REFLEX VISUAL SENSATIONS AND ANOMALOUS TRICHROMATISM

By W. A. Anderson, B.Sc.

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SYNOPSIS.

SECTION 1. INTRODUCTION.

This contains a brief summary of the principle of reflex visual sensations as discovered by Allen. The author, whose vision is somewhat abnormal, sets out to determine the character of these reflexes for his abnormal vision.

SECTION 11. APPARATUS AND METHODS OF MEASUREMENT.

All experiments were performed in a daylight room, using the critical frequency of flicker method. The results, which are quantitative, were obtained by making measurements on pure spectral colors.

SECTION 111. NORMAL CURVES.

Abnormal vision is shown by the character of the persistency curve, taken under normal conditions of daylight adaptation. The type of curve, which was found to be the same for both eyes, is compared with one for normal vision and one for partial red color blindness.

SECTION 1V. REFLEX CURVES.

This contains the descriptions and results of experiments carried out by fatiguing the left eye and making measurements of the changes in the visual response of the right to light from the different parts of the spectrum.

The nature of any change in the response was always found to be an enhancement of brightness of the affected colors. Red and green were found to be more susceptible to this reflex enhancement than the violet. Certain colors, .660µ, .505µ, .425µ, and the entire region .520µ to 480µ, showed no reflex transferred to the other eye. The magnitude of the reflex was greatest for fatiguing colors near the ends of the spectrum. The effect of dark adaptation was also transferred to the other eye similarly to fatigue.

SECTION V. FATIGUE CURVES.

This contains descriptions and results of experiments in which the measurements were made on the fatigued eye, the other being always in daylight adaptation.

It was found that the red sensation was very difficult to fatigue, but very susceptible to enhancement. The violet showed the reverse character, and the green an intermediate position. No effect was obtained for fatigue colors, .665µ, .589µ, .570µ, and only a small effect for .520µ. The effects of darkness and strong white light are very similar, both showing fatigue characteristics.

SECTION VI. THE THEORETICAL CONSIDERATIONS.

The experimental results show that every ray of light produces both a direct and a reflex effect upon all three fundamental sensations, which are shown to be red, green, and violet. The author's type of color vision is shown to be that of an anomalous trichromat, and experimental evidence is applied to give a fuller meaning to the phenomenon as well as to explain it. The principle of visual reflexes is applied to the Young-Helmholtz and Hering theories to show that the two can no longer be regarded as rival theories, but can be harmonized by this principle.

1

INTRODUCTION

In recent investigations by Allen[1], abundant experimental evidence has been brought forth establishing a new principle of color vision, the application of which to the Young-Helmholtz theory offers simple and satisfactory explanations of many of the phenomena of color perception, which were admittedly inexplicable on the basis of the trichromatic theory.

His results show that the effect of fatiguing a given area of one retina with any spectral color, except an equilibrium one, is to lower the luminous response of that area to colors corresponding to the sensations directly affected by the fatiguing stimulus, and to enhance its response to colors, exciting chiefly the complementary sensations. However, when the colors are

[1] J.O.S.A & R.S.1, 7 p.583; 1923

received upon a portion of the retina adjoining the fatigued area,[2] or by the retina of the other eye, the physiological luminosity of the entire spectrum is enhanced. Thus the conclusion is drawn, that every ray of light produces two effects, a direct and a reflex. In the stimulated area of the retina, the direct action fatigues either one or two of the fundamental sensations, according as the color stimulus is simple of compound in its nature; the reflex effect enhances the luminous response of the remaining complementary sensations. It is further concluded that the reflex is transferred to the adjoining areas of the same retina, and also to the other eye, in such a way as to enhance all three sensations.

The author of this paper set out to repeat some of these observations but immediately discovered, from the character of his normal persistency curve, that his perception of light and color is somewhat abnormal. It was therefore of interest to determine the character of these direct and reflex actions of light for one of abnormal vision.

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APPARATUS AND METHODS OF OBSERVATION.

The apparatus used and the method adopted was, in most respects, the same as that employed by Allen.

[2] J.O.S.A. & R.S.1, 7, p.913; 1923.

For the purpose of measurement the apparatus was essentially the same as that originally devised by E. L. Nichols.[3] The source of light was an acetylene flame, for which the gas was supplied at a constant pressure. The light was focused upon the slit of the collimator of a Hilger spectrometer, fitted with four prisms equivalent to three of sixty degrees each. This gave a spectrum of considerable dispersion, narrow strips of which could be isolated in a shutter eyepiece. Between the acetylene flame and the condensing lens an aluminium disk with two opposite open sectors of ninety degrees each was rotated. The speed of rotation, which was regulated by means of a brake, was electrically recorded upon a chronograph. The gas flame was enclosed on all sides, except the top, in a wooden box fitted with a small glass window which transmitted the light to the spectrometer. This box served two purposes, first, in preventing air currents, produced by the rotating disk, from affecting the flame, and second, in shielding the light from the observer's eyes. The spectrometer was properly screened from all extraneous light, and a shield, closely fitting about the eye, was attached to the eyepiece, thus enabling all measurements to be made under exactly the same conditions.

The spectrum used for fatiguing the eye, in the case of nearly all the reflex and also for some of the fatigue curves, was obtained from an arc light by

3. E. L. Nichols, Am. Jour. Sci. 28; 1884.

means of a two-prism Browning spectrometer. A narrow but quite long rectangular patch of the spectrum was isolated by the shutter eyepiece. The spectrum was so intense that the colors in the middle portions of it approached whiteness in appearance. For the majority of the fatigue curves a constant deviation Hilger spectrometer was employed to furnish the fatiguing color. With this instrument the source of light for the blue and violet was always the electric arc, and for the remainder of the fatiguing colors, sometimes the arc was used, and at other times an incandescent bulb, which produced a red of about the same intensity as that of the arc spectrum. The use of the Hilger spectrometer and incandescent bulb made a more convenient arrangement of the apparatus, enabling measurements to be made within a few seconds after removing the eye from the fatiguing color.

While fatiguing one eye, or making measurements, which was always done with the right, the unused eye was directed at a neutral grey surface about ten inches away. Sometimes, when recording observations on the dim ends of the spectrum, the left eye was closed for a few seconds, which did not exceed half a minute. No difference could be detected in the time of the critical frequency of flicker, as recorded for the brighter parts of the spectrum when the left eye was closed for a few seconds, and it was assumed that the time was unaffected for the dim colors.

All the apparatus was mounted in a room well illuminated with daylight. Measurements were not attempted if it was too cloudy or dull or towards sunset, and never with artificial lighting, for Allen has shown that dim light and darkness tend to obscure the reflex action of light.

The rotating sectored disk produced a flickering sensation in the isolated patch of the spectrum, due to the rapid succession of equal intervals of color and darkness. After adjusting the speed of the motor until the flicker was just imperceptible, the chronograph was started, and while the record was being made, which required about half a minute, the speed of the disk was varied slightly, keeping the flicker just on the point of appearing and disappearing. At least two independent records, representing the time of 120 to 400 revolutions of the disk, were made for each point, and if these did not show good agreement more readings were taken. So constant were the conditions, that the independent records gave values for the duration of a single flash, at the critical frequency of flicker, with a variation seldom greater than 0.0002 sec., except for points in the dim ends of the spectrum. The values used in plotting points in the bright parts of the spectrum were means of usually two or three imdependant measurements, and for the extreme violet and red the mean of about four readings was taken.

These experiments stretched over an interval of about fifteen months, most of the work being done, however, during the first three and the last five months. The curves were not necessarily taken in the order presented in this paper, although nearly all of the reflex curves were completed during the first three months and before any fatigue curves were attempted.

III

NORMAL CURVES.

In making measurements for a normal curve, the following procedure was adopted. The spectr~~um~~eter was set so that the shutter eyepiece isolated a narrow rectangular patch of the spectrum, the mean wave length of which was known. The spectral color was observed by the right eye, while the speed of the disk was regulated to give the critical frequency, which was then recorded. Care was taken to fixate the color directly, and to prevent the eye from wandering while judging the point of critical frequency. The eye was then rested for a minute or two, and a second chronographic record made on the same portion of the spectrum. Between the measurements made on different points in the spectrum the eye was rested in the diffuse daylight of the room for from five to ten minutes, according to the brightness of the spectral color. Since the spectrum, upon which all measurements were made, was not very brilliant, and the time required to record one reading about half a minute, the eye was not likely to become appreciably fatigued. In this way, observations were made on fifteen or more points of the spectrum.

The persistency curves, obtained by plotting wave lengths as abscissae and the persistence of vision as ordinates, show that the duration of these light impulses varies as some inverse function of the luminosity of the color observed. It was discovered by Ferry,[4] and subsequently in another manner by Porter,[5] that the duration of the sensation of undiminshed brightness of a flash of light, at the critical frequency of flicker, depends only on the luminosity of the light and in no way on the wave length. The Ferry-Porter law, as it is known, is represented by the equation, $D = \frac{1}{k \log L + k_1}$ where D is the persistence of vision, L the luminosity, and k and k_1 two constants. According to this law, a lowering of the persistency curve may be in-terpreted as an increase, and an elevation as a decrease, in the luminosity of the spectrum as perceived by the eye.

Considerable difficulty was experienced at first in obtaining a satisfactory normal curve. The author was not aware that his vision was abnormal in any way, and expected to get a smooth curve as obtained by other observers of normal vision. After every set of readings, the curve proved to be irregular between .59μ and .66μ, and it was thought for a time that this was

[4] Am. Jour Sci. Vol. 44, 1892.
[5] Proc. Roy. Soc. Vol. 63, 1898; Vol.70;1902.

due to the writer's inexperience in making such measurements. The readings were repeated again and again, the greatest care being taken to make correct observations, yet a smooth curve was never obtained through this region. After two weeks of strenuous work and several hundred measurements the writer was forced to realize that his color vision was not completely normal. The normal curve was finally plotted showing the abnormal elevation between .594μ and .66μ, the exact character of which was accurately determined by making observations on several additional points in this part of the spectrum.

Another difficulty experienced in obtaining a satisfactory normal was the gradual lowering of the entire curve as the constant re-reading of the points continued from day to day. This gradual depression of the curve, which was most pronounced during the first three weeks and before a satisfactory normal was obtained, continued to drop very slowly for several weeks more. The phenomenon appears as one peculiar to the author himself, for three other observers, using the same apparatus and working under the same conditions for several months, did not experience it. One observer was noticeably color deficient in red, while the other two were of normal color vision and obtained almost identical persistency curves. Because of this gradual lowering of the normal the readings were repeated every few days, and if any appreciable change had taken place, the fatigue or reflex curves, taken since the last normal observation, were discarded. It was found, however, after about one month's work that the normal remained almost constant. During continuous work from week to week the change in the normal, if any, was always a general lowering and never the reverse. However, on resuming the work after an interval of seven months, the normal had slightly raised, but came back to its original position after working for a week. In the second column of each table of data are geiven the readings of the normal curve against which the following reflex or fatigue curves are plotted.

Fig. 1 represents three stages in the lowering of the normal curve, the data of which are given in Table 1. The first normal plotted was that obtained after one week of steady work, the second after two weeks, and the third is the final curve which remained almost constant during the last five months. In Fig. 2 the author's final normal, marked W.A.A., is plotted with two other normals obtained by experienced observers, who used the same apparatus and worked under the same conditions. The curve marked F.A. is Allen's normal which is almost identically the same as obtained later by M. S. Hollenberg. The third, marked A.H., is that of A. Hollenberg, whose color vision is noticeably deficient in the red. A comparison of the author's persistency curve with the normal type, as obtained by Allen, indicates that the former's eye is much more sensitive to light of all wave lenghts, the maximum difference being in the green and the minimum in the orange. As shown by Allen,[6] color deficiency is revealed by those portions of the persistency curve elevated above the normal type. This is well illustrated in A. Hollenberg's curve, whiwh shows almost complete coincidence with the writer's throughout the violet and blue, but is greatly elevated, even above the normal type, in the yellow, orange and red.

At the close of the research a normal curve for the left eye was taken. This curve, plotted against the final normal for the right eye is shown in Fig. 3. It will be observed that it is of the same character as that for the right eye, the slight deviation being probably due to the fact, that the left eye was unaccustomed to taking readings. The data for all the normal curves discussed above are given in Table 1.

IV

REFLEX CURVES

All curves, plotted from results obtained by fatiguing the left eye and then making measurements on the spectrum with the right, are called reflex curves. The procedure was similar to that used to obtain a

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[6] Phys. Rev.11, p.257; 1900.

normal curve, except that the left eye was first fatigued for three minutes with the given spectral color. Care was taken in fatiguing the eye to fixate on the centre of the patch of color and to prevent the eye from wandering. The interval elapsing between the removal of the eye from the fatiguing color and the commencement of the chronographic record was from 15 to 30 seconds, while the time required to complete the record was about another 30 seconds. Since the left eye was fatigued for three minutes before every reading, and the time elapsing from one period of fatigue to the next seldom longer than a minute and a half, the eye was under almost continuous fatigue. The readings for an entire curve were usually taken at one session of two and a half to three hours. Any readings, which were obviously inaccurate, were repeated a few hours later or, as was often the case, the next day. At least two or three hours, and usually one night, intervened between the taking of readings for two different fatiguing colors. In each figure two curves are plotted together to the same scale, one, the normal or reference curve, which throughout is shown as a dashed line, the second, the reflex curve, drawn as a continuous line. The coincidences and divergences of the reflex and normal curves show the effect of the fatiguing color in the left eye, upon the physiological luminosity of the spectrum as perceived by the right.

The deviation of the reflex curve from the normal is shown in another manner, at the bottom of each figure, by giving an arbitrary value of 100 to all points in the normal curve, and reducing the reflex curve in proportion. The data for all the reflex curves are given in Tables 2, 3 and 4. The fatiguing color used is marked at the bottom of the figures by an arrow.

The result of fatiguing the left eye with wave length .687µ is shown in Fig. 4. The entire curve is depressed below the normal, the depressions being greatest in the two ends and middle of the spectrum, and least at the two points, about wave lengths .50µ and .66µ, which approximate the normal curve. It is evident that the effect of fatigue on the left eye has had a reflex effect upon the right, resulting in the enhancement of the physiological brightness of the entire spectrum. Fig. 5, which shows the result when the fatiguing color was .670µ, indicates an enhancement from the extreme red to .50µ, and coincidance at .66µ and from .50µ to the violet end. When wave length .660µ was used to fatigue the eye, the reflex curve, Fig.6, agrees closely with the normal in nearly all points, except for a slight depression in the orange, and a small elevation in the extreme violet, which may be partly due to the difficulty of making accurate measurements in this dim region of the spectrum. It is quite probable that some color close to .660µ, such as .663µ or .665µ, might be found to give a more complete coincidence. Wave length .660µ is one of the equilibrium colors discovered by Allen,[7] which shows no reflex enhancement in the other eye.

The reflex curve for a fatiguing color of .589µ, Fig. 7, shows a further reduction in the extent of reflex enhancement, as compared with Figs. 4 and 5. The enhanced effect is confined to the middle part of the spectrum between wave lenghts .50µ and .66µ, while the remainder of the curve coincides with the normal. The transferred reflex enhancement for fatigue color .570µ, as shown in Fig. 8, is very similar to that for .589µ, except that the amount of enhancement in the orange is a little greater. Since wave length .570µ, another of the equilibrium colors discovered by Allen, did not give the same result for the writer, another color near to it was tried, namely, .565µ. This proved to be an almost perfect equilibrium color, as shown in Fig. 9. The reflex curve for .535µ, as plotted in Fig. 10, shows, like some of the previous curves, an enhancement in the red and yellow-green, and coincidence with the normal from .50µ to the end of the violet. It differs from the other reflex curves by showing coin-

[7] Phil. Mag. 38, p.55; 1919. Also J.O.S.A. 7, p.583; 1923.

cidence in the region corresponding to the abnormal part of reference curve, which, however, includes .66µ.

All fatigue colors chosen from the spectrum between wave lenghts .520µ and .480µ resulted in giving good equilibrium curves very similar to Fig. 9. Curves for the following wave lengths were obtained, .520µ, .513µ, .505µ, .495µ, and .480µ, the data for which are given in Tables 3 and 4, but the curves themselves are not reproduced in this paper since they resemble closely Fig. 9. In this part of the spectrum Allen found three equilibrium colors, .520µ, .505µ and .480µ, while wave lengths .513µ and .495µ gave small reflex enhancements. Since most of the transferred reflex effects obtained by the writer are smaller than those shown by Allen's curves, it is quite probably that, if any reflex action is produced by either .513µ or .495µ in the writer's eye, it is too small to be detected.

The reflex curve for wave length .450µ as shown in Fig. 11, reveals a decided enhancement b throughout the entire spectrum. The effect is most pronounced in the red, and least again about .50µ and .66µ. It may be observed that most of the reflex curves tend to coincide with the normal at these two points,which Allen has called "coincidence points". When wave length .420µ was used to fatigue the eye a small reflex enhancement was obtained, as shown in Fig, 12,but when .425µ was tried the reflex curve coincided throughout with the normal, thus giving the same equilibrium color as found by Allen.

Although the luminosity of the violet fatiguing color was comparatively low, yet the largest reflex effects were obtained for the fatigue colors .405µ and .410µ. The results of the latter are shown in Fig. 13. Like .450µ, it produces a large enhancement throughout the entire spectrum except at the coincidence points .50µ and .66µ.

An examination of the reflex curves as a whole, shows a very interesting fact, namely, that the largest reflex enhancements are not obtained by fatiguing with the brightest colors, but rather with the dim colors, such as .687µ, .450µ and .410µ. These wave lengths stimulate predominantly one sensation each;the first is confined almost entirely to the red sensation, while the latter two affect chiefly the violet. It would appear therefore, that the large enhancements, obtained by fatiguing with the above colors, is due, either to their lower luminosity, or to the simplicity of their stimulations of the fundamental sensations. A comparison of the various reflex curves shows, that a reflex enhancement in the violet is obtained, only when the fatiguing color is one of comparatively low luminosity, such as a red or violet. When a reflex does occur it is always manifested in the most luminous portion of the spectrum, and with the exception of the reflex curve for .589μ, also in the red. It was therefore of interest to determine the reflex effect of an intense white light.

The left eye was fatigued with a similar patch of white light, obtained by removing the prisms from a spectrometer and viewing the white light in the eyepiece. By this means, the area of the retina stimulated was the same as for the other fatigue colors. The results, as shown in Fig. 14, are similar to those obtained for bright colors throughout the middle of the spectrum. The curve from .48μ to the violet end coincides almost completely with the normal, while the remainder, with the exception of about .68μ, shows a distinct reflex enhancement. The data for this curve and the next are given in Table 8.

Before taking any readings for the reflex effect of darkness adaptation in one eye upon the perception of the luminosity of colors by the other, the left eye was blindfolded for about an hour, and kept in that state until all the observations, which were taken at the rate of one every five minutes, were completed. This curve, as plotted in Fig. 15, is quite different from any of the other reflex curves, in that the entire curve, with the exception of the abnormal region .59μ to .66μ is elevated above the normal. This clearly verifies the observations made by Allen, that dark adaptation in one eye lowers the physiological luminosities of colors perceived in the other, a fact, which shows the importance of investigating reflex phenomena in daylight, when the unused eye is under natural light adaptation.

The majority of the reduced curves, shown at the bottom of the figures, indicate a division into three parts, two of which correspond to the sensations of red and violet, while the third is in the middle portion of the spectrum, where green may be considered as the predominant sensation stimulated.

These curves fully verify the principle discovered by Allen, that the effect of fatigue, by a light stimulus in one eye, is transferred to the other by a reciprocal or reflex action of some kind, resulting in an enhancement of the physiological luminosity of the spectral colors perceived by the unfatigued eye. They differ from his in that the amount of enhancement is generally less, being sometimes very slight or even absent, especially in the blue and violet, or that part which stimulates chiefly, the violet sensation. The wave lengths of the equilibrium colors are approximately the same as found by Allen, except for the additional colors between .520μ and .480μ, which also gave very good equilibrium curves. The two coincidence points, .50μ and .66μ, also agree well with his.

with the normal, as was obtained for the reflex curve. Instead, however, as shown in Fig. 18, the curve is similar to the previous two, showing even a greater enhancement in red and also a greater fatigue in the yellow and green. The two coincidence points, .50µ and .66µ are well marked. This curve was also repeated on another day after having carefully checked the normal, as was always done every few days. The results fully verified the first curve.

The three fatigue curves, now described for different wave lenghts of red, show largest enhancements in regions about .72µ and .64µ, and greatest fatigue about .44µ. In an attempt to locate, if possible, an equilibrium color in the region of .660µ, wave length .665u was tried as a fatiguing color, with the result that both curves showed very good coincidence throughout the entire spectrum, as shown by the data in Table 5. A distinct difference in the effects of fatigue by .665µ and .660µ could be noticed on the red end of the spectrum, the former causing but little change in either saturation or apparent brightness, while the latter caused the red to appear noticeably less saturated but brighter.

It was of interest to determine the effect of fatiguing the eye with a color selected from that part of the spectrum, which gives the abnormal elevation in the reference curve. Wave length .630µ was selected and a fatigue curve obtained for it, the character of which is shown in Fig. 19. Like other fatigue curves for red a smooth curve was obtained without any trace of an irregular elevation between .59µ and .66µ. As has been observed, the curves for wave lengths .687µ and .670µ both of which are on the same side of the equilibrium color, .665µ, are very similar; so, too, the curves for .660µ, and .630µ, on the other side of .665µ, show close resemblances. Wave length .630µ shows smaller enhancement in the red, but much larger fatigue in the green. The disproportionately large enhancement occurring about .72µ, as also referred to in the previous figures, is a noticeable feature. The observations on this point were repeated for nearly all the red fatigue curves, but in every case, the new readings confirmed the original.

When .589µ, the brightest color in the spectrum, was employed to fatigue the eye, another surprising result was obtained. As shown by the data in Table 6, the readings are almost identical with those for the normal curve, .72µ being the only point to show any appreciable variation, and this in the nature of a slight enhancement. For the writer's eye, therefore, wave length .589µ is an equilibrium color, when measurements are made on the fatigued eye. It may be recalled, that even the reflex curve for .589µ, Fig. 7, coincided with the normal except in the middle part of the spectrum from about .53µ to .66µ. The fatigue equilibrium color, corresponding to .565µ of the reflex curves, was found when .570µ was employed. As shown by the data in Table 6, a very good agreement exists between the normal and most of the fatigue readings.

The fatigue curves for wave lengths .550µ and .535µ are quite similar, as shown in Figs. 20 and 21. Both show an enhancement in the extreme red, fatigue in the yellow, orange and orange-red, very little change in the green, but considerable fatigue in the blue. In the violet there is a difference, one showing distinct fatigue, the other coincidence except for a slight enhancement in the last point.

Fig. 22 shows the curve for fatigue color .520µ, which, although not quite an equilibrium color, yet suggests that a slightly shorter or longer wave length would result in such. When making observations for the reflex curves, all colors between .520µ and .480µ showed no change in the persistency curve, but when these same colors were employed to obtain fatigue curves, none were found to give equilibrium effects. Figs. 23, 24 and 25, show the curves for the fatigue colors, .513µ, .505µ, and .480µ respectively. All three curves are somewhat similar, showing fatigue to a greater or less degree in all parts, except in the extreme red and violet. Wave length .513µ, however, indicates also a fatigue of the extreme violet. According to the intersections of the equal area sensation curves of König and Dieterici,[8] this portion of the spectrum is quite complex and it is therefore, not surprising that almost all parts of the spectrum should show fatigue. On the other hand, the largest reflex effects in the unfatigued eye were obtained for the comparatively pure colors, red and violet, which arouse predominantly one sensation each and but slightly the other two. Since white light, and most colors stimulating the three sensations to a considerable degree, produce comparatively small reflex results, it is not surprising that the above mentioned complex region of the spectrum should give equilibrium reflex curves.

The fatigue curves for wage lengths .450μ and .425μ, Figs. 26 and 27, show fatigue in all parts of the spectrum, the former, except in the extreme red, to a much more marked degree. It may be observed from these two curves, and also from .480μ, that greatest fatigue is shown in that part of the spectrum corresponding to the fatiguing color. When the dim violet, .410μ, was employed, the fatigue was only evident in the less bright parts of the spectrum, as shown in Fig. 28. It is possible, that the considerably brighter region of the spectrum, from .50μ to .66μ, rapidly

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8. Parsons: "Colour Vision" p.222

overcame the state of fatigue due to the dim violet. It is also possible, that the eye was under partial darkness adaptation, due to the comparative darkness of the spectrometer tube, in the centre of which, the dim violet was fixated for three minutes out of every four. This latter possibility seems the more probable in view of the effect of darkness adaptation on the same eye with which the measurements were made. This effect is shown in the next curve.

Before taking any readings for the fatigue curve for darkness, as it may be called, since the results are similar to fatigue, the right eye was blindfolded for about one hour. Readings were made every five minutes on the spectrum, still in the daylight room by uncovering the eye for the brief period of about thirty seconds which was required to make the chronographic record. While uncovering the eye and placing it in the shield attached to the spectrometer eyepiece, care was taken to prevent any daylight from entering the eye. Although the appearance of the spectrum to the dark adapted eye was such as to suggest an increase in the brightness, yet the true effect must be judged by the actual measurements obtained. These measurements, as plotted in Fig. 29, clearly show that the effect of darkness adaptation is to lower the physiological luminosity of the spectrum, a fact, which was pointed out by Allen[9] over twenty years ago. The effect, as obtained by the writer, is not marked in the most luminous part of the spectrum. This may be caused by the rapid disappearance of the effects of darkness adaptation in the presence of the comparatively bright spectral colors, upon which the measurements were being made; for it has already been pointed out, that the author's eye is much more sensitive than normal to a light stimulus.

To obtain a fatigue curve for which white light, the eye was fatigued by a moderately bright light, transmitted through a spectrometer with the prisms removed, as was the case for the reflex curve. A very brilliant light made it almost impossible to get consistent readings because of the vivid after image produced. The readings from which Fig. 30 was plotted, showed, however, good agreement. The character of this curve is interesting in the relation which it bears to all the otherfatigue curves. This curve is really the combined effect of the main types of fatigue curves,for it reveals a large fatigue in the yellow, green, blue and violet colors, as is also shown to a greater or less extent by nearly all the fatigue curves, but shows little or no fatigue in the red and of the spectrum, a result which is about the average effect for all the fatigue colors. The data for the two curves on white

[9] Phys. Rev. 11, p. 265; 1900.

light and darkness are given in Table 8.

A general survey of all the fatigue curves, except those for equilibrium colors, reveals three fairly distinct types, which change more or less gradually from one type to the other. When the fatiguing color is any hue of red, there is always an enhancement in the extreme red and orange-red, the amount of which is less for the fatigue color, .630μ than for those of longer wave length. The depression in the brightness of the green region of the spectrum increases in amount with a decrease in the wave length of the red fatiguing color, while the violet end shows always a distinct lowering of the physiological luminosity. The equilibrium curves for yellow fatiguing colors separate the red type from the green, or second type. Fatiguing with green gives an enhancement in the red, the amount of which decreases as the fatigue color moves towards the blue, the blue showing little or no effect on the longer red waves; on the orange-red the effect is a lowering of the brightness, the amount of which increases with a decrease in the wave length of the fatigue color. Green fatigue curves also show a depression in the brightness of the green, blue and violet colors, the amount of which increases as the fatigue color becomes more blue.

The second type changes gradually through the fatigue curves for blue to the third type, which is for violet fatiguing colors. The transition curves in the blue show but little fatigue or enhancement for the extreme red or violet, and an increasing fatigue in the brighter colors. The violet curves give a depression in luminosity throughout the entire spectrum, the amount of which decreases, as the fatiguing color approaches the extreme end of the spectrum, until for .410μ the brighter part of the spectrum shows no change.

The reduced curves at the bottom of the figures show a tendency to divide, in most cases, into three regions, which are not regular enough in all the curves to say that they indicate always the three fundamental sensations, red, green and violet. The existence of these three fundamental sesnations is indicated more particularly by the natural division of the curves into the three main types as already described.

VI

THEORETICAL CONSIDERATIONS

The experimental results, which have now been considered, fully verify Allen's discovery of the dual action of light in arousing visual sensations. Although the character of many of the curves, given in this paper, differ considerably from his, yet they clearly show that in addition to the direct effect of light, which tends to produce fatigue, there is also a reflex effect, resulting in an enhancement of the fundamental sensations. Several of the reflex curves are very similar to Allen's showing that, when a light stimulus falls upon one eye, the sensory reflex is transferred to the other causing an enhancement of all three sensations. Certain colors, which are termed equilibrium colors, apparently produce no effect in the physiological brightness of the colors perceived by the unfatigued eye, while fatigue by still different wave lengths, enhances only the red and green sensations in the opposite eye and not the violet. The violet sensations in the writer's eye seems the least sensitive to stimulation by a sensory reflex, transferred from one eye to the other.

In the same eye, Allen found that the direct effect of a color stimulus was to cause a diminution in the physiological brightness of the colors, corresponding to the primary color sensations represented in the fatiguing color, and that the reflex effect was to enhance the brightness of those colors which stimulate chiefly the complementary sensations.

The majority of the author's fatigue curves, however, are quite different from those obtained by Allen. When red of any wave length, except .665μ, was employed as the fatiguing color, the result was not a dimunition in the brightness of the red, observed in the other spectrometer, and a corresponding enhancement of those colors representing predominantly the green and violet sensations. Instead, the red sensation was actually enhanced, the violet fatigued, and the green little affected, except by the shorter red waves which fatigued it. Stimulation with green shows fatigue in the green and violet and enhancement in the red, but violet however fatigues more or less all three sensations.

Although these results are not of the normal type, yet it is evident that the conclusions drawn from Allen's researches do not give a complete statement of the direct and reflex stimulation of the fundamental color sensations when light falls upon the retina. A more comprehensive statement, which is based on the results shown by the curves in this paper, may be expressed as follows:-

Light of every hue falling upon the retina affects all three sensations both directly and reflexly. For example, a green light stimulates by direct action all three sensations, but predominantly the green, and by reflex action also the three sensations, but predominantly the red and violet. The direct effect always tends to produce fatigue, and the reflex, enhancement. In normal vision under ordinary conditions, if we again take green as the fatiguing color, the direct effect on the green sensation overbalances the reflex action on the same sensation, resulting in a fatigue of the greeen sensation; and the reflex effect on the complementary sensations, red and violet, overbalances the direct effect on the same sensations, thus producing enhancement of the complementary sensations, While the eye is still being stimulated by the green light, the direct effect usually predominates over the reflex, the net result being a sensation of green with an underlying whiteness, which increases with fatigue. However, under certain conditions, and especially in cases of abnormal vision, the above is not always the net result of direct and reflex stimulation of the sensations. The discussion of this point, however, will be postponed until after the author's type of abnormal color vision has been considered.

Helmholtz suggested that every ray in the spectrum affected each of the three sensations, red, green and blue. Abney in referring to Helmholtz's suggestion states,[10] "If Helmholtz's diagram, p.214, were correct, one colour would never stimulate one sensation by itself. As it is, however, the red stimulates only red sensation in one part of the spectrum, whilst the violet stimulates both the red and the blue, and not the green sensations. A green color stimulates not only the green sensation, but it stimulates the red and blue as well, as is shown in Helmholtz's diagram. The trichromatic theory requires this to be the case." The experimental results given in this paper show that Helmholtz

[10] "Researches in Color Vision" p.230

was right in his assumptions, although unaware that the three fundamental color sensations are stimulated reflexly as well as directly by every hue. Abney failed to detect the dual nature of the action of light upon the retina, partly no doubt, because of the negative effect of darkness adaptation, and partly because many of his observations were based on the assumption that light falling upon one eye has no effect upon the other, a conclusion which these researches show to be incorrect.

Anomalous Trichromatism.

The author has no difficulty whatever in passing ordinary wool and card tests for color deficiency, nor has he, at any time, experienced any phenomena apart from these experiments to indicate that his vision is in any way abnormal. Slight pleochroism in certain minerals under the polarising microscope can be observed, even when the effect is too weak to be detected by as many as one quarter of a class. There is also no shortening of the spectrum at either end, as compared with those whose color vision is undoubtedly normal. However, a comparison of the author's normal persistency curve, and especially his fatigue curves, with those obtained by Allen, indicates that an abnormality of some sort certainly exists. Allen's curves have been fully confirmed by M. S. Hollenberg,[11] who not only obtained the same normal curve, but also the same type of reflex and fatigue curves. Their results appear therefore, as those of observers whose color vision is in every way normal.

A comparison of the author's normal curve with that of Allen, Fig.2, shows that the greatest deviation is in the green and yellow, or that part which corresponds predominantly to the green sensation, and the least departure from the normal type in the orange and orange-red, from .59µ to .66µ. An examination of the sensation curves of König and Dieterici,[12] shows that the green sensation falls to zero in this region. Although, in light of the principle of reflex stimulation of sensations, all three sensation curves should extend to the ends of the visible spectrum, yet the above mentioned curves are no doubt correct in indicating that, at least, the direct stimulation of green beyond .66µ is very small. The elevation in the author's normal curve between .59µ and .66µ would appear, therefore, to be due to a deviation of the green sensation curve, rather then the red, from that of the normal type. It seems probable that, if the writer's sensation cuves were determined and plotted as equal area curves after the manner of those of König and Dieterici, the green sensation curve would be found to show a depression, as compared with the normal type, for the region between

[11] In process of Pub. in J.O.S.A & R.S.I.8;1924
[12] Parsons: "Colour Vision" p. 222.

.59μ and .66μ, and a corresponding elevation throughout the yellow and green parts of the spectrum.

It is well known that there are individuals, who show no color deficiency whatever, but who, in matching a spectral color, by two mixed colors, differ in their equation from that of the normal. For example, when making the equation, .670μ + .535μ = .589μ, some require more red and others more green than the normal. Those requiring more red are commonly called red anomalies, and those requiring more green, green anomalies. Edridge-Green states,[13] "There are also those who will make normal equations when the red employed is λ670, but will make an anomalous equation with a red of larger wave length, as for instance λ690, putting in twice as much red in the mixture compared with the normal equation in similar circumstances". It is quite conceivable that an individual, who is not color deficient, may not only agree with the normal in the equation, .670μ + .535μ = .589μ, but also with a few other equations, and yet differ from the ~~neomal~~ normal when still different wave lengths are employed. Such individuals must be classed as anomalous trichromats.

As the results of the experiments, given in this paper, were studied more closely it became more convincing that their abnormal characters must be due to anomalous trichromatism. It therefore became

[13] "Physiology of Vision" p. 223.

desirable to test the author's color vision by means of color equations.

The apparatus used was Allen's trichromatic spectrometer,[14] in which two colors can be isolated and mixed in the upper part of the shutter eyepiece, and a single color in the lower part. Each of the three colors were obtained from the separate spectra of three acetylene flames of constant luminosity. The intensity of a color was altered by opening or closing the collinator slit.

The first equation attempted was $.670\mu + .535\mu = .589\mu$, but in this the author agreed with the normal equation as obtained by Allen and others. It will be noticed by reference to the normal curve, Fig 2, that these three wave lenghts are outside of the writer's particular abnormal region, $.59\mu$ to $.66\mu$. The red was then changed to a longer wave length $.690\mu$, but again the difference was not sufficient to say that an actual disagreement existed. The same was true when a longer wave length of $.720\mu$ was used instead of $.690\mu$. The next step was to select a wave length from the abnormal region, $.59\mu$ to $.66\mu$, as one of the three colors. The first equation made was $.670\mu + .535\mu = .630\mu$. In this case, when the match was perfect for the normal eye, it appeared distinctly too yellow to the writer, and the amount of green had to be decreased to give a good match.

[14] J.O.S.A & R.S.I, 8. p. ; 1924.

When the red was changed to .690μ and .720μ the same results were obtained.

Wave lengths .630μ affects chiefly the red and green sensations; and since a less amount of green, or a greater amount of red, is required than normal to match .630μ, then it is evident, that either the green sensation is comparatively less stimulated, or the red more stimulated than normal by colors between .59μ and .66μ. A comparison of the writer's normal persistency curve with that of a normal trichromat, as has already been pointed out, would indicate that the abnormalty is due to an over sensitiveness of the green sensation to wave lengths of the yellow and green regions of the spectrum, and an under sensitiveness of the same sensation to wave lengths between .59μ and .66μ. In this respect, therefore, the author is an anomalous trichromat, but according to the general distinction between green and red anamalies he would be classed as a red anomaly, since he requires more red in the equations than the normal.

Anomalous trichromatism, and in fact color vision in any phase, cannot be studied fully unless both the direct and reflex action of a light stimulus on the retina be taken into consideration. Heretofore, only the direct effect of light was considered, and that not generally to the extent that every ray effects, to a greater or less extent, all three sensations. An individual may be not only anomalous in respect of the direct effect of light, but also anomalous in the development of his reflex sensations. The latter phase is probably most easily detected after prolonged stimulation, since the reflex sensation, which may be set up in a very small fraction of a second, increases with continued stimulation.

While fatiguing the eye with a brilliant green light it was observed that, at the end of about 25 seconds, the light began to lose its green color and to assume a purple tinge, which increased in saturation for another 25 seconds, at the end of which the color appeared more purple than green; the purple then gradually decreased until at the end of about 90 seconds it again appeared a dull green of much reduced intensity and saturation. A similar effect was observed when fatiguing with a strong white light. The white light became distinctly pink, which gradually increased for a short time and then slowly disappeared as the fatigue reached a maximum. However, when using a brilliant red light no tinge of green could be observed although at first it was expected. These observations may be readily explained as follows:

An examination of the fatigue curves shows that the author's violet sensation is easily fatigued by nearly all hues to a greater or less extent. From the reflex curves, it may also be seen that violet perceived by the other eye is not markedly enhanced by a transferred reflex stimulation, except when the fatiguing color is near either end of the spectrum. It therefore appears, that with prolonged stimulation, the net result of the direct and reflex action of the different hues upon the violet sensation is nearly always in favor of fatigue. Fatigue curves show, that the green sensation is also fatigued by most hues, but the fatigue, except by a few colors, is not marked. Reflex curves, on the other hand, show, except for equilibrium colors, fairly distinct enhancements. The red sensation, however, is very difficult to fatigue and shows fatigue only in the extreme red and only when the fatiguing color has a wave length of .480µ or less. According to the sensation curves of König and Dieterici the red sensation curve terminates at about .480µ. It has already been pointed out that the experimental evidence given in this paper, would indicate that the red sensation curve really extends to the violet end of the spectrum, as Exner's curves show.[15] However, the curves of König and Dieterici may be taken as showing, that the direct stimulation of the red sensation by wave lengths longer than .480µ is at least very small. If the fatiguing color is any hue of red or green, except equilibrium colors, the fatigue curves show that the effect of prolonged stimulation is an enhancement of the red

15. Parsons: Colour Vision . 223.

sensation, due to the reflex action overbalancing the direct. The reflex curves also show that the red sensation is far more susceptible to reflex stimulation than the other sensations. It must be remembered, of course, that the experimental results were obtained by removing the eye, after strong stimulation for three minutes, to a less intense spectrum upon which the measurements were made. Therefore, when a bright white light is fixated by the author's eye for about 30 seconds it assumes a pink tinge due to the strong enhancement of the red sensation by reflex action. With longer fixation the direct effect overtakes the reflex and fatigue predominates, with the result that the pink tinge disappears leaving a white of a much reduced intensity. Similarly, when a brilliant green color is fixated, the reflex enhancement of the red sensation, which is the sensation predominantly stimulated by the reflex action of green, outgrows the green sensation, which is being fatigued by direct stimulation, thus resulting in giving the color a purplish tinge. Longer fixation again results in favor of the direct action on the green and the color appears a green of a much reduced luminosity and saturation. However, when fixating upon a brilliant red color, the author's red sensation is so difficult to fatigue, and so sensitive to enhancement by reflex action, that the reflex green never outgrows the red, and therefore, no green tinge was ever observed when fatiguing with red.

Although anomalous trichromatism may, in part, be explained as due to a shift of one of the sensation curves, yet the experimental evidence given in this paper shows that a more comprehensive explanation is possible. Since direct stimulation of the retina is always accompanied by a sensory reflex, then any abnormal development of the reflex stimulation must produce at least anomalous results in color vision. In general, therefore, anomalous trichromatism is due to an abnormal ratio of the direct stimulation of the sensations to their reflex enhancement. Since this ratio depends to some extent upon the intensity and duration of a stimulus, it is quite conceivable, as Edrige-Green has observed, that [16] "There are also persons who will make normal equations in one set of circumstances and anomalous equations in another." He has also observed, that some individuals will agree with the normal equation when a red of wave length .670µ is used but will make an anomalous equation with a red of .690µ. Now, .670µ is very close to an equilibrium color which the author found to be at .665µ, while .690µ is a color which gives large reflexes. It is quite possible, therefore, that these anomalous trichromats, examined by Edridge-Green, had an equilibrium color close to .670µ, the stimulation of which would result in a balance being set up between the direct and reflex effects of the color, while the effect

[16] "Physiology of Vision" p.223.

of employing a red of .690µ would be to produce abnormal reflex enhancements and consequently an anomalous equation.

The following observations, made by various experimenters, clearly show when viewed in the light of this paper, that the reflex sensation may, under certain conditions and with certain individuals, actually predominate over the direct effect of a light stimulus.

"If the primary stimulus (white) is more intense or acts for a longer time coloration may commence before obscuring the eye (Fechner)."[17]

"A vivid blue-green after image may be seen not only in the absence of all green light but whilst the eye is still being stimulated with a red light."[18]

"The case of a strongly colored red surface whose image extends over the greater part of the retina is especially striking. The colour fades very slowly but steadily, giving rise to a peculiar sensation of loss of power of the eye until the field becomes quite grey and colourless. At this stage the state is one of kinetic equilibrium, and a subjective fluctuation, like those which are always taking place in self light, may suddenly result in a rise of the threshold values of the weak green and blue sensaations. If that occurs the colour of the field will suddenly flash into

17. Parsons: "Colour Vision", p.110.
18. Edridge-Green: "Physiology of Vision,p.145.

perception as a strong green. The effect is unusually striking, but is not easy to attain."[19]

This last quotation is really a careful description of what may be called the growth of the reflex sensation until the effect of direct action, which affects predominantly the red sensation, is equalled by the reflex action, which enhances chiefly the complementary green, thus resulting in a grey. An equilibrium between the two effects then exists until the reflex enhancement of green suddenly predominates over the direct excitation of red.

The Application of the Principle of Reflex Visual Sensations to the Young-Helmholtz and Hering Theories.

The Young-Helmholtz trichromatic theory of color vision with the various modifications and extensions, made by von Kries, Abney and others, furnishes a simple and satisfactory explanation of a great mass of phenomena associated with the perception of light and color. The theory originated out of a study of color mixtures, which are explained by it in a very satisfactory manner. Dichromatic vision is explained as due to the absence of one of the sensations, and monochromatic vision as the identity of all three. Anomalous trichromatism, according to this theory, is due to a partial reduction in one or more of the sensations, or in some types, to a shift in one of the sensation curves.

19. Peddie: "Colour Vision." p. 175

The theory, apart from the principle of reflex sensations, offers no adequate explanation of the phenomena of after images, for both positive and negative after images may be experienced in the absence of stimulation by white light. If dichromatic vision is due to the absence of one component sensation, it is difficult to understand why a certain portion of the spectrum should be seen as grey and not colored, if the remaining two sensations are stimulated, nor almost completely dark, if none of the sensations be affected. Again, it does not appear consistent to suppose, that dichromatic vision is due to the absence of one color sensation, while monochromatic vision is the identity of the three. The theory is also deficient in offering an explanation for the various types of color blindness with normal luminosity curves. The facts of spatial induction or simultaneous contrast were regarded by Helmholtz as "illusions of judgment", an explanation which abandoned physiology completely.

These researches are not intended to confirm the Young-Helmholtz theory, although they do indicate three fundamental sensations corresponding to red, green and violet. The evidence rather corrects and extends the theory by recognizing the reflex action of light upon the visual mechanism in addition to its direct effect.

This addition of the principle of reflex visual sensations, as discovered by Allen and as extended both by him and in this paper, offers on the basis of the trichromatic theory, simple and satisfactory explanations for successive and simultaneous contrast, the whiteness underlying all colors, the saturation of color in after images, complementary colors, anomalous trichromatism, etc. von Kries' duplicity theory, which offers an explanation of scotopic or twilight vision, may yet prove an unnecessary addition, for, as all colors tend to become white at high intensities, due to the reflex enhancement being equal to the direct, so too, the absence of color in all lights at low intensities may be due to another equality between the direct and reflex action of light in stimulating the sensations. It is quite possible that color blindness, either partial or complete, may also be caused by certain balances set up between the direct action of light and the complementary reflex, resulting in grey. The correctness of the above predictions, can only be determined, in the first case, by an experimental study of reflexes at low intensities, and in the second by investigating them in the color blind.

The value of any theory is twofold, first, in offering satisfactory explanations of many related phenomena, and second, in stimulating fruitful research. In this respect the trichromatic theory of Young-Helmholtz has become more and more firmly established, until now, in the light of the recent researches in reflex visual sensations, little room seems left for many of the opposing theories. However, it seems quite improbable that a rival theory, which also explains many phenomena of color vision, and which too has stimulated much valuable research, should not contain a considerable degree of truth. Such a theory is that proposed by Hering.

The Hering theory assumes six psychophysical processes, corresponding to the six primary sensations, which may be arranged in pairs, red-green, yellow-blue, white-black, Three photochemical substances are supposed to exist in the retina, one corresponding to each of the three pairs of sensations. The first named sensation in each pair is supposed to arise from the dissimilation of the photochemical substance and the second sensation from its assimilation. All rays of the visible spectrum have a dissimilating action on the white-black substance but different wavelengths in different degrees. When mixed light produces equal dissimilation and assimilation in the red-green or the yellow-blue substances colorless light is the result. The action is not complementary but rather antagonistic, for yellow and blue do not produce white light by their combination, but by destroying each other's effects, and leaving visible the white, which is already there through the dissimilation of the white-black substance by the mixed light. Each visual response is therefore a mixture of three sensations excited by dissimilation together with the three arising from assimilation, the resulting color being due to the one of the six that produces relatively the greatest effect.

The principles deduced from the experimental evidence given in this paper show that two opposite effects are produced whenever light of any hue stimulates the retina. The direct and reflex action of light, although apparently antagonistic, produce their full effects without in anyway destroying or inhibiting each other. The net result is not the excess of one action over the other, but rather the combined effect of the two. Because of the underlying whiteness of all spectrum colors, Hering assumes the existence of a white-black substance, in which the antagonistic action results in a series of greys. The discovery, however, of reflex visual sensations no longer necessitates this assumption, since white is the result of equal stimulation of the three fundamental sensations, red, green and violet, whether it be by direct action, reflex action, or by a combination of both which it appears must generally be the case.

Both the Young-Helmholtz and Hering theories recognize that the nature of color vision is essentially trichromatic, the former by supposing the existence of three fundamental sensations, and the latter by the assumption of three pairs of psycho-physical processes. The first theory explains most satisfactorily phenomena, such as those of color mixtures, which arise chiefly from the direct action of light; the second, phenomena relating to color contrast, which have now been shown by Allen to be due largely to the reflex effect of a color stimulus.[20] Each theory therefore is mainly based on only one of the two phases of color perception. In the light of a visual reflex of a sensory nature, the Young-Helmholtz and Hering theories can no longer be regarded as antagonistic. The existence of a reflex, affecting predominantly the complementary sensations, explains fully the apparent antagonism of color sensations, which Hering recognizes as an essential feature of color perception.

[20] J.O.S.A & R.S.I. 7, p.913; 1923.