VISUAL ACUITY AND ILLUMINATION IN DIFFERENT SPECTRAL REGIONS

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I

INTRODUCTION AND PROCEDURE

It has long been known that visual acuity increases with the illumination (Uhthoff, 1886, Koenig, 1897). A precise study of this function with white light (Shlaer, 1937) has shown that the data fall into two distinct functions, one at intensities below about 0.1 photon, and the other at intensities above that. This separation is understandable in terms of the duplicity theory.

Because of the different sensibilities of the rods and cones in the spectrum, it is to be expected that the short wave end of the spectrum will give the greatest separation between the rod and cone functions, that the long wave end will give practically a pure cone function, and that the intermediate spectral regions will give intermediate separations. Such a situation has already been found in intensity discrimination, flicker, dark adaptation, and is indicated in Koenig's (1897) visual acuity data (Hecht, 1937). We therefore determined to measure the relation between visual acuity and illumination in lights of different restricted spectral regions, using the same two test objects as in the previous study with white light. These were a broken circle (C) with the break equal to the width of the line forming the circle and one-fifth its outside diameter, and a grating having opaque and transparent bars of equal size. Because visual acuity measurements are extremely difficult and tedious to make, and because the intermediate spectral regions give results of but secondary importance, most of the measurements to be presented here were made with only the two extremes of the visible spectrum, the red and the blue.

The apparatus we used has already been described in detail (Shlaer, 1937). It consists essentially of a device in which the test object is presented at a fixed distance of 1 meter from the eye in the center of a uniform field about 30° in diameter, and is viewed through an artificial pupil. The size of the test object may be changed continuously over a 1 to 100 range by means of a variable focus projection system, while the illumination is varied in small steps by means of neutral filters. The neutral filters were calibrated in light transmitted by the color filters, using a Koenig Martens photometer. The heterochromatic density of the color filters was determined by comparison with similar filters calibrated by Hecht and Smith and used in the flicker investigation by Hecht and Shlaer (1936).

The procedure was for the most part as already described. The subject was first completely dark adapted. His visual acuity was then determined at the lowest intensity possible after he had become completely adapted to that field brightness. The intensity was then raised a suitable amount and the measurement repeated after the subject had again become adapted to the new brightness. This was continued till a little more than half the complete intensity range had been covered. The very next day measurements were begun a little below the highest point reached in the previous session and carried to the end of the intensity range. In this way exceptional fatigue of the observer was avoided, while the overlapping points of the two consecutive sessions gave assurance that no change in the sensitivity of the observer had occurred. Other differences from the previously described procedure will be noted below in the relevant sections.

Measurements were made with the right eye of E.L.S. and of A.M.C., while S.S. was the manipulator. E.L.S. and A.M.C. had served as observers in the previous study with white light.

II

Results with the C Test Object

Measurements with the C as test object were made with light of two different spectral regions: (1) that transmitted by Eastman Kodak Wratten filter No. 70 (the color is red of dominant wavelength 670 mμ), and (2) that transmitted by Wratten filter No. 75 and Corning filter No. 428 (the color is blue of dominant wavelength 490 mμ). Filter 75 was chosen in preference to 76 (violet, of dominant wavelength 450 mμ) because its visual density is much lower, enabling maximal visual acuities to be attained, while the displacement of the rod and cone sections of the data is nearly the same as that produced by violet light. A fixed pupil of 2 mm. diameter was used for both.

The Corning filter served two purposes. It absorbed the small amount of red light transmitted by the blue Wratten filter, and was ground to be a lens of −1 diopter (focal length of 1 meter). The latter overcomes the difficulty of the emmetropic eye in focusing the test object in blue light because of chromatic aberration.[1]

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[1] This phenomenon may be simply demonstrated by means of the "monochromat" series of Wratten filters of Eastman Kodak Company. If one looks through these filters at some distant object, one finds that fine detail is readily perceived through all but filters 75 (blue) and 76 (violet). With these a lens of about −1 diopter at once restores the sharpness of vision.

The data are given in Table I. Each datum is the average of determinations made in two different complete runs. Those in black type represent measurements in subjectively colorless fields. The data of columns 2 and 5 are shown in Fig. 1 and those of columns 3 and 6 in Fig. 2. To separate the measurements, the data for red light are plotted 0.5 log units lower on the log visual acuity axis.

TABLE I

Visual Acuity and Illumination, C Test Object

The bold faced numbers represent determinations with peripheral vision in a subjectively colorless field; the italic numbers, with parafoveal vision in a colored field; and the rest, with foveal vision in a colored field.

Red (λ = 670 mμ)			Blue (λ = 490 mμ)		
Log *I* in photons	Log visual acuity		Log *I* in photons	Log visual acuity	
	A.M.C.	E.L.S.		A.M.C.	E.L.S.
1	2	3	4	5	6
−1.875	−1.434	−1.481	−3.865	**−1.468**	
−1.546	−1.192	−1.304	−3.392	**−1.181**	**−1.363**
−1.243	−0.954	−1.055	−3.084	**−1.067**	**−1.233**
−0.841	−0.657	−0.715	−2.785	**−0.949**	**−1.108**
−0.522	−0.435	−0.468	−2.269	**−0.824**	**−0.885**
−0.219	−0.269	−0.314	−1.961	**−0.782**	**−0.778**
0.193	−0.104	−0.121	−1.662	**−0.734**	**−0.708**
0.512	0.018	0.016	−1.317	*−0.649*	**−0.654**
0.815	0.118	0.108	−1.009	*−0.564*	*−0.563*
1.147	0.213	0.199	−1.009		−0.653
1.466	0.258	0.251	−0.710	*−0.482*	*−0.446*
2.086	0.302	0.324	−0.710	−0.720	−0.520
2.718	0.328	0.353	−0.273	*−0.377*	*−0.270*
3.439	0.364	0.370	−0.273	−0.460	−0.310
4.154	0.374	0.387	0.035	*−0.278*	*−0.126*
4.776	0.381	0.400	0.035	−0.316	−0.148
			0.334	−0.140	−0.002
			0.759	0.019	0.144
			1.068	0.118	0.215
			1.367	0.212	0.267
			1.883		0.321
			2.191	0.302	
			2.490		0.389
			2.835	0.347	
			3.143		0.403
			3.442	0.371	
			3.879		0.410
			4.187	0.389	
			4.486	0.402	0.411

It can be seen from these figures that the data with blue light fall into two distinct curves, one (for the rods) at low intensities of illumination and one (for the cones) at the higher intensities. The data with red light fall into a single continuous curve with the possible exception of the first point at the very lowest intensity.

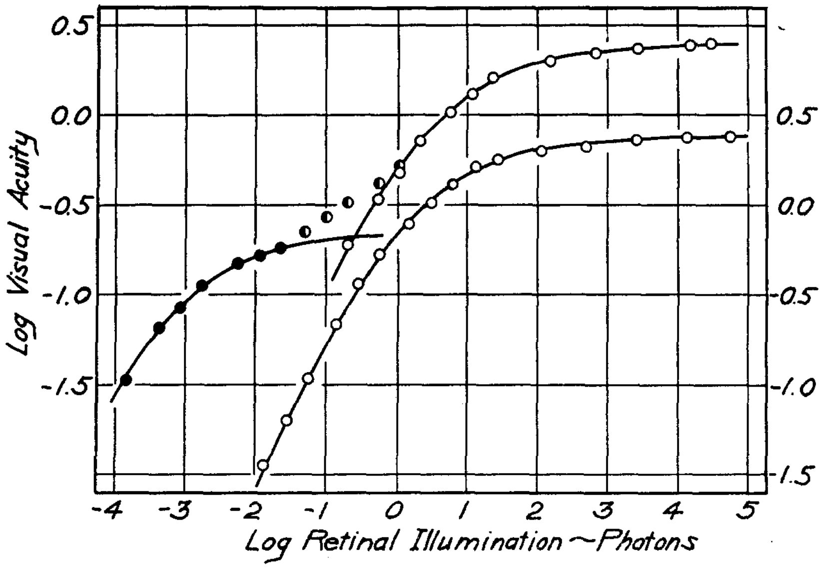

FIG. 1. The data of A. M. C. with the C test object from Table I, columns 2 and 5. The lower data (ordinates at the right) are with red light. The upper data (ordinates at the left) are with blue light. The filled circles are the measurements made with the periphery in a subjectively colorless field and represent pure rod function. The half-filled circles are the measurements made with the parafovea in a subjectively colored field and represent combined rod and cone function. All other circles are measurements made with the fovea and represent pure cone function. The curves drawn through both the rod and cone data are of equation (1) where $m = n = 2$ and visual acuity is proportional to x^n.

The curves drawn through all the cone data are theoretical and are the same ones previously drawn through the cone data with white light. These curves are graphs of Hecht's (1937) stationary state equation for the photoreceptor process:

$$KI = x^n / (a - x)^m \tag{1}$$

where I is the intensity of illumination, $(a - x)$ is the concentration of photoproducts, m and n are the orders of the photochemical and thermal reactions respectively, and K is a constant. In the form used here, visual acuity is proportional to x^n while m and n are both 2. Because the rod data obtained with blue light are more extensive, a more critical selection of the theoretical curve is possible. In these figures the curves drawn through the rod data are the same ones drawn through all the cone data.

Comparison with Fig. 1 of the earlier work with white light (Shlaer, 1937) shows that the rod function in blue light is situated about 1.5 log units lower on the intensity axis than in white light. This is in accordance with expectation and is similar to the behavior of other visual functions (see review by Hecht, 1937). The intensity scale is, by definition, that of the cones. Because the spectral sensibility of the rods lies further towards the blue end of the spectrum than does that of the cones, a blue light of a given cone intensity will have a greater brightness to the rods than a white light having the same cone intensity. This is the familiar Purkinje phenomenon. Therefore any visual function of the rods dependent on intensity will be shifted to lower intensities on a cone brightness scale when the short wave end of the spectrum is used.

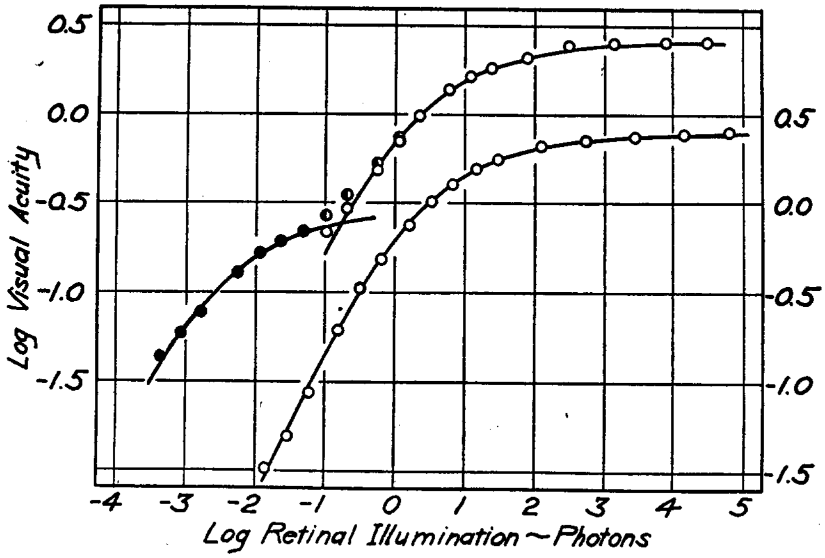

FIG. 2. The data of E.L.S. with the C test object from Table I, columns 3 and 6. The symbols and curves are as in Fig. 1.

With white light there exists an intensity range at the beginning of the cone function where foveal fixation of the test object gives lower visual acuities than parafoveal fixation (Shlaer, 1937). This was ascribed to the behavior of parafoveal cones.

We have now studied this phenomenon somewhat more fully by determining at each intensity of this region the visual acuity first with the more sensitive parafoveal region, and then with foveal fixation. The former values appear in italics in the table and in half-filled circles in the figures.

It will be seen that this phenomenon is present in the measurements made with blue light, but is entirely absent in those made with red light. This must mean that those values of visual acuity that lie above the curves at the transition region are mediated by both rods and cones. For if they were due only to the parafoveal cones, they should appear also in the red light data; moreover, if they were due only to the rods, then these points should appear at the same intensity above the rod threshold in both the white and blue light data. This demands that these points lie about 1.5 log units lower on the intensity axis (cone scale) since that is the amount that the rod curve has been shifted in blue light as compared to its position in white light. Neither of the above two conditions obtain in these data; on the contrary, these points appear only at the region of transition from rod to cone function. It is therefore clear that these points are the result of the cooperative activity of both the rods which are near their maximal activity and the cones whose activity is just becoming apparent.

It has long been known that the brightness of a field may be the result of simultaneous activity of both rods and cones. Thus the luminosity function determined at certain intermediate intensities is intermediate between the bright (cone) function and the dim (rod) function (Koenig, 1891). However, this is the first time, we believe, that an increase in a visual function dependent on brightness has been demonstrated to take place when both rods and cones act simultaneously.

III

Results with the Grating Test Object

The measurements with the grating in colored light were made under somewhat different conditions than in white light. Because the colored filters reduce the illumination by a factor of 100 or even 1000, the ground glass sources used with white light were removed and the apparatus was used as for the C so that sufficient brightness for maximum visual acuities was available. The small central dot used previously as a plane-finding fixation mark served adequately at high intensities but was quite invisible at low ones. To overcome this deficiency a ring of 62 mm. outside diameter and 7.5 mm. wall thickness was mounted on the field lens. Such a ring is visible at the lowest intensities used.

It was shown (Shlaer, 1937) that for grating resolution a pupil less than 2.3 mm. in diameter is the limiting factor at maximal brightness in white light. This limitation is the result of two factors. (1) A repetitive pattern such as the grating gives rise to diffracted spectra in the plane of the pupil. For every point in the source there is formed an undeviated and undiffracted image (zero order spectrum) to both sides of which lie the different higher order spectra in which the deviation is proportional to the wavelength. (2) For a lens to form a true image of such a repetitive object it must be large enough to transmit the entire diffraction pattern formed by it (Abbe, 1873). As the lens aperture is made smaller and smaller the image becomes poorer and poorer until, when only the zero order spectrum alone is transmitted, no discernible pattern at all can be detected in the image plane. For the human eye in white light the pupil need be only large enough to transmit the zero order spectrum and most of one first order spectrum in order that the retina be able to resolve the image. Since the red end of a diffraction spectrum is furthest from the undiffracted source image, it follows that a larger pupil is necessary to achieve maximum visual acuity in red light than in any other colored or white light. It will be shown below that a diameter of 3 mm. is more than adequate to eliminate the pupil as a limiting factor even for red light. For this reason the relation of visual acuity and illumination was determined with both a 2 and 3 mm. pupil in red light and with only a 2 mm. pupil in blue light.

TABLE II

Visual Acuity and Illumination, Grating Test Object

The bold faced numbers represent determinations made in a subjectively colorless field.

Red (λ = 670 mμ) 2 mm. pupil			Red (λ = 670 mμ) 3 mm. pupil			Blue (λ =490 mμ) 2 mm. pupil		
Log I in photons	Log visual acuity		Log I* in photons	Log visual acuity		Log I in photons	Log visual acuity	
	A.M.C.	E.L.S.		A.M.C.	E.L.S.		A.M.C.	E.L.S.
1	2	3	4	5	6	7	8	9
−1.546		−0.818	−1.210	−0.440	−0.650	−3.392	**−0.982**	**−1.007**
−1.243	−0.566	−0.652	−0.907	−0.313	−0.501	−3.084	**−0.906**	**−0.900**
−0.841	−0.372	−0.383	−0.505	−0.154	−0.377	−2.786	**−0.832**	**−0.836**
−0.522	−0.226	−0.193	−0.186	−0.073	−0.225	−2.269	**−0.764**	**−0.738**
−0.219	−0.106	−0.118	0.117	0.015	−0.138	−1.961	**−0.665**	**−0.649**
0.193	−0.012	−0.025	0.529	0.092	−0.017	−1.662	**−0.615**	**−0.610**
0.512			0.848	0.129	0.046	−1.317	−0.517	−0.476
0.815	0.075	0.081	1.151	0.172	0.111	−1.009	−0.401	−0.336
1.466	0.137	0.140	1.802	0.215	0.197	−0.710	−0.314	−0.223
2.086	0.162	0.167	2.422	0.263	0.254	−0.273	−0.185	−0.131
2.718	0.179	0.195	3.054	0.300	0.308	0.035	−0.101	−0.064
3.439	0.192	0.209	3.775	0.320	0.318	0.334	−0.017	−0.009
4.154	0.200					0.759	0.077	0.076
						1.367	0.145	0.151
						2.191	0.192	0.206
						2.835	0.234	0.254
						3.442	0.262	0.286
						4.187	0.261	0.289

*The values of log I in this column are those of column 4 to which the value 0.336 has been added. The added value represents the logarithm of the ratio of the effective pupil areas; *i. e.*, the actual areas corrected for effectiveness from the data of Stiles and Crawford (1933). The difference between the effective and actual area ratios is small, the logarithm of the latter being 0.352.

The data are given in Table II. Each value of log visual acuity represents the average of determinations obtained in three complete runs with the exception of the initial value of column 3 which is the average of only two runs. As with the white light data, it is possible to plot the observations of both observers on the same grid and to fit them with one curve. The only exception is the data of column 6. These data were taken during an interval shortly after E.L.S. recovered from a severe cold. The result is that the entire curve is shifted about 0.5 log units higher on the intensity axis as compared to his previous and also subsequent data, as well as compared to the data of A.M.C. in column 5. For this reason all of these data are plotted 0.5 log units lower on the intensity axis than given by the table.

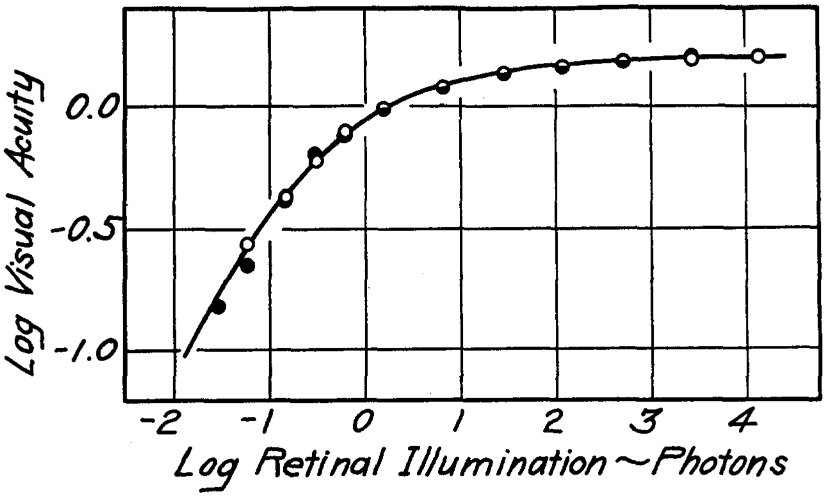

FIG. 3. The data of both observers with the grating test object, red light, and a pupil of 2 mm. diameter. The unfilled circles are for A.M.C. from Table II, column 2. The filled circles are for E.L.S. from Table II, column 3. The curve drawn through these data is of equation (1) where $m = n = 2$ and visual acuity is proportional to x^n.

The data with red light and a 2 mm. pupil are plotted in Fig. 3; those with red light and a 3 mm. pupil in Fig. 4; and those with blue light in Fig. 5. The curve drawn through the data of Fig. 3 is theoretical and is the same one drawn through the cone data with white light; that drawn through the data of Fig. 4 and through the cone data of Fig. 5 is of the same equation but of half the slope as that in Fig. 3. The rod data of Fig. 5 appear about one log unit lower on the intensity axis as compared to those of white light, but are still too scanty to permit of any critical curve fitting.

It will be recalled that the white light grating data were adequately described by the same equation that described the C data, namely,

$$KI = x^n / (a - x)^m \tag{1}$$

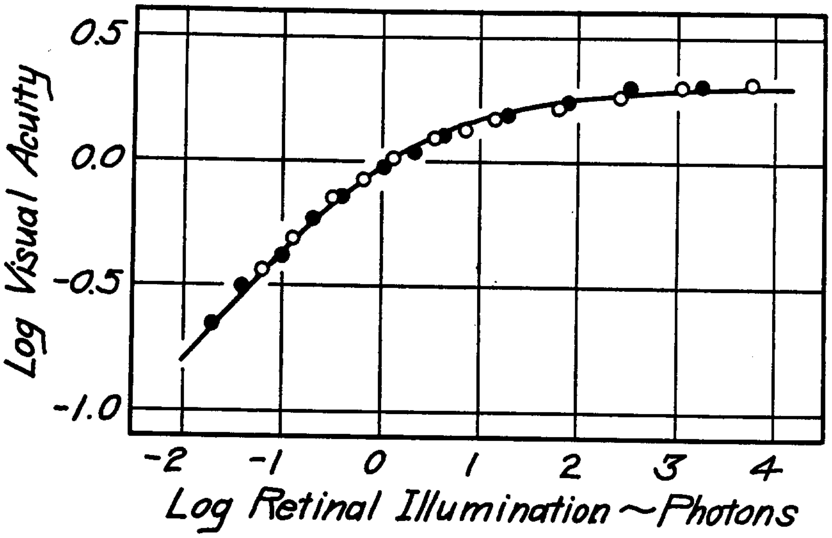

FIG. 4. The data of both observers with the grating test object, red light, and a pupil of 3 mm. diameter. The unfilled circles are for A.M.C. from Table II, column 5. The filled circles are for E.L.S. from Table II, column 6, but plotted 0.5 log units lower on the intensity axis than given in the table (see text). The curve drawn through the data is of equation (1) where $m = n = 2$ and visual acuity is proportional to x.

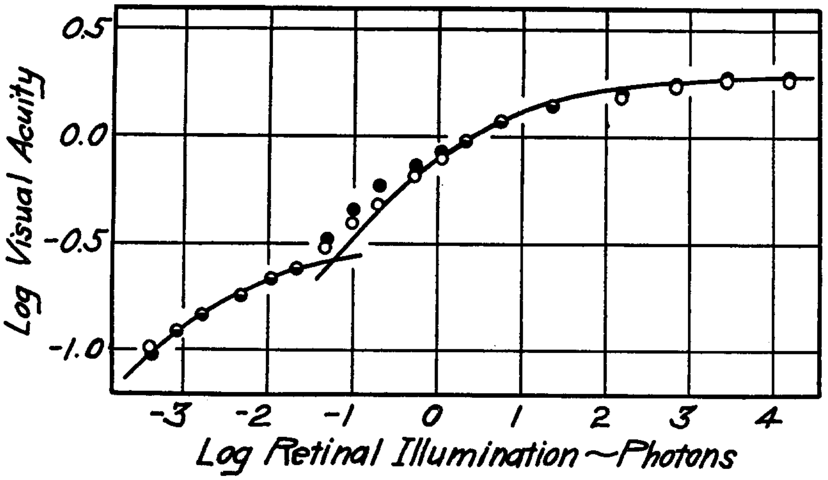

FIG. 5. The data of both observers with the grating test object, blue light, and a pupil of 2 mm. diameter. The unfilled circles are for A.M.C. from Table II, column 8. The filled circles are for E.L.S. from Table II, column 9. All the data below a log I value of -1.5 were made in a subjectively colorless field and represent pure rod function; those made at higher intensities were made in a colored field. The curves drawn through both sections of the data are of equation (1) where $m = n = 2$ and visual acuity is proportional to x.

where both m and n are 2, and visual acuity is proportional to x^n. These data were taken under conditions where the pupil size was the limiting factor for visual acuity. The data in Fig. 3, where the 2 mm. pupil lowers the maximum visual acuity even more because of the red light, are also adequately described by the same equation. However, when the pupil diameter is eliminated as a limiting factor, as in the data of Fig. 4, this form of the equation is quite inadequate. The best fit to these data was given by the form of this equation where both m and n are again 2 but where visual acuity is proportional to x instead of to x^n. Since n is 2, it means that the latter curve has half the slope of the former.

It is difficult to believe that the difference in pupil size can have such a profound effect on the entire course of this relationship. It may be that the small pupil affects only the upper part of the data where the visual acuity values approach the limit set by it. Perhaps the explanation of this apparent effect lies along the following lines. The graphs of the various forms of equation (1) may be arbitrarily divided for convenience into an initial rising straight line portion, and an upper turning-off to an asymptote. Since the visual acuity range of the grating data is quite small, the first characteristic is a relatively poorer criterion than the second which then is practically the dominant one in curve fitting. If the limiting pupil affects only the higher visual acuity values, the data would turn off to an asymptote more sharply, giving a good fit with the steeper curve. This is clearly shown in Fig. 6 where the data for A.M.C. with the two different pupils in red light are plotted together, those with the 2 mm. pupil being moved slightly to the right on the intensity axis to bring the lower parts of the two curves into superposition.

Visual acuity is, by definition, a measure of angular separation. Essentially, a linear distance is measured. The two test objects used in this investigation differ with respect to the resolvable areas involved. In the broken circle the area is a function of the square of the separation since both dimensions of the gap change simultaneously, while in the grating the area is a linear function of the separation since the length remains constant. If area is the important variable in detail perception, then the relation of visual acuity (a distance measure) to illumination should be twice as steep for the grating as for the broken circle. The previous data with white light (Shlaer, 1937) seemed to show that this relationship of visual acuity and illumination was the same for both test objects. The conclusion was then drawn that detail perception was a function of linear distance rather than of area. However, if the foregoing interpretation of the red light data is correct and it is accepted that the relation of visual acuity to illumination is half as steep for the grating as for the broken circle, then the previously drawn conclusion must be invalid.

The curve drawn through the blue cone data in Fig. 5 is the same as the one drawn through the red 3 mm. pupil data in Fig. 4. The first three points of the colored field data in Fig. 5 lie above the theoretical cone curve. This may, perhaps, mean that here, as with the C, there is a cooperation between rods and cones to produce a higher visual function than does either alone, the one log unit shift in the rod curve produced by blue light being essential to bring this out.

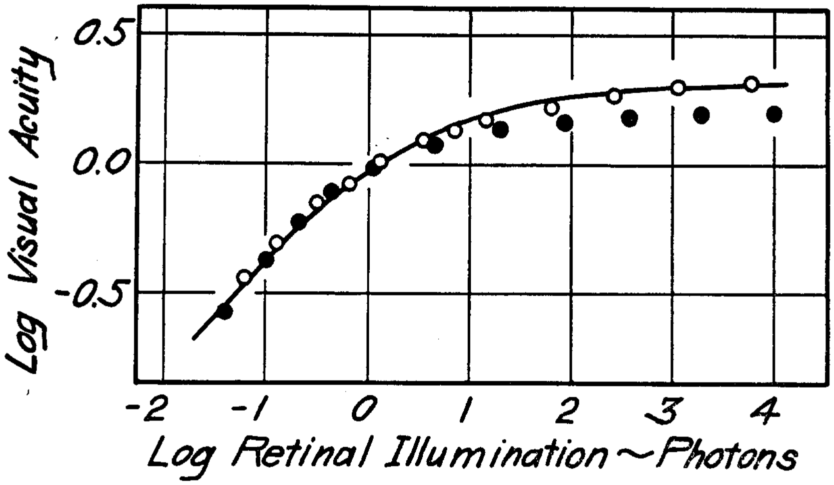

FIG. 6. The data of A.M.C. with the grating test object and red light, showing the effect of a limiting pupil upon the relation between visual acuity and illumination. The filled circles are from Table II, column 2, where the 2 mm. pupil limits the maximum visual acuity attainable. The unfilled circles are from Table II, column 5, where the 3 mm. pupil is no longer limiting. The curve drawn in this figure is of equation (1) where $m = n = 2$ and visual acuity is proportional to x.

IV

Factors Limiting Maximum Visual Acuity[2]

It can be seen from the data already presented that at intensities above about 1000 photons the illumination is no longer a controlling factor for visual acuity. What then does set the limit to the resolving power of the eye? Hartridge (1922) advocated intensity discrimination of the retina as the limiting factor in the resolving power of the eye. He argued that because of the chromatic aberration of the eye and of the diffraction of the light by the pupil, the image of small objects on the retina is very diffuse, and that unless the object is large enough to produce at least a 10 per cent reduction in intensity on a retinal element, it could not be resolved. This question might perhaps best be discussed separately for each of two types of test object: (1) a repetitive pattern such as the grating, and (2) a single object such as the C.

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[2] The data of this section were presented to the April, 1939, meetings of the American Physiological Society at Toronto, Canada. *Am. J. Physiol.*, 1939, **126**, 627.

1. *The Grating.*—It was previously shown (Shlaer, 1937) that the intensity discrimination of the retina in the image of a grating composed of equal opaque and clear spaces could not be the limiting factor; that the pupil diameter, if small enough, could be; and that the size of the central cones was the probable ultimate limiting factor. The grating test object diffracts the light from each point of the source into a series of spectra in the same manner that ordinary diffraction gratings do, but to a smaller extent because of its coarseness. These spectra lie in the plane of the pupil. If the pupil is not large enough to transmit the zero order spectrum and one first order spectrum up to a wavelength of about 630 mμ in white light, no resolvable image is formed on the retina. It follows that when restricted regions of the spectrum are used in making these determinations, the long wavelength regions will require larger pupils to achieve maximum visual acuities, since the red end of the spectrum lies farther from the zero order spectrum.

TABLE III

The Effect of Color on the Resolving Power of the Eye. Grating Test Object. Pupil Diameter 2.35 Mm. Average of Both Observers

Color λ in mμ	Red 670	Red 625	Orange 605	Yellow 575	White	Green 535	Blue 490	Violet 450
Visual acuity	1.80	1.91	1.99	2.08	2.10	2.14	2.11	2.07
	Pupil diameter 3 mm.	Pupil diameter necessary to raise the red (670 mμ) value to maximum is 2.8 mm. Such a pupil transmits the first order spectrum up to a λ of 750 mμ at maximum visual acuity.						
Visual acuity	2.09							

This corollary was verified in the following manner. With a fixed pupil of 2.35 mm. diameter, just large enough to achieve maximal values in white light, the maximum visual acuity for each observer was determined in light filtered through each of the seven "monochromat" filters of Eastman Kodak Company in turn.[3] The illumination in every case was so high that it was no longer a factor. The data are presented in Table III, each value of visual acuity being the average of all determinations of both observers. Each determination is the average of eight readings, two in each of the four different meridians used with the grating, and was made at least twice and on different days for each observer. It can be seen at a glance that the expected reduction in visual acuity at the red end of the spectrum is realized. Maximum values are not achieved in light of longer wavelength than the yellow ($\lambda = 575$ mμ).

The maximum visual acuity in the extreme red ($\lambda = 670$ mμ) is only 1.8, a loss of about 15 per cent from the average maximum of 2.1 when the pupil is not limiting. Since maximum visual acuity is directly proportional to pupil

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[3] The authors are indebted to Dr. Joseph Mandelbaum, who assisted in recording some of these measurements.

diameter when it is limiting, it follows that an increase in the pupil of 15 per cent would eliminate it as the limiting factor. Such a pupil is 2.8 mm. in diameter. Using a pupil of 3 mm. diameter, we found the maximum visual acuity to be 2.09, which is experimentally the same as the expected 2.1.

With white light (tungsten of color temperature about 2700° K) a pupil of 2.3 mm. gave maximal visual acuities. Under these conditions the pupil transmits the first order spectrum to about 630 $m\mu$. One may consider that when the excluded portion of the spectrum fails to interfere optically with certain transmitted radiation, an equivalent brightness is spread over the dark lines in the retinal image and thus lowers the contrast. However, the deterioration of the image on the retina by the exclusion of all wavelengths longer than 630 $m\mu$ is just not enough to lower the resolving power of the eye as set by the size of the retinal mosaic and the intensity discrimination ability of the cones. When the red filter, which absorbs all light shorter than 640 $m\mu$, is used, a pupil of 2.35 mm. gives a maximum visual acuity of 1.8 and under these conditions the first order spectrum up to a wavelength of about 750 $m\mu$ is transmitted. The same amount of the spectrum is transmitted when the pupil is 2.8 mm. and visual acuity is maximal at 2.1. It therefore seems that for the normal eye in tungsten light filtered through the Eastman Wratten filter No. 70, the long wave limit of useful light is at 750 $m\mu$.

2. *The C*—The fact that the relationship between visual acuity and illumination when the C is the test object is identical with the relationship between intensity discrimination and illumination is suggestive that perhaps Hartridge's notion is valid for single objects. However, the difficulty of computing the precise distribution of light in the image of the C prevents a quantitative evaluation of this idea.

This led Hecht and Mintz (1939) to investigate this relationship with a single line as a test object. They found that the intensity difference in the retinal image of their test object, as computed from the diffraction of a 3 mm. pupil, was directly proportional to the size of the line (and therefore to the visual acuity) for the entire cone range; and that the minimum difference that a single row of cones can detect was of the order of 1 per cent, which is very nearly the best intensity discrimination of which the retina is capable. They concluded that for their test object the intensity discrimination capabilities of the retina at all intensities determine the visual acuity, and suggested that perhaps the same might be true for all single objects such as the hook and broken circle.

It follows that when the visual acuity of the eye is controlled by the intensity discrimination of the retina, any increase in the intensity difference in the retinal image will result in a rise in visual acuity. Such increases in the contrast can be produced by two means: (1) homogeneous light which eliminates chromatic fringes in the image, and (2) an increase in the pupil diameter which decreases the diameter of the diffraction circle. Preliminary rough measurements showed this to be true. A 4 μ wire at 1 meter cannot be seen in white light with a 2 mm. pupil, but can be seen in monochromatic light with a 2.3 mm. pupil.

The effect of improving the retinal image of the C by the above means was then determined. The data are presented in Table IV. Each value of visual acuity is the average of four successive readings and all values in each horizontal row were taken at one continuous sitting. It is apparent that no improvement in visual acuity results from either monochromatic light or a 3 mm. pupil or both. Therefore, the intensity discrimination of the retina is probably not the limiting factor for the C at maximal intensities.

A better indication that at the higher intensities the situation with the C is not similar to that with the wire is given by the following experiment. A half-silvered mirror was mounted behind the field lens (F.L. in the apparatus diagram, Fig. 1, Shlaer, 1937), as viewed by the observer, and at 45° to the optic axis of the instrument. An auxiliary lamp, lens, and neutral wedge were then mounted at right angles to the optic axis of the instrument so that an image of the auxiliary source was formed at the pupil of the instrument by means of the auxiliary and field lenses. The illumination of the center field as viewed by the observer through the pupil consisted of two superimposed parts, one from each of the two sources. By diaphragming opposite halves of each of these two beams at the mirror it became possible to adjust the brightness of them to equality in a photometric match by means of the wedge. The brightness of the central field when these half field diaphragms were removed consisted of two equal parts, one from the regular instrument and the other from the auxiliary equipment.

TABLE IV

The Effect of Pupil Diameter and Color on the Resolving Power of the Eye. C Test Object

λ (mμ)	670—Red		575—Yellow		White		490—Blue	
Pupil diameter, *mm.*	2	3	2	3	2	3	2	3
Visual acuity	2.56				2.54		2.56	
(E. L. S.)	2.56	2.51			2.55	2.56	2.52	2.48
Visual acuity	2.78		2.76		2.78		2.79	
(A. M. C.)	2.76	2.73			2.78	2.79		

When a test object is inserted in the regular manner and viewed through the pupil, it becomes equivalent to having a test object whose brightness, instead of being zero, is exactly one-half the total field brightness. In other words, it is like a test chart in which the letters are printed in light grey ink having a reflection factor of one-half that of the white card background. In the retinal image this is equivalent to reducing the intensity discrimination fraction by somewhat more than half. Suppose that the situation on the retina when only the main instrument light is on is as follows: the intensity on a cone in the general field is 50, the intensity on a cone in the image of the circle is 40, and the intensity on a cone in the image of the break in the circle is 45. The discrimination ratio between the break and the rest of the circle is 5 parts in 40. When the auxiliary lamp is turned on, the intensity of the field becomes 100; that of the circle, 90; and that of the break, 95. The ratio now is 5 parts in 90 which is less than half the previous fraction. The smaller the discrimination fraction, the nearer the second ratio is to half the first.

If maximal visual acuity at the highest intensities is determined by intensity discrimination for the C as it is for the single line, then the maximum visual acuity should fall to half when this half-field-brightness test object is used. An examination of the data in the first two lines of Table V will show that such is not the case, a maximum drop of only 12 per cent having occurred. Each datum of Table V is the average of four successive determinations, and the data in each column were taken during a single continuous sitting.

TABLE V

The Effect of Diluting the Contrast of the Test Object on the Resolving Power of the Eye. C Test Object

Color	Test object brightness as per cent of field	Pupil diameter	E. L. S.				A. M. C.	
			Visual acuity	Loss in visual acuity	Visual acuity	Loss in visual acuity	Visual acuity	Loss in visual acuity
		mm.		*per cent*		*per cent*		*per cent*
White	0	2	2.59	0.0	2.62	0.0	2.59	0.0
White	50	2	2.39	7.7	2.31	11.8	2.24	9.7
White	50	3			2.31	11.8		
Blue	50	2	2.39	7.7	2.31	11.8		
Yellow	50	2	2.47	4.6	2.33	11.1		
Yellow	50	3	2.46	5.0	2.46	6.1		

When a drop in maximal visual acuity occurs as a result of the diluted test object, visual acuity must be limited by the intensity discrimination of the retina. The visual acuity should then be improved by the same two means, namely, homogeneous light and a larger pupil, that improve the resolution of the eye for a wire. The lower portion of Table V records the effect of these two variables. These measurements were made with only E.L.S. as observer on 2 different days. It is apparent that the larger pupil alone is without effect, that monochromatic blue light alone is also without effect, but that the combination of monochromatic yellow light and large pupil has a large effect, raising the visual acuity almost half way to normal. The measurements with yellow light and the small pupil are inconsistent for the two runs, the effect being large in the first and small in the second. These measurements are not extensive enough to permit the determination of any precise relationship, but they are adequate to show that maximal visual acuity with the C test object can be improved by means of homogeneous light and a larger pupil when the intensity discrimination of the retina is the limiting factor.

It must be emphasized that the experiments in this section are concerned only with maximal visual acuity where the illumination is so high that it is no longer a factor. It is certain that under these conditions something other than the intensity discrimination of the retina is the limiting factor. This factor may very well be the diameter of the foveal cones since the geometric size of the break in the C is only a little smaller than that. What may be the controlling factor or factors at submaximal values of visual acuity is still uncertain.

V

SUMMARY

The relation between visual acuity and illumination was measured in red and blue light, using a broken circle or C and a grating as test objects.

The red light data fall on single continuous curves representing pure cone vision. The blue light data fall on two distinct curves with a transition at about 0.03 photons. Values below this intensity represent pure rod vision. Those immediately above represent the cooperative activity of rods and cones, and yield higher visual acuities than either. Pure cone vision in this intensity region is given by central fixation (C test object). All the rest of the values above this transition region represent pure cone vision. In blue light the rod data with the C lie about 1.5 log units lower on the intensity axis (cone scale) than they do in white light, while with the grating they lie about 1.0 log unit lower than in white light.

Both the pure rod and cone data with the C test object are precisely described by one form of the stationary state equation. With the grating test object and a non-limiting pupil, the pure rod and cone data are described by another form of the same equation in which the curve is half as steep. The introduction of a small pupil, which limits maximum visual acuity, makes the relation between visual acuity and illumination appear steeper.

Determinations of maximum visual acuities under a variety of conditions show that for the grating the pupil has to be larger, the longer the wavelength of the light, in order for the pupil not to be the limiting factor.

Similar measurements with the C show that when intensity discrimination at the retina is experimentally made the limiting factor in resolution, visual acuity is improved by conditions designed to increase image contrast. However, intensity discrimination cannot be the limiting factor for the ordinary test object resolution because the conditions designed to improve image

contrast do not improve maximum visual acuity, while those which reduce image contrast do not produce proportional reductions of visual acuity.

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