	0 83	0 81	0 79	0 79	0 78	0 79	0 79	0.80
6						0 97	0 95	0 93	0 91	0 90	0.89	0 87	0 85	0 85	0 83	0 82	0 81	0.81	0 80	0 81	0.79
7							0 98	0 96	0 93	0 92	0 91	0 89	0 87	0 86	0 86	0 83	0 82	0 82	0 82	0 82	0 79
8								0 99	0 95	0 93	0 92	0 91	0 89	0.88	0 87	0 85	0 84	0 83	0 83	0 83	0 79
9									0 96	0 95	0 94	0 93	0 90	0 89	0 89	0 87	0 86	0 85	0.84	0 85	0 79
10										0 97	0 96	0 95	0 93	0.91	0.91	0.89	0 88	0 87	0 87	0 87	0 79
12											0.98	0 97	0 96	0 94	0 93	0.92	0.91	0 90	0 90	0 90	0 82
14												0.99	0 98	0.96	0 95	0.94	0 92	0 92	0 91	0 92	0 84
16													0 99	0 98	0 96	0.96	0 94	0 93	0 93	0 93	0 83
19														0 99	0.98	0.97	0 96	0 95	0 95	0.95	0 83
22															0 99	0.98	0 97	0 97	0 97	0 97	0 83
25																0 99	0 98	0 98	0.98	0 98	0 83
28																	0 99	0 99	0 99	0 99	0 82
31																		0 99	0 99	0 99	0.82
34																			0 99	0 99	0 83
37																				0.99	0 84
40																					0 84

[1]To be significant at the 0.01 level of confidence r should be 0 155 All the obtained correlations exceeded this value

ing the mathematical process which follows, although plotted independently in Figure 1.

Model for Dark Adaptation as a Function of Age

For the sake of convenience in examining the level of dark adaptation as a function of age as well as time, the mean data given in Table 3 have been replotted as time

TABLE 3

DARK ADAPTATION AS A FUNCTION OF AGE AND TIME LOG_{10} $\mu\mu$l LUMINANCE

	Age							
Time	16-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89
30 sec	6.9294	6.7803	6.9492	7.0310	7.0590	7.2065	7.4874	7.6174
1 min	6.4198	6.1635	6.3834	6.6640	6.7873	6.9382	7.2554	7.4248
2 min	5.9346	5.6547	6.0472	6.2884	6.4988	6.7261	7.0634	7.2458
3 min	5.6602	5.4286	5.8517	5.9818	6.2562	6.5894	6.9865	7.1198
4 min	5.5830	5.2672	5.8470	5.8701	6.1794	6.4937	6.9687	7.0748
5 min	5.3598	5.0480	5.4505	5.6762	6.9549	6.2732	6.7029	6.9006
6 min	5.0760	4.8323	5.1558	5.4246	5.6407	5.9269	6.2839	6.7056
10 min	3.8543	3.9493	4.1648	4.5095	4.8026	5.2064	5.7469	6.1104
16 min	3.2399	3.1413	3.4364	3.7780	4.2024	4.5028	4.9947	5.5511
22 min	2.8718	2.8450	3.0387	3.3346	3.7404	4.0360	4.6035	5.2667
28 min	2.6422	2.7193	2.8611	3.1334	3.4973	3.7451	4.2207	4.9015
40 min	2.4272	2.6029	2.6945	3.0159	3.3459	3.6419	4.1043	4.8055

curves (Fig. 2). Here age has been entered on the x axis, and $\log_{10}$ $\mu\mu$l luminance entered on the y axis. Each curve in Figure 2 represents the level of dark adaptation as a function of age at a given time in log units. The slope of the curves becomes greater as a function of age and time. When plotted in this way, the data appear as a family of positive exponential curves.

A suitable mathematical model (Model A) of dark adaptation as a function of age and time, as plotted in Figure 2, is as follows:

$$\text{Log } y = G^{(Ct)^{f_1(A)}} \qquad (4)$$

A detailed exposition of the method of derivation of this model can be found in (9).

To evaluate the derivation two procedures were devised.

Test Procedure 1.—In procedure 1 Model A (Eq. 4) was used to reconstruct theoretical dark adaptation curves. Then the original data were compared with the theoretical constructs. Both sets of curves are shown in Figure 3. Although the dark adaptation level for the 80- to 89-year old group was slightly overestimated, probably because of the concentration of several cataract defects found in persons who

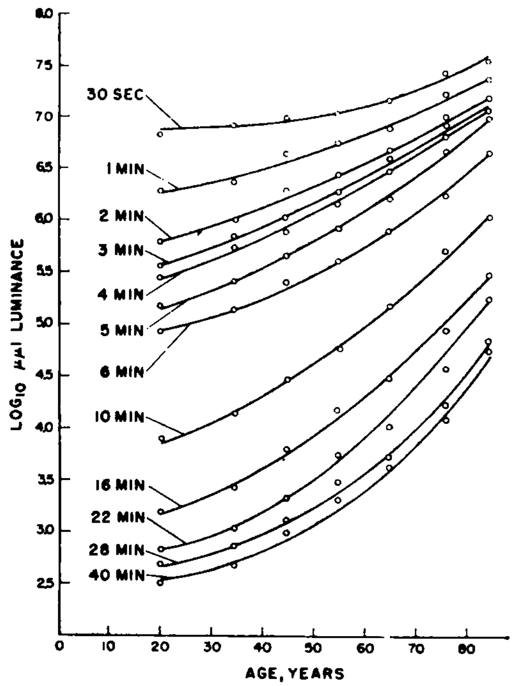

Figure 2. Dark adaptation curves as a function of time plotted against age.

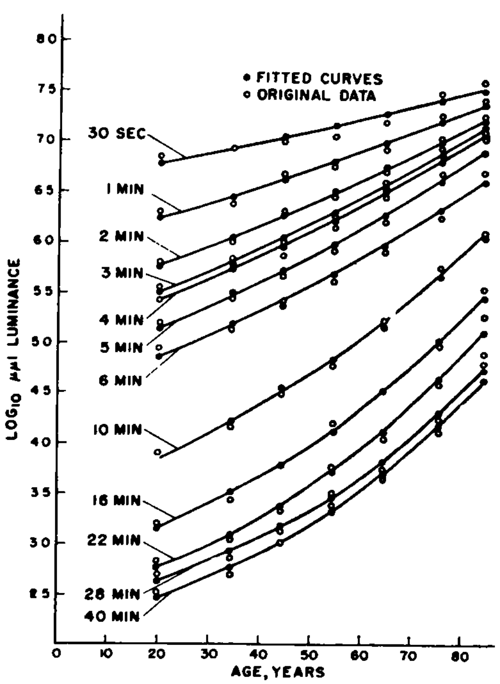

Figure 3. Comparison of the original data as shown in Figure 1 with the reconstructed data obtained from Model A. Model A is shown to fit the original data very closely.

were at the far end of the age range, no serious challenge to the efficiency of the derivation was found. The correspondence of the predicted mean curves with the obtained mean curves is unusually close—so close that one could be substituted for the other without effect on the interaction of the age-time co-variables in the dark adaptation phenomenon. For instance, test retest dark adaptation data often vary by a displacement of one-half of a log value. Model A fits the present data with far greater exactness.

Because the theoretical curves so closely resemble the original distributions, the model was considered valid for the obtained data. What remained was the need to test whether the model could be generalized; that is, extended to alternative independent samples. Test procedure 2 was designed to assist in evaluating this question.

Test Procedure 2.—A more rigid test of the generality of the equations would depend on demonstrating that the model derived from one sample predicted the performance of other independent samples. The present data were treated in the following way to enable approximating the execution of such a test.

The second test procedure was divided into two parts: (a) one part for cone data, and (b) one part for rod data. The reason for treating cones and rods independently was to demonstrate that the stability of the model was not dependent on the method of sampling.

TABLE 4

AGE GROUPS FOR MODEL B

Criterion Category (Cones) Decades	Test Category (Cones) Decades (1)	(2)	(3)
16-29[a]			
	30-39		
40-49			
		50-59	
60-69			
			70-79
80-89			

[a]The 16-19, 20-29 age groups were combined, hence the enlarged range, 16-29.

Test Procedure 2a for Cone Data.—The principle of testing the mathematical model by deriving the data from one group and then predicting the performance of a second independent group was modified in the following way. There were 8 age groups. They were assigned to two general classes: a criterion category, and a test category (Table 4).

TABLE 5

AGE GROUPS FOR MODEL C

Criterion Category (Rods) Decades	Test Category (Rods) Decades (1)	(2)	(3)
	16-29[a]		
30-39			
40-49			
50-59			
60-69			
		70-79	
			80-89

[a]The 16-19, 20-29 age groups were combined, hence the enlarged range, 16-29.

Then using only the data contained within the criterion group, a second model, Model B for cones, was derived independently from Model A. Therefore, there remained three independent test groups, the data from which did not enter into the construction of Model B, and thus could have in no way influenced the new Model. Special attention is called to the fact that the age ranges of the criterion groups are different from the age ranges of the test groups.

Test Procedure 2b for Rod Data.—In the procedure applied to rod data, the age groups were assigned to two categories, a criterion category and a test category, in the following way, as given in Table 5.

Then, using only the data contained within the criterion groups, that is, the middle 50 percent of the age range data, Model C for rods was constructed. There remained three independent test groups, all at the extremes of the age range distribution. The age category 16 to 29 contained 25 percent of the scores, and each of the age range categories, 70 to 79, and 80 to 89 contained 12.50 percent of the scores, respectively. Thus, one-half the data were used for deriving Model C for rods and half for test scores.

Once again there was no modification of the form of the model and practically no change in the coefficients and exponents larger than would be expected within rounding error (9).

It follows that Models B and C are virtually identical to Model A, not only in form but in coefficients and exponents as well. Since Model A fits the data with great fidelity so will Models B and C. Hence, Models B and C will predict the scores of their representative test groups, which are for the cone model the mean scores of age groups 30 to 39, 50 to 59, and 70 to 79, and which are for the rod model the means of the age groups 16 to 29, 70 to 79, and 80 to 89.

To demonstrate the similarity among Models A, B, and C, the curves for all ages at time intervals 30 sec, 2, 10, and 28 min have been calculated, using Models A, B, and C independently. Reproducing the entire range of curves for each model would be redundant, since any possible differences found among the models would remain constant, or approximately so, and thus would be as easily shown at one time interval as another. The graphic results are shown in Figure 4.

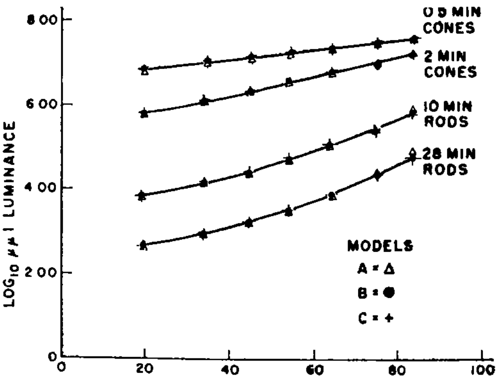

Figure 4. Comparisons of Models A, B, and C.

Rate of Dark Adaptation as a Function of Age

To simplify the mathematical technique in the following analysis, Model A has been used to derive rate of dark adaptation that would appear at the mean ages of 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 years. The original data, through the use of the model, have simply been extrapolated to ages 10, 90, and 100 years. Since all the mean ages exist within the boundaries of the model, no mathematical rule has been broken when these are substituted for the actual mean ages, which are 19.7, 34.2, 44.3, 54.2, 64.2, 75.5, and 83.9.

The equation of the cone curve was differentiated in order to obtain an equation for rate of dark adaptation. Thus,

$$R = \left(G^{(Ct)^{f_1(A)}} \right) \left(\frac{(Ct)^{f_1(A)}}{t} \right) f_1(A) \ln G \qquad (5)$$

The data for rate of dark adaptation at the 30th second and the 6th minute for mean ages 10, 20..., 100 years are given in Table 6 and shown in Figures 5 and 6. When the dark adaptation rate data were plotted as a function of age the resulting distributions were curvilinear.

Individual Prediction

However, measuring dark adaptation sensitivity near the asymptote of the function requires between 30 to 40 min. In situations where it would be highly desirable to examine and screen large numbers of persons a test of this length would be impractical. Therefore, a short test of dark adaptation predictive of thresholds near the asymptote was developed as recognition of the importance of this phenomenon has grown.

Intercorrelation Between Age and Dark Adaptation Threshold at the 40th Minute. —

TABLE 6

RATE OF DARK ADAPTATION

Mean Age	Log₁₀ μμl Luminance/Min — Time, 30 Sec	Log₁₀ μμl Luminance/Min — Time, 6 Min
10	-2.13237	-0.1241
20	-1.95500	-0.1208
30	-1.76747	-0.1166
40	-1.56913	-0.1114
50	-1.35980	-0.1051
60	-1.13860	-0.0973
70	-0.90500	-0.0881
80	-0.65833	-0.0769
90	-0.39790	-0.0636
100	-0.12346	-0.0480

Age was correlated with the dark adaptation threshold at each of 20 time intervals. To illustrate: age was correlated 0.71 with threshold sensitivity at the second minute of adaptation, 0.82 with the third, 0.80 with the fourth, etc. The greatest degree of correlation of threshold with age was 0.84 at the 37th and 40th min (Table 2). However, a correlation of 0.84, though indicating an extremely close relationship between age and dark adaptation threshold, was not considered to be adequate for predicting sensitivity thresholds for individuals.

Intercorrelations Among Dark Adaptation Thresholds.—Each dark adaptation threshold at each of 20 time intervals was correlated with all other thresholds. Since age was included as an independent variable the result was a 20 x 21 correlation matrix shown in Table 2. All correlations were highly significant. Table 2 shows that the range of intercorrelations of thresholds

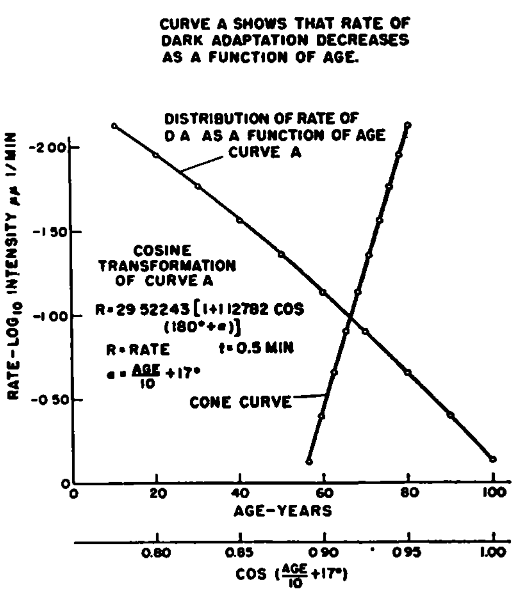

Figure 5. Rate of dark adaptation is shown to be inversely related to age at time 30 sec (cones). See extrapolation to age 5 and 100 years. The cosine transformation results in a straight line.

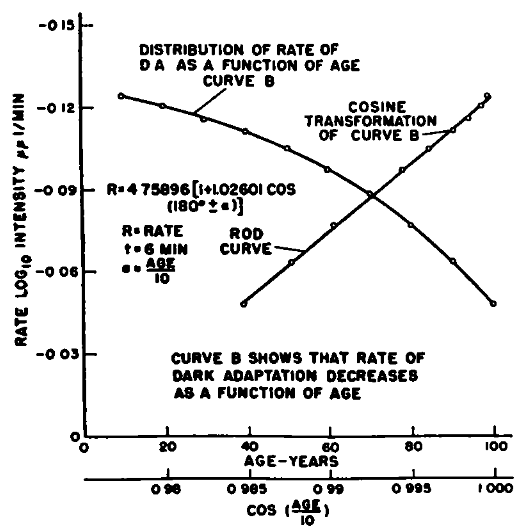

Figure 6. Rate of dark adaptation is shown to be inversely related to age at time 6 min (rods). See extrapolation to age 5 and 100 years. The cosine transformation results in a straight line.

was 0.69 to 0.99. The extremely high intercorrelation among thresholds, for example, at the 0.99 level, often was dependent upon the time relationships among thresholds. For instance, it would be expected that the thresholds obtained during the 14th minute would be highly correlated with thresholds taken at the 16th minute, and they were, merely because during that 2-min interval the dark adaptation thresholds changed very little. Nonetheless, the correlation between the 12th and the 40th minute threshold, far more remote in time, was also 0.90. This was large enough to permit individual predictions of the 40th minute threshold from knowledge of the 12th minute threshold alone, regardless of age. On the other hand, when the age variable was correlated with dark adaptation thresholds, the maximum amount of correlation was not high enough to permit predicting final thresholds for individuals.

The intercorrelation matrix shows the relationships among threshold or between age and thresholds at a given time. It does not show what the relationship would be were the intercorrelation of thresholds and the intercorrelation of thresholds and age statistically combined and handled simultaneously as conjugate variables. Theoretically, combining both variables should have resulted in increasing the predictive power of the data by a substantial margin. This was shown to be correct.

Multiple Correlations Among Age and Dark Adaptation Thresholds.—The development of a short test of dark adaptation depended on the degree to which age combined with several thresholds obtained during the first few minutes predicted thresholds remote in time. Since the dark adaptation process is nearly complete after 40 min, the thresholds at the 40th minute were arbitrarily selected as those remote in time to be predicted. Thus, threshold sensitivity at the 40th minute became the criterion.

Since the $S.D._{(est.)}$ as well as k, the coefficient of alienation (k equal to the square root of $1-r^2$ or R^2), increases rapidly as r or R decreases, the error of prediction for individual scores increases rapidly when r or R drops below 0.90. Therefore, the identification of the time interval conjoined with the age variable at which R reached at least 0.90 became the statistical objective.

In cumulative succession the thresholds obtained at time intervals 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 16, 19, 22, 25, 28, and 31 min were combined with the age variable. Then the multiple correlations were calculated from the regression equations for each of the age-time combinations. The results are given in Table 7 which also contains the coefficient of determination, r and R^2, the beta coefficient for the age variable, and the standard errors of estimate, $S.D._{(est.)}$.

Combining the threshold variables with age in cumulative succession resulted in a steady increase in the correlation with the criterion until at the 10th minute of dark adaptation r equal to 0.9074, the minimum value making individual predictions tenable, was reached. Thus, at the 10th minute age plus all the intervening thresholds correlated 0.91 with the criterion, that is, the threshold values at the 40th minute. Therefore, it is evident that a short test of dark adaptation could be administered in 13 min including 3 min of pre-exposure to the bleaching light plus 10 min of testing thresholds every minute from 2 through 10 min. The 3-min pre-exposure could be reduced somewhat if the intensity of the pre-exposure light was increased. However, the effect of changing the intensity of the bleaching light on the statistical relationships characteristic of the present data would have to be experimentally determined.

Application

The following illustrations will show in detail how the statistical procedure can be used advantageously.

The Prediction of Mean Threshold at the 40th Minute.—The general regression equation is as follows:

$$T40 = Bo + b1(A) + b2(t1) + b3(t2) \ldots bn\ (tn) \qquad (6)$$

in which

T40 = the criterion; the thresholds at the 40th minute—the predicted threshold value;

Bo = the unstandardized regression coefficient for the multiple R;

b1 = the unstandardized regression coefficient for age;
b2 = the unstandardized regression coefficient for threshold at time equal to 2 min;
b3 = the unstandardized regression coefficient for threshold at time equal to 3 min;
A = age; and
t = mean threshold at time x (Table 1).

TABLE 7

MULTIPLE CORRELATION OF AGE PLUS DARK ADAPTATION THRESHOLD FOR 17 SUCCESSIVE TIME INCREMENTS WITH 40th MINUTE THRESHOLDS, THE CRITERION

Variable Order	Variables Contained in the Multiple R	r	R	R^2	Beta	S.D. (est.)
1.	Age	0.8378		0.7020	0.84	0.48
2.	Age plus threshold at 2nd min		0.8498	0.7222		0.46
3.	and plus 3rd min		0.8577	0.7356		0.45
4.	and plus 4th min		0.8604	0.7403		0.45
5.	and plus 5th min		0.8612	0.7418		0.45
6.	and plus 6th min		0.8741	0.7641		0.43
7.	and plus 7th min		0.8797	0.7742		0.42
8.	and plus 8th min		0.8862	0.7854		0.41
9.	and plus 9th min		0.8960	0.8028		0.39
10.	and plus 10th min		0.9074	0.8234		0.37
11.	and plus 12th min		0.9173	0.8416		0.35
12.	and plus 14th min		0.9267	0.8589		0.33
13.	and plus 16th min		0.9412	0.8858		0.30
14.	and plus 19th min		0.9559	0.9138		0.26
15.	and plus 22nd min		0.9715	0.9439		0.21
16.	and plus 25th min		0.9811	0.9628		0.17
17.	and plus 28th min		0.9892	0.9787		0.12
18.	and plus 31st min		0.9946	0.9893		0.09

Note: Thresholds at each successive time level are added to the multiple correlation, R. Thus, by the 31st time interval, age has been combined with all intervening thresholds. All correlation values are significant beyond the 0.001 level.

It is well known that the regression equation predicts the mean exactly. Therefore, no specific calculations of mean thresholds will be made. The regression equation would predict that the mean threshold was 2.43 log μμl which was exactly the value obtained for the mean age of the group between 16 and 29 years, that is for mean age 19.7 years. For the subjects in the 50-59 age group, mean age 54.2, the predicted and obtained mean was 3.32 log μμl (Table 1).

However, the thresholds of individual subjects were distributed around the means of their respective age groups, as well as being distributed around the mean of the entire sample. Since the S.D.(est.) and k are not zero, then prediction of individual scores would be less accurate than the prediction of mean thresholds. However, holding to the criterion that R must be at least 0.90 before individual scores were predicted guaranteed that prediction of thresholds would be highly accurate. Of course, higher criteria increase accuracy still further. The second illustration will demonstrate the effectiveness of selecting a stringent criterion before attempting to predict individual scores.

The Prediction of Individual Thresholds at the 40th Minute.—In the second illustration the performance of an individual subject will be predicted. Each of the first 10 equations was solved independently to show the improvement in the predictions as the first 10 thresholds are successively added to the predictive equations. A naive subject, No. 241, who was not included in the sample, and therefore who was statistically independent from it, reported the thresholds shown in Table 8. The threshold obtained for each minute where the threshold to be predicted was 3.76 log μμl at the 40th minute is given, together with the predicted thresholds for the first 10 equations. Table 8 is read as follows: When age and the first threshold at the second minute were used in the regression equation, the threshold predicted for the 40th minute was 4.54 log μμl. When age plus the first 9 thresholds were utilized the equation predicted that the threshold at the 40th minute would be 4.08 log μμl. Since the obtained threshold was 3.76 log μμl the error was reduced to a negligible quantity. Thus, in this illustrative random case the regression equation was highly predictive. The error was less than ½ log μμl, or about the usual error expected between two tests on the same subject. The values for the final equation were T40 = 0.263568 + 0.0164337(82) +

TABLE 8

PREDICTION OF DARK ADAPTATION THRESHOLDS AT THE 40th MINUTE FOR AN INDIVIDUAL SUBJECT NO. 241, AGE 82

Threshold	2 (min)	3 (min)	4 (min)	5 (min)	6 (min)	7 (min)	8 (min)	9 (min)	10 (min)	12 (min)	40 (min)
Obtained	7.395	7.263	7.203	7.167	7.143	6.999	6.903	6.303	5.281	4.075	3.76
Predicted for time 40	4.54	4.52	4.54	4.55	4.71	4.72	4.82	4.64	4.08	3.42	-

0.0498(7.395) + 0.0127(7.263) + 0.0093(7.203) - 0.2727(7.167) + 0.1781(7.143) - 0.1245(6.999) - 0.1166(6.903) + 0.1808(6.303) + 0.5957(5.281) = 4.0798 μμl.

DISCUSSION

Those who have studied the relationship between age and dark adaptation or efficiency of night vision are not all in agreement with respect to the degree of the correlation (30), nor are all in accord concerning the significance of the association of aging and the process of dark adaptation. Negative correlations which ranged -0.25 and -0.31 have been reported (2). Other results have been reported by Birren, Bick, and Fox (3), McFarland and Fisher (21), Liljencrantz (19), Birren and Shock (4), Ives, Shilling, and Curley (11), Robertson (30), and Pinson (27). Pinson, however, stated that the relationship, although positive, was less than the range of individual differences and of minor significance. On the other hand, McFarland and Fisher (21), having obtained one of the highest correlations among physiological phenomena, state that the linear correlation is so high that it may be used to predict level of dark adaptation within the narrow limits of error.

Systematic data describing the decline of dark adaptation with age should provide one kind of index representing the aging process. For instance, it has been shown that the efficiency of dark adaptation varies as a function of anoxia (23), CO concentration (25), hypoglycemia (24), and vitamin A deficiency (14, 15). This evidence suggests that metabolism in the retina may resemble metabolism in the central nervous system. Thus, because the central nervous system depends on the oxidation of blood sugar, any reduction of this substance would decrease the rate of oxidation. In a parallel manner the aging process is thought to be associated with a progressive decrease in rate, amount, or other aspects of cerebral circulation and, therefore, interference with the transport or utilization of oxygen (16). It would follow, all else being equal, that as age increases there would be a progressive increase in the demand for light. Therefore, since aging is universal, considerable variation of dark adaptation efficiency is to be expected in the general population.

For instance, Boothby, Berkson, and Dunn (5), and Lewis, Duval, and Iliff (18) have all shown that oxygen comsumption per unit of surface area declines with age. It has been indicated by Shock (32) that age and metabolic rate are inversely related. Also, the dark adaptation threshold is directly influenced by oxygen deprivation.

Since it has been shown that dark adaptation threshold and age are directly related and that physiological processes of which dark adaptation is a function in turn are related to age, then it would be expected that rate of dark adaptation would also vary, that is, decrease as chronological age increases. However, experimental evidence for a change in rate of dark adaptation relative to age is insufficient. Thus, Friedenwald (11) stated that there was a positive correlation between age and rate of dark adaptation, but the evidence in the source he cited (10) was inadequate. In this presentation the data were given in table and graphic form but no statistical evidence showing that age and rate were correlated was included. Hammond and Lee (12) calculated that the correlation between age and an indirect measure of dark adaptation, that is, drop time, was correlated -0.06 with age. McFarland and Fisher (21) obtained a correlation of -0.13 with drop time and age. There values are no greater than chance would allow. Pinson's (27) findings are in the opposite direction, since he discovered that the area subtended by the dark adaptation curve for younger subjects was greater than the area subtended by the dark adaptation curve for older subjects.

Since the original individual scores obtained by Pinson were not included in the study, no independent statistical analysis could be devised to test his conclusion. Birren and Shock (4) have asserted that there is no correlation between age and rate of either cone or rod adaptation.

The review of the literature strongly suggested that evidence regarding the relationship of rate of dark adaptation and age is unclear. Therefore, the present study has tended to clarify the uncertainty in the literature and has added quantitative data toward the solution of the relationship between the thresholds and the rate of dark adaptation as a function of age.

Turning from theoretical consideration to the matter of interpreting these data the question of significance presents itself. The group was heterogeneous, and the results obtained suggest that the aging process introduced a very large decrement into these data. The mean value at the 40th minute of adaptation for the 80- to 89-yr group was $\log_{10}$ µµ1 I 4.805 (antilog = approx. 63,830), and the level of dark adaptation at the same time for teenagers between 16 to 19 years of age was 2.427 (antilog approximately equal to 267). This means that on the average the just noticeable light stimulus for the elderly group was 68,830/427, or approximately 239 times greater than the least stimulus noticed by teenagers after each group had nearly reached the 40th minute of adaptation. It would be expected that the difference between the first values obtained at 0 to 59 seconds would not be as great. This proved to be correct. For the youngest group the $\log_{10}$ µµ1 value for the first score was 6.929 (antilog = approx. 8,490,000) and the value for the elderly group was 7.617 (antilog = approx. 41,000). Thus, 41,400,000/8,490,000 is equal to a factor of about 4.88. Even at that moment immediately following the pre-exposure period teenagers, on the average, were able to perceive a just noticeable stimulus about 5 times less bright than were the average persons in the elderly group. Since these values were obtained from the means of the dark adaptation curves there were subjects in the younger group who fell below their mean, and subjects in the oldest group who fell above their mean. Therefore, the absolute differences between the most and the least efficient persons in the entire sample would be larger than the values indicated above.

It can be seen in Figure 1 that although the intersections of the cone and rod curves are independent of age because they all appear at approximately the same time they are not identical with respect to level of luminance present at the time the curves separate. It should be pointed out that the concept of a certain level of luminance above which cones function and below which rods function is valid only with respect to an individual dark adaptation curve. For instance, it is generally accepted that 0.01 millilamberts is the approximate degree of luminance at which cone and rod vision separate. But this does not represent the population at all. As a matter of fact in this study the approximate mean time at which the two curves separated was the 5th-6th minute of adaptation. But the mean level of luminance varied from 5.26 $\log_{10}$ $\mu\mu$l I for the 20-29 age group, to 7.075 $\log_{10}$ $\mu\mu$l I for the 80-89 age group at the intersection of the cone and rod curves for those two groups as shown in Table 1.

Another way of interpreting these data would be to compare the relative dark adaptation thresholds of the various age groups at different times. For instance, it requires 40 minutes for the most elderly group to develop the equivalent sensitivity characteristic of the youngest group at the 6-7th minute of adaptation. And dark adaptation at the 6-7th minute of adaptation is very limited regardless of the age of the viewer. In other words, youths achieve in 6 to 7 minutes of dark adaptation a level of sensitivity that is not reached by elderly persons in more than 6 times that amount of time. Even at the average age of 55 at the 40th minute of adaptation the viewer has no greater dark adaptation threshold than youths 16 to 29 years of age at the 15th minute of adaptation, some time before the final level of adaptation is approximated.

It is unlikely that either youths or elderly persons enter on tasks demanding the degree of sensitivity characteristic of their ultimate level of dark adaptation. There is little to be seen under the levels of luminance as low as between 2 and 5 $\log_{10}$ $\mu\mu$l I, except, of course, the perception of some light source itself. In some military operations (2, 12, 17, 19, 27) such as night wätch, dark adaptation is important for exactly this reason. Otherwise the viewer could function as well in total darkness for which no adaptation is necessary.

There are, however, other kinds of situations which may, by and large, be just as important and perhaps more so because of their ubiquity. Thus, old and young alike undertake tasks that require partial adaptation, for instance, the operation of transport equipment at night (1, 22, 20) under the conditions of intermittent, unpredictable changes of luminance. The range of luminance is quite great, and high enough to involve both the rod and cone cells of the retina (29). Therefore, the continuous process of bleaching and adaptation of the retina means that crossing over from rod to cone vision and vice versa is a common event. Rate of adaptation now becomes exceedingly important. But it is precisely in this region that certain types of inefficiency arise. The terminal level of adaptation of the cone cells almost defines the moment when 3-dimensional vision, acuity, and color vision become greatly limited, and the moment before the rod cells have generated any useful degree of sensitivity.

If these data are interpreted as baseline values for the age group and the experimental conditions under which they were obtained, then estimates of probable dark adaptation thresholds may be calculated directly from Tables 1 and 2.

For example, the probable 40th minute threshold of dark adaptation for an individual 85 years of age is shown in Table 1 to be 4.81 $\log_{10}$ $\mu\mu$l plus or minus 0.72. For a youth age 19.7 years a comparable level of dark adaptation sensitivity at the 40th minute is shown to be 2.43 $\log_{10}$ $\mu\mu$l plus or minus 0.17. The difference between the two individuals is statistically significant beyond the 0.001 level of confidence.

It is suggested that these data have practical applications. To illustrate: since age is so highly correlated with all dark adaptation thresholds, and since all dark adaptation thresholds are highly intercorrelated, the development of a short clinical test of dark adaptation is entirely feasible. Thus, the first few thresholds of dark adaptation as a function of age were shown to predict remote dark adaptation thresholds for individuals with great accuracy.

SUMMARY

In order to describe one family of dark adaptation curves obtained from an age sample of 240 men, ranging from 16 through 89 years, a mathematical model, Model A (Eq. 4), was derived.

Variation in rate of adaptation was determined by differentiating Eq. 5 at 30 seconds and 6 minutes.

It was determined that age is highly correlated with all dark adaptation thresholds which in turn are highly intercorrelated; the correlation between age and dark adaptation thresholds tends to increase as time in the dark increases; cone and rod thresholds are highly correlated; and the reduction in threshold and rate of dark adaptation in relation to age is very marked.

It was also demonstrated that a short clinical test of dark adaptation was entirely possible because thresholds obtained during the first few minutes of adaptation predicted dark adaptation sensitivity remote in time.

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