JOURNAL OF THE OPTICAL SOCIETY OF AMERICA VOLUME 43, NUMBER 6 JUNE, 1953

The Disappearance of Steadily Fixated Visual Test Objects*

LORRIN A. RIGGS, FLOYD RATLIFF,† JANET C. CORNSWEET, AND TOM N. CORNSWEET
Psychological Laboratory, Brown University, Providence, Rhode Island

(Received January 21, 1953)

A system has been devised for causing an image to remain at one point on the retina regardless of eye movements. A beam of light, reflected from a plane mirror on a contact lens, is used to project onto a screen an image of a dark line against a bright background. The screen is viewed by the same eye through an optical system which compensates for the doubling of the angle of rotation of the beam projected from the mirror on the contact lens. Thus, any motion of the eye causes a deviation of the beam such that the retinal image of the projected line undergoes the same displacement as do the retinal receptor cells. By comparison with normal viewing of the same test objects it is found that (1) when first presented, the finest lines are seen with normal or slightly better than normal acuity, (2) within a few seconds the lines begin to disappear, and (3) within one minute even coarse lines are seen only intermittently. The results may be interpreted in terms of local retinal adaptation to a stationary field.

INTRODUCTION

VISUAL acuity is usually measured by instructing the observer to look directly at a succession of dark test objects whose critical dimension is progressively reduced. The effects of diffraction, aberrations, and scatter are such that the retinal image of a dark test object is gray and blurred. Rays from a point source, as O'Brien[1] has shown, can never be so accurately directed as to stimulate a single retinal receptor element; nor can the image fail to stimulate by falling entirely between elements. Instead, the image of a fine black point or line results merely in a slight reduction in the illuminance on a number of receptor elements. Thus, resolution may be regarded as a special form of brightness discrimination,[2] in which relatively few receptor elements are involved. Conversely, the failure to resolve a fine line may result from the fact that the image of the line is not perceptibly less bright than the surrounding field.

Hecht[3] has pointed out that uniform stimulation of visual receptors should result in a photostationary state in which the processes of breakdown and restoration come into equilibrium with one another. This situation is approached when a person stares for a long time at a uniformly illuminated field, as when the head is surrounded by an integrating sphere or when light enters the eye by shining through closed eyelids. One often hears the comment after prolonged exposure to these conditions that the experience is like that of being blind or in darkness. Even the experience of watching a speaker in a dimly illuminated auditorium may lead to a "washing out" of the visual field. These familiar experiences, which may well be related to the establishment of a stationary state, are similar to some of the observations in the present experiments.

Hartline[4] has recorded the activity of single optic nerve fibers in the frog under conditions of prolonged stimulation. Some few fibers continued to respond over long intervals of steady stimulation by light (maintained discharge fibers) while the majority of fibers responded either to the onset and cessation of the light (on-off fibers) or to the cessation alone (off fibers). When a dark line was imaged upon the receptive field of a fiber of the on-off or off type no response occurred so long as the line remained stationary. A small movement of the line resulted, however, in the discharge of a few impulses. A large movement, particularly a rapid one, produced a burst of many impulses in rapid succession. In this case the line was found to have moved completely away from one set of receptor elements and onto a new set. Vigorous on and off responses have also been recorded by Granit[5] in the cat and other mammals. The human retina may also respond vigorously to motions of the retinal image.

Recent investigations[6,7] of normal eye movements have shown that under favorable conditions of fixation the eyes may be remarkably steady for short intervals of time. The limiting motion is a tremor whose angular extent is typically from 10 to 20 seconds of arc. The tremor appears to be aperiodic, but it includes wave-like motions whose frequencies range from 30 to 100 per second. Over longer intervals of time other types of eye movement occur. These include relatively large slow waves, saccades, and slow drifts of fixation. Any of these motions may amount to several minutes of arc, and they occur often enough so that they limit any attempt to fixate steadily for more than a second or two. In short, the eye is always in motion, and even the use of a fixation point fails to stabilize the retinal

* These experiments were conducted in the Psychological Laboratory at Brown University under contract with U. S. Office of Naval Research, Department of the Navy.

† Now at Harvard University, Cambridge, Massachusetts.

[1] B. O'Brien, J. Opt. Soc. Am. **41**, 882–894 (1951).

[2] S. Hecht and E. U. Mintz, J. Gen. Physiol. **22**, 593–612 (1938–39).

[3] S. Hecht, Physiol. Rev. **17**, 239–290 (1937).

[4] H. K. Hartline, Am. J. Physiol. **130**, 690–699 (1940).

[5] R. Granit, *Sensory Mechanisms of the Retina* (Oxford University Press, London, 1947).

[6] M. Lord and W. D. Wright, Repts. Progr. in Phys. **13**, 1–23 (1950).

[7] F. Ratliff and L. A. Riggs, J. Exptl. Psychol. **40**, 687–701 (1950).

image with respect to individual receptor cells except for very short flashes of light.

In a previous paper[8] one of us mentioned that "preliminary investigations have indicated that it may be possible, by means of a suitable optical arrangement to provide an image on the retina which is motionless with respect to the retina itself." The present paper reports the further development of this technique, together with the results of experiments on the effects of minimizing motion of the image across the retina on acuity for dark test objects. Independently, Ditchburn and Ginsborg[9] have devised a similar technique and have reported preliminary observations on differential adaptation effects. Observers in both experiments reported that the most striking subjective effect of immobilizing the retinal image is the rapid fading out and ultimate disappearance of contours within the test field. The present experiments reveal that this fading out is effectively reduced by normal eye movements and is practically abolished by movements of even greater extent.

APPARATUS

The principal function of the apparatus was to provide an image which would remain essentially motionless on the retina despite normal eye movements. To this end, a plastic contact lens was worn on the right eye of the subject as shown in Fig. 1A. Mounted on the contact lens was a high quality first-surface mirror situated at the temporal edge of the corneal bulge. In this location the mirror did not occlude the axial rays entering the pupil. A separate lens was fitted to each subject and optically corrected to give clear vision. The contact lens was fitted with the mirror by drilling a 4.76-mm (diameter) hole with an end milling tool. A circular mirror was ground down to a light press fit in the hole and sealed in by means of soft wax. The purpose of the mirror was to reflect the rays from a projector to a screen in front of the eye. The reflected rays formed an image of a test object on the screen. The subject viewed the screen through a compensating system, details of which will be described later. This system resulted in a retinal image which was essentially motionless with respect to the receptor cells.

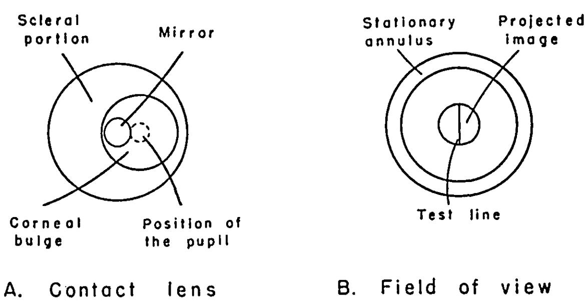

FIG. 1. A, The contact lens used in the present experiment. B, The appearance of the visual field.

[8] F. Ratliff, J. Exptl. Psychol. 43, 163–172 (1952).
[9] R. W. Ditchburn and B. L. Ginsborg, Nature **170**, 4314, 36–37 (1952).

The appearance of the visual field, as seen by the right eye of the observer, is shown in Fig. 1B.

The circular test field and fine lines were provided by a special slide projector and a set of fine wires of various diameters. Each of the wires used was mounted in a separate rigid steel slide, being stretched vertically across the center of a round aperture in the slide.

Rays from the projector formed an image of a wire and its bright circular background on a screen coated with magnesium oxide. The quality of the image was such that the edges of the vertical line were sharp and clear even when examined microscopically. Figure 2 shows schematically the arrangement used for projecting the image on the screen.

In order to provide a stationary fixation field, an auxiliary viewing device was inserted into the compensating path by the use of a thin plane of glass (microscope cover slip). By means of this arrangement an annular field was introduced; the annulus appeared to surround the projected test field as shown in Fig. 1B. The annulus had a luminance approximately equal to that of the projected image (five ft-L), an effective outer diameter of 67′ (visual angle) and an inner diameter of 52.5′. Each test object appeared at the approximate center of this annulus.

The actual distance from the eye (center of rotation) to the screen was 30 cm. The image was viewed, however, through a series of 90° reflecting prisms and a pair of dove prisms, in a compensating path such that the viewing distance from the screen to the eye was the optical equivalent of 60 cm in air.

CONDITIONS OF OBSERVATION

The subject viewed the test objects under three different conditions, which were designated as follows: Condition I, compensated; Condition II, normal; Condition III, exaggerated effects of eye movements.

Condition I

This condition is the one in which the image was "stopped" on the retina as shown in Fig. 2.

It may be seen in this figure that if the eye rotates through an angle α, the rays reflected to the screen are deviated through angle 2α. Owing to the compensating path, which doubles the distance from the screen, rays from the screen enter the eye at an angle α. In other words, the eye and the image move through the same angle and in the same direction, so that the image of the target is "stopped" on the retina. That is, the retinal image covers the same receptors regardless of eye movements. A pair of dove prisms was in fact present in the compensating path but they were set opposite one another and had no net effect on the directions of rays in Condition I. Compensation is for

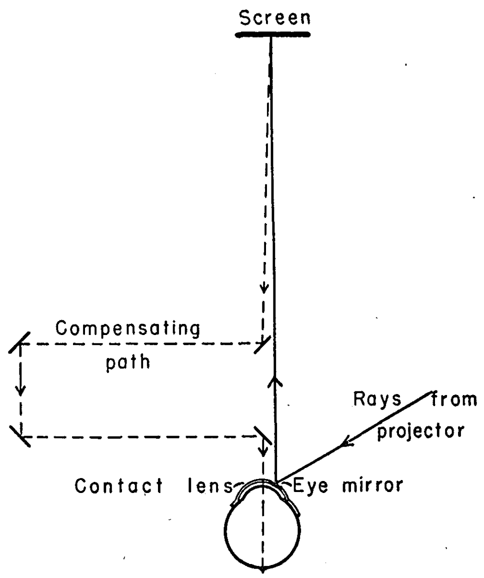

FIG. 2. Diagram of the method for counteracting the effects of eye movements. The viewing path is effectively double the distance from the eye to the screen. The compensating path includes two dove prisms and an arrangement for providing fixation at the center of a bright annular field.

movements in the horizontal plane; in other planes there is incomplete compensation because the mirror is not located on the vertical meridian of the eye. This is of little consequence, however, since horizontal motions are of primary significance in relation to vertical line targets. Slippage of the contact lens is a negligible factor for all small motions of the eye.[7] It becomes significant for large amplitudes beyond those encountered in steady fixation.

Condition II

This condition was one in which eye movements had their normal effect of moving the retinal image across the receptors. In this condition the subject wore the same contact lens with mirror as in Condition I but the rays from the projector were reflected not from the contact lens mirror but from a similar mirror mounted on a rigid support located near the eye. The optical viewing path is the same as that of Condition I. The target image therefore remains motionless with respect to the screen, and eye movements cause proportional excursions of the image across retinal receptors. The test objects are viewed with normal vision.[10]

Condition III

Two purposes were served by using this condition. In the first place, it provides double the amount of motion of the retinal image in normal vision (Condition II). In the second place, it provides a control experiment with which to compare Condition I, since the optical systems and procedure are nearly identical in the two cases. The only difference between Conditions I and III is that in the latter one of the dove prisms is rotated through an angle of 90°. This reverses the usual direction of rays from the screen to the eye. If now the eye moves through an angle α to the right, the rays from the screen enter the eye from an angle α to the left. The effect of this is an excursion of 2α of the image with respect to the retinal receptors.

Thus, any observed differences in results with Conditions I and III may be attributed to the exaggerated motions of the retinal image in Condition III as opposed to the stopping of the retinal image in Condition I.

[10] Strictly speaking, the measures of acuity for Conditions I and II are not exactly comparable because the images are reflected from different mirrors for the two conditions. Thus, the images may have been slightly different in quality or luminance.

GENERAL PROCEDURE

In all experiments the right eye alone was used and the left eye was occluded. The position of the head was fixed by the use of a biting board and the subject was instructed to maintain fixation on the center of the stationary annulus field.

The test object in each case was a fine black line forming a vertical diameter of the projected field of light (Fig. 1B). This diameter subtended an angle of 36′ at the eye. The widths of the various test lines subtended 93.3, 61.7, 46.4, 34.8, 31.9, 23.4, 21.0, 12.1, 8.1, 6.4, and 5.8 seconds of visual angle. The viewing conditions were the three discussed above, namely those in which motions of the retinal image were "compensated," "normal," and "exaggerated." In the first set of experiments, the test object was viewed for one full minute. In the second set, presentation was achieved by the use of brief flashes.

THE EFFECTS OF PROLONGED FIXATION

The purpose of this experiment was to determine how varying the amount of motion of the image across the retina affects vision during one minute of attempted steady fixation on the test object.

Procedure

In any single experimental session, the subject was first positioned so that the rays from the projector

TABLE I. Data on viewing the test objects for one full minute. Widths of line test object are in seconds of visual angle. Data are mean percentage of time during which test object is reported to be seen. In parentheses are the numbers of repetitions on which the means are based.

Line width (seconds of arc)	Subject LAR Condition I	II	III	Subject FR Condition I	II	III
34.8	60(4)			71(2)		
31.9	45(5)			60(4)		
23.4	28(4)	60(5)		56(4)	97(2)	
21.0	37(5)	68(4)		50(4)	88(4)	96(2)
12.1	16(5)	26(4)	99(5)	29(4)	42(3)	85(3)
8.1		7(5)	84(5)		4(4)	65(4)
6.4			58(2)			29(2)
5.8			47(5)			17(4)

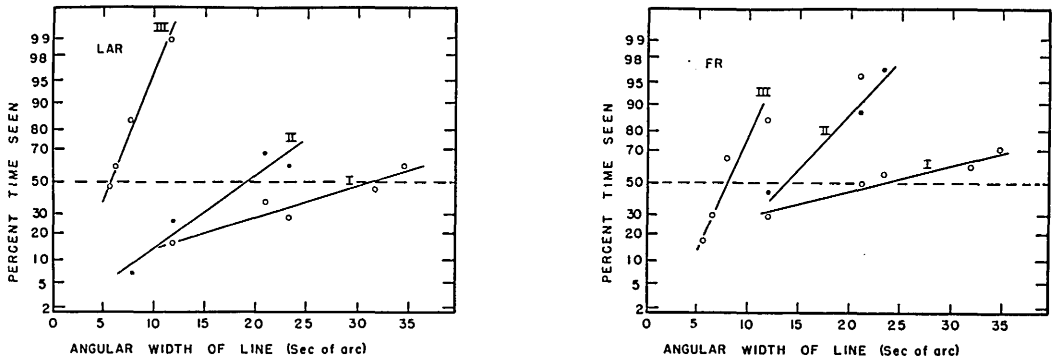

FIG. 3. Percent time seen as a function of width of line for one-minute exposures, subjects LAR and FR. Condition I is the condition in which the effects of eye movements were "compensated," Condition II "normal," and Condition III "exaggerated."

were reflected from his eye mirror to the screen at the region on which he was fixating (at the center of the annulus). Next, the projector was turned off for fifteen seconds and turned on again for a one minute exposure. The surfaces of the contact lens and mirror were cleaned, in the eye, before each change in viewing condition. The subject had a key which he held down during all of the time he was able to see the test line. He released the key during the time the line was not visible. A continuous photographic record was made on which appeared two signal traces. One of these indicated the time during which the projector was on. The other signal, actuated by the subject's key, indicated the time during which the subject was able to see the fine vertical line.

Data were obtained on target visibility as a function of time, and on the proportion of time over which a target of a given width was seen under each of the three experimental conditions. For each viewing condition, test object sizes were chosen so that time seen in the one minute interval approached 100 percent for the widest line and 0 percent for the narrowest line of the series. The orders of test object sizes and viewing conditions were varied at random from session to session. The numbers in parentheses in Table I indicate the number of one-minute exposures of each wire.

Results

The different effects of the three experimental conditions were immediately noticed by both of the subjects. In Condition I, the "compensated" condition, the black line target was clearly seen when it first appeared. The subject was surprised by the fact that the line was always at the center of the field regardless of eye movements. Soon, however, the line began to fade out. Finally it disappeared altogether, so that the projected image seemed to consist only of a bright circular field. Occassionally the bright field also disappeared; in these intervals the subject saw only the stationary annulus. A fine black line usually disappeared during the first few seconds of viewing, and failed to reappear later. Heavier lines took longer to disappear and often reappeared from time to time during one minute of steady fixation.

In Condition II, the "normal" condition, the fading of the image did occur for the fine lines, but the lines reappeared sporadically. Heavier lines seldom disappeared.

In the "exaggerated" condition, Condition III, there was scarcely any disappearance of even the finest lines. The impression was that the target was "locked in place" so that steady fixation was effortless, automatic. It may be noted that in this condition the usual cues for fixation are exaggerated. The eye muscles are

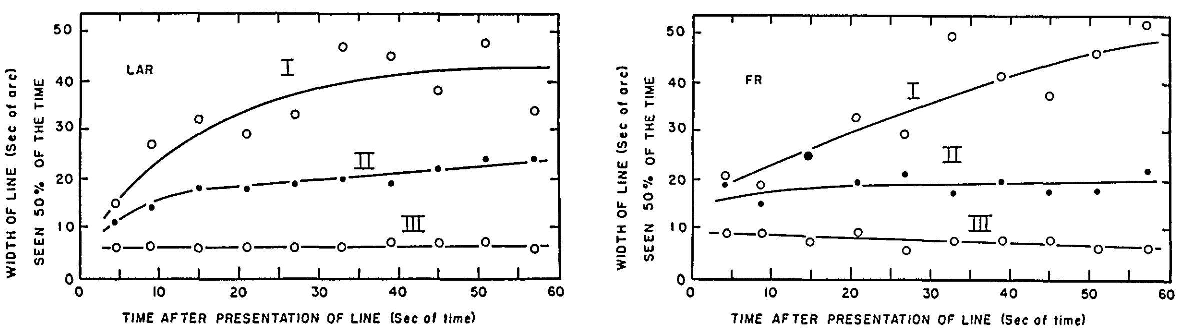

FIG. 4. Width of line seen 50 percent of the time during successive sections of the one-minute interval under viewing Conditions I, II, and III, subjects LAR and FR.

TABLE II. Data on short exposures of the test object. Data are percentage of flashes in which test object was reported seen. Subject LAR.

	Exposure duration (sec)											
	0.034 Condition			0.110 Condition			0.213 Condition			0.472 Condition		
Line width (Seconds of arc)	I	II	III	I	II	III	I	II	III	I	II	III
93.3	96	100	83	100	100	100	100	100	100	100	100	100
61.7	83	62	71									
46.4	50	38	42									
34.8	42	33	17	92	92	58	87	100	87	100	100	100
31.9	17	33	22	46	38	50	54	67	54	100	92	100
23.4	21	25	8	67	42	38	50	67	29	75	83	96
12.1	12	8	21	12	17	8	12	8	4	8	25	62
8.1	4	12	0	29	8	8	0	4	0	4	12	25
6.4	8	8	8									

provided with double the normal feedback from any drifting of the image away from optimal fixation.

In order to get quantitative evidence of the differences in vision produced by varying the amounts of retinal image movement, the 50 percent threshold width of test object was calculated for each condition. This is defined as the width of the line which can just be seen 50 percent of the time during the one minute exposure. These values for observer LAR are 31, 19, and 6 seconds of visual angle for the "compensated," "normal," and "exaggerated" conditions, respectively. Comparable values for observer FR are 24, 14, and 8 seconds of visual angle. These thresholds were determined by the following method. For each of the conditions, the percentage of time during which the dark line was seen was determined for each of the black-line test objects. These percentages, given in Table I, were plotted as a function of target width on arithmetic probability paper, test-object width being plotted on the linear axis as in Fig. 3. The abscissa values for the points at which the curves cross the 50 percent ordinate line are the 50 percent threshold values quoted above.

It is of further interest to determine the changes in threshold as the one minute interval progressed. To do this, the interval was divided into 10 sections of 6 seconds each. Each section was then treated as was the one minute interval above.[11] Thus the 50 percent threshold widths of line were determined for each condition for each six-second section, using probability plots. The thresholds so derived for each condition of viewing are plotted in Fig. 4. Here it is apparent that seeing deteriorates markedly with prolonged viewing in Condition I, where the motion of the image is minimized. With the exaggerated motion of Condition III no such deterioration occurs even at the end of a minute of steady fixation. The normal eye movements of Condition II result in intermediate amounts of fading out.

[11] The data from the first three seconds of each one-minute period were discarded because variations in the subjects' reaction time obscured the meaning of those data. The remainder of these six seconds was treated as the first section of the breakdown of the one-minute period.

THE EFFECTS OF SHORT EXPOSURES

Prolonged viewing of the test object has clearly been shown in the above experiments to benefit by the presence of normal or exaggerated eye movements. A stationary eye might well be capable of good resolution of fine detail, yet fail to maintain detail vision during prolonged fixation. In order to minimize the long-term deterioration of seeing, short exposures were used in some experiments now to be reported. Conditions were the same as those described above, with the exception that now the test object appeared only briefly, and the subject simply said "yes" or "no" to indicate whether or not he had seen the fine line during the flash.

Thresholds were determined with the short flash experiments by finding the widths of line seen 50 percent of the time under each condition of viewing and exposure. The viewing conditions used were "compensated," "normal," and "exaggerated," as discussed above. Four exposure times were used, as follows: 0.034 sec, 0.110 sec, 0.213 sec, and 0.472 sec. These exposures were achieved by the use of an Ilex photographic shutter located near the focal plane in the projected beam. The shutter was calibrated by the use of oscillographic recording.

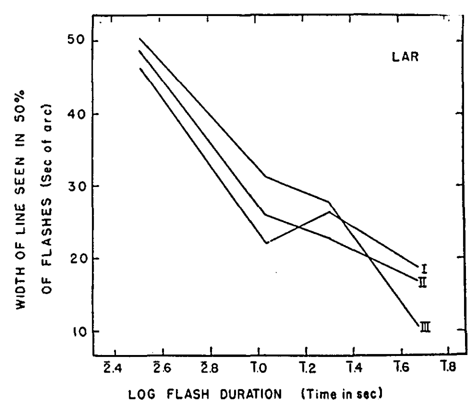

FIG. 5. Width of line seen in 50 percent of flashes as a function of flash duration under viewing Conditions I, II, and III, subject LAR.

Procedure

During any single session, the subject was aligned as before. Again the projector was turned off for 15 sec, after which time exposure flashes of a given duration were presented at 8-second intervals. The first series of exposures consisted of 6 exposures of each of 6 wire widths presented in random order. After the 36 exposures the subject rested, his contact lens and mirror was cleaned, and the order was repeated for 36 more exposures. During any one experimental session, the above procedure was followed for each of the three viewing conditions. Thus a total of 216 judgments were made in one experimental session, 72 judgments under each condition of viewing. Two such experimental sessions were run on separate days for each exposure time. The 432 judgments so obtained were composed of 24 judgments on each of 6 widths of line for each of three viewing conditions. Table II indicates the experimental design more completely.

Results

The data obtained on one subject in the short-flash experiments are shown in Table II. From plots of these results, 50 percent thresholds were determined for each condition for each exposure time. The resulting thresholds are represented in Fig. 5.

Figure 5 shows no striking differences for short flashes among the three experimental conditions. Consistently, however, the "compensated" image of Condition I yielded the best seeing for the shortest flashes. The "exaggerated" condition, III, begins to excel at exposure times beyond 0.2 sec. It is of interest to note that in all cases the intermediate Condition II yields results which lie between those of Conditions I and III.

DISCUSSION

The principal finding of the present experiments is certainly the demonstration that, with an essentially motionless retinal image, prolonged fixation results in the disappearance of objects from the field of view. The results are consistent with the theory that under uniform stimulation conditions each photoreceptor may attain a stationary state in which a minimum number of impulses are initiated in the retina. Conversely, the capacity of a receptor cell to initiate impulses is related to the time rate of change of the illumination falling upon it. The manner in which such changes in illumination occur is importantly related to the duration of exposure and the extent of eye movements.

With very short exposures (0.01 sec or under) the eye is essentially motionless. The typical extent of eye movements during 0.01 sec is less than 5 seconds of visual angle, the result primarily of the minute tremor (physiological nystagmus).[12] Each receptor receives a momentary change of illumination which is determined only by the intensity of light falling upon it. This intensity is obviously less for those receptors immediately covered by the dark lines of the retinal image as compared to those covered by the bright test field. With such short exposures, however, time and intensity of exposure are reciprocally related. Hence the differential responses of stimulated and unstimulated retinal elements might be expected to increase with exposure duration.

With somewhat longer exposures (0.01 to 0.10 sec) the product of intensity and time is increased. Eye movements are also of greater consequence, the typical movement during 0.10 sec being about 25 seconds of arc, approximately the diameter of a foveal cone. The data of the present experiments show that these eye movements interfere to some extent with visual acuity, and this result agrees with the earlier findings of Ratliff[8] on brief (0.075 sec) exposures of a grating type of test object. With these exposure times the eye gets but a single "look" at the target; there is not sufficient time for any fixational eye movement to occur after the exposure begins. Within this range of exposure times, the "compensated" image condition yields the best visual performance in the present experiments. In this condition the boundaries of the retinal image are fixed, so that all receptor cells within the dark image area are stimulated with less light than are those in the surrounding bright field. In the other two conditions, however, the motion of the retinal image may cause some of the receptors to lie within the image area for a part of the exposure and outside the image area for the remainder of the exposure. Since intensity and time are reciprocally related, this means that such receptors are stimulated more effectively than are those lying completely within the dark image area, but less effectively than those lying completely outside. Hence the net effect may be considered one of blurring the retinal image, with a resultant loss of visual acuity.

Exposure times from 0.10 to 0.50 sec exceed the "critical duration" below which there is reciprocity of intensity and time. During 0.50 sec the typical amount of eye movement is 2 minutes of arc. This means that any point on the image may sweep over several retinal receptor cells, causing each to undergo a large change in illumination. Corrective eye movements are also possible, since there is sufficient time for fixational movements to occur. It is within this range of exposure times that the relative standings of Conditions I and III are interchanged. Condition III, involving exaggerated movements of the image, yields more and more effective vision for exposure times beyond 0.20 sec. Condition I excels in exposures of shorter duration.

Exposure times longer than 0.50 sec involve eye movements of several minutes of arc in normal viewing.

[12] L. A. Riggs and J. C. Armington, Am. Psychologist 7, 252 (1952).

These eye movements, and even more those of double the normal amount in Condition III, clearly serve to maintain prolonged seeing. Hartline's experiment on the frog retina lends support to the idea that motion of the retinal image may serve to trigger "on" and "off" responses of individual retinal units.

The relationship of eye movements to visual acuity is evidently a complex matter. With short exposure times there is no doubt that eye movements are bad for acuity. For longer exposures, however, eye movements shift the acuity task from one set of receptors to another in rapid succession so that not all of the receptors at any one time have achieved a stationary state. A brief, but inadequate, summary of these points might be to the effect that eye movements are bad for acuity but good for overcoming the loss of vision due to uniform stimulation of the retinal receptors.

CONCLUSIONS

1. Vision is impaired under conditions such that the retinal image of an object remains essentially motionless with respect to the retina. During prolonged viewing under these conditions single-line test objects gradually disappear from view. The rate of disappearance is related to the angular width of the line.

2. Normal involuntary eye movements prevent the disappearance of test objects during long periods of observation. Exaggerated movements of the retinal image are even more effective in preventing the disappearance of images.

3. In the case of short exposures (less than 0.10 sec) of test objects, the above relations appear to be reversed. Vision is poorer under conditions of normal or exaggerated motion than under conditions of reduced motion of the retinal image.

JOURNAL OF THE OPTICAL SOCIETY OF AMERICA VOLUME 43, NUMBER 6 JUNE, 1953

A Comparison of the MacAdam and the Adams-Nickerson Indexes of Color Differences

G. W. INGLE AND L. RUDICK*
Plastics Division, Monsanto Chemical Company, Springfield, Massachusetts
(Received October 28, 1952)

A simplified version of the MacAdam equation for color difference is presented. It is used in comparison with the Adams-Nickerson index for hypothetical colors in C. I. E. space and for colors of selected plastic samples. The two indexes disagree seriously except when the color difference involves differences in only one, and the same, chromaticity coordinate. Visual estimates of color differences shown by plastic samples show preferential agreement with the MacAdam index. The suggestion is made that this simplified MacAdam formula be given wider trial.

INTRODUCTION

INTEREST in color difference measurement and specification is increasing rapidly. An important part of this interest lies in those industries where an index of color difference could be used as a reliable measure of quality expressed as resistance to color change in manufacture or in performance. This seems particularly true in plastics and paint technologies.

Among existing formulas for color-difference, the Adams-Nickerson equation seems the most popular. Presumably this arises from its useful balance of tolerable accuracy and relative simplicity. But when applied to the wide range of colors commonly obtained in plastics, especially those outside the relatively low purity core of Munsell colors on which this method is based, the question of its adequacy becomes a real one. Its limited accuracy has been recognized.[1]

Unlike this technique and others based on Munsell color order, the MacAdam experimental data on perceptibility of color differences, throughout the C.I.E. color solid, offer an entirely different basis for computing color difference. Requiring no conformance with an uniform chromaticity scale system, and applicable to all colors in the established C.I.E. color space, this technique is deserving of wider use. Davidson's recent work in this connection is appreciated.[2]

I. SIMPLIFIED MACADAM EQUATION FOR COLOR DIFFERENCE

In either of its given forms including the following, the MacAdam equation for the noticeability of a color-difference, in multiples of the standard deviation of color-matching ΔS, is not distinguished by its simplicity:

$$\Delta S^2 = g_{11}\Delta x^2 + 2g_{12}\Delta x\Delta y + g_{22}\Delta y^2 + 2g_{23}'\Delta y\Delta Y + g_{33}'\Delta Y^2 + 2g_{13}'\Delta x\Delta Y.$$

If we neglect the two terms concerned with the declination of the luminance axis, since their coefficients g_{23}' and g_{13}' are generally small compared with the others, and are not available in comparable precision

* Present address, Technical Director, Krieger Color and Chemical Company, Hollywood, California.

[1] E. A. Stearns, Am. Dyst. Reporter 40, 563–574 (1951).

[2] H. R. Davidson, J. Opt. Soc. Am. 41, 1052–1056 (1951).