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# Color-vision and Color-blindness

Before entering into a discussion of the various theories of color-vision, it is necessary to give an impartial description of the facts of the case, both on their physiological and on their psychological side. On the psychological side, ~~color vision~~ colors are divided into two groups. One of these constitutes the linear scale of qualities from white through grey to black; the other is circular in form, and extends from crimson red along the colors of the spectrum up to violet, and from there along a series of colors which can only be physically obtained through the mixture of waves from both ends of the visible spectrum - the purples - back to crimson red again. The color-scale differs from the scale of wave-lengths furnished by the spectrum ~~from~~ of a diffraction-grating in several ways. In the first place, the colors of the spectrum are not evenly spread; the eye sees little variation throughout the whole length of the red, which occupies more than two-thirds as much space as the very different colors orange, yellow and green, together. The blue and violet also are spread out over a long stripe ~~of the spectrum~~. In the second place, ~~one~~ a color may be produced by the mixture of vibrations ~~neither~~ none of which alone would give it. Yellow may thus be produced by the mixture of green and orange. In the third place, certain colors ~~of the~~ seem to be turning-points in the color-series. ~~Yellow~~ Red, yellow, green, and blue appear to have this property.

The black-white and the red-yellow-green-blue series do not exhaust our power of perceiving colors, for colors as well as colorless lights may differ in brightness. Every red, for instance, has a corresponding grey, and there are light reds and dark reds just as there are light greys and dark greys. Also, between every color and its corresponding grey there are numerous intermediate shades. This series of shades is called a series of saturations or chromas. Very light and very dark colors have less chroma, or difference from their grey, than those of intermediate tint. The different colors do not have their maximum chroma at the same tint. The tint at which a color has its maximum chroma is called its specific brightness. Yellow has the great~~of~~est specific brightness, red next, green next, blue next.

When two colors are presented in succession ~~at the same tint~~ to the same part of the retina, a third color results, whose brightness may be expressed by the formula, $B = \frac{ab + a_1 b_1}{a + a_1}$, where $b$ and $b_1$ are the ~~respective~~ brightnesses of the two component lights, and $\frac{a}{a_1}$ the ratio formed by the ~~amour~~ respective amounts ~~of the two~~. The hue of the resultant light depends upon the position of the two components on the scale of colors; for every color there is a color which when mixed with it in the right proportions will give a grey; thus red and blue green or blue and yellow are pairs of complementary colors, as a pair having these properties is called. Two colors which are not complementary will when mixed produce a color of intermediate hue and of lower saturation than either component. Under normal intensities of light, a color formed by a mixture will behave in mixtures like a pure color.

When a color has been presented to the eye for some time, on looking away from it, it may first seem to persist for an instant, then comes a second or two when nothing is seen, and then ~~it~~ there appears a sensation of the same form, but of complementary color and of a brightness on the opposite side of neutral grey. This is known as the negative after image. Also, when one looks at a color on a colorless background, one sees the background tinged with the opposite shade and complementary color.

In low intensities of light, ~~the color~~ ~~sense~~ vision seems to undergo a deep-seated change. The colors first become invisible, red and green dropping out before blue and yellow. In the spectrum, which then appears as a band of brighter or darker greys, the point of maximum brightness shifts from the yellows to the region which would be green in more intense light. At the same time, the fovea ~~.~~ ceases to be the site of the clearest vision. The red end of the spectrum is shortened.

Another interesting phenomenon of color-vision is that, even in daylight, the periphery of the eye is unable to distinguish colors. As we go out from the fovea, first red and green, then blue and yellow are lost before we ~~reach~~ loose white and black. That is, the periphery of the eye is always dark-adapted.

The whole of the eye of certain people who are utterly unable to see colors is also dark-adapted. The brightest point of the spectrum is for them also in the green. The fovea is, in a large number of these cases, completely blind, so that they are unable to fixate any object. Now, the receiving ~~end~~-organs of the eye are of two sorts, rods and cones. Of these, the rods are thickest in the periphery and absent in the fovea, whereas the cones are almost absent in the extreme periphery and closely-packed in the fovea.

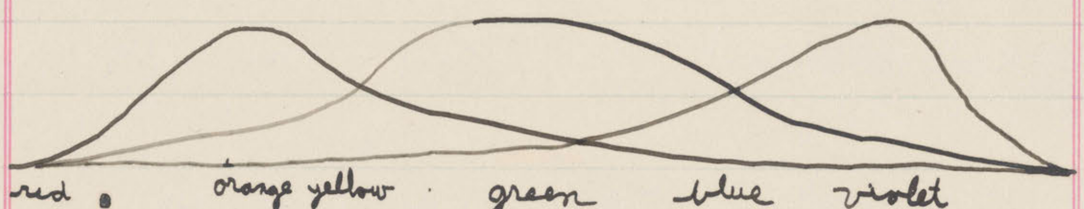
In combination with the facts just mentioned, it would seem that the rods are the organs of uncolored, twilight vision, whereas the cones are chiefly sensible to colored light, and only secondarily to uncolored. This is confirmed by the fact that many ~~purely~~ purely nocturnal animals, such as the owl, lack the cones, while some purely diurnal animals, such as the fowl, lack fully developed rods. It would appear that in those totally color-blind persons who have foveal vision, the cones simply fail to act for color, while in those who lack it, they either are missing, or if they are present, are functionless. Whether the functioning of the rods has anything directly to do with the decomposition [redacted] and regeneration of the peculiar pigment found in the rods ~~and~~ which is known as the visual purple is still a matter of uncertainty, but the bulk of the evidence seems to be [redacted] against it. A fact in favor of it is that [redacted], the visual purple is decomposed most quickly by those rays which appear brightest in twilight vision. A fact which tends to make it ~~this~~ less certain, however, is that this same phenomenon of shifting of the point of greatest brightness (known as the Purkinje phenomenon) takes place also in the fovea; and although in the dark foveal vision is not so good as peripheral vision, the fovea ~~it~~ has some sight, notwithstanding the fact that it contains ~~possesses~~ ~~has~~ only cones, which lack ~~certain no~~ visual purple. So this theory, which was propounded by Schultze and supported by Nagel is in need of much revision before it will be able to fit the facts of the case. No theory of colorless vision is complete which does not account for the achromatic vision of the cones as well as that of the rods.

Besides the total color-blindness, or absence of all chromatic sensations, which we have already discussed, there ~~are~~ is a group of far more common and far more interesting types of color-blindness. In these, two complementary colors, only, are seen as mere lights. In perhaps ninety-nine percent of the cases, these two colors are red and green, those colors to which the middle zone of the eye is insensitive. That is, the spectrum appears ~~as first a~~ (running from red to violet) as first a grey, then a series of more or less saturated, brighter or darker yellows, then (in what would be green to the normal eye) another grey, and finally, a group of blues. That is, for the color-blind person, all colors can be produced by mixtures of various proportions of two colors, whereas three are necessary for the normal eye.

It might seem from what has been said above that, since green and red are both seen as if they were pure lights, no variations of this type of color-blindness would be possible. There are, however, two well-marked varieties of red-green blindness. In one of these red light appears ~~as if it were~~ of the same brightness as it appears to the normal eye; in the other, it appears many times ~~darker~~ less bright. The first is known by the misleading name of green-blindness; the second, as red-blindness. In red-blindness, the visible spectrum ~~seems~~ is abbreviated at the red end, and the grey point in the green is of shorter wave-length than in green-blindness. Besides these two types of congenital color-blindness, there is a third, in which blue and yellow are confused, and the blue end of the spectrum is abbreviated. This latter anomaly is extremely rare, and has not been investigated in a completely satisfactory manner. Besides these congenital varieties of achromatopsia, acquired varieties, resulting from various causes, such as ~~tobbc~~ tobacco amblyopia, are known. In these failure of color-vision is usually associated with other deficiencies of ~~vision~~ sight. The order of the loss of the colors is, first red, then green, then yellow, then blue, in many cases, at least, ~~so~~ here again, complementary colors have a degree of mutual independence.

Besides these cases of the total ~~loss~~ absence of one or more color-sensations, there are all gradations of anomalous vision in which one or more color-sensations are merely weaker than usual. The most common case of this sort is one where the red end of the spectrum is abbreviated. This is known as abnormal trichromatism. In this, all reds appear very dark, and more red has to be mixed with green on the color-wheel to give grey.

To account for all these facts of color-perception, many theories have been propounded. The first which has remained in currency up to the present day is that propounded by T. Young in 1801 and revived by the ~~physic~~ physicist Helmholtz in 1856. It refers all visual sensations to three chemical processes going on in the eye. One of these reaches its maximum in the red, one in the green, and one in the violet, but all run throughout the whole spectrum to a greater or less degree, as the following diagram shows.




When two colors are mixed, the resulting color has its content of any element of the three equal to the sum of the contents of the components. Equal parts of the three components give white. Pure colors are approached as we get one component free of the other two. After-images are due to the exhaustion of the ~~expo~~ components which have been stimulated continuously for a long time. Contrast colors are due to our judging one color as if it were covered by a film of the adjacent color. Dichromatic color-blindness is due to the absence of one or the other of the three components in color-vision, absence of red giving the so-called 'red-blind' variety of red-green blindness, absence of green giving 'green-blindness', and absence of violet giving violet-yellow blindness. Total color-blindness is due to the flattening down of all three curves until they coincide[1]; or else to the absence of two factors.

This theory has many difficulties. In the first place, yellow does not fall apart in introspection into red and green, nor white into red, green, and ~~purp~~ violet. If it be answered that ~~some~~ purple does not fall apart, either, into violet and red, and that we ~~[illegible]~~ have no right to infer ~~psy~~ physiological simplicity from psychological simplicity any more than the reverse, this answer can, in turn, be responded to by the fact that the relation between yellow and red or green is introspectively different from the relation

[1] This theory was supported by Fick

between purple and red or violet, and that this difference must have some physiological basis. In the second place, after images ~~a~~ cannot be accounted for by fatigue for two reasons. First, there is a ~~an~~ brief interval between the disappearance of the positive after-image and the appearance of the negative after-image; secondly, the exposure needed for the production of a negative after-image is too ~~brief~~ short to allow of fatigue. Although part of the effect of contrast may be due to illusions of judgement, it occurs too uniformly and regularly where there is absolutely no evidence of judgement for this to be an adequate explanation in every case.

As to color-blindness, the evidence of a few cases of persons color-blind in one eye but not in the other ~~leads one to~~ indicates that the color-blind person sees white in the same way as the normal person, and not as a mixture of the two remaining components. ~~There is this to be said for its explanation of color-blindness, however, in the cases of~~ monocular ~~color-blindness~~

What is in favor of the Young-Helmholtz theory is the excellent way in which it accounts for the facts of color-mixing. It is usually held by those who approach vision from the side of physics, in contradistinction from the psychologists and physiologists, for this reason.

The theory which the psychologists favor most, or rather used to favor most, is that of Hering. He postulates the existence in each cone of three different chemical substances, each capable of existing in two states. Every state he supposes able to give a different sensation. One of the substances is changed from one state to another by red light, and brought back to its original condition by green light[1]; blue light breaks another down, and yellow resynthetises it, while the third is decomposed in any light, and formed again in the dark. After-images are explained through the tendency of the ~~eye~~ substances to return to ~~their original condition~~ equilibrium after disturbance. Contrast is accounted for by the action of a process in one part of the eye causing the reverse process in

[1] The first change is called dissimilation, the second, ~~dissimilation~~ assimilation. Red, yellow, and white dissimilate green, blue, and black assimilate.

adjasent parts. The peripheral color-blindness found in the normal eye is explained as due to the absence first of the red-green process and then of the blue-yellow process. Color blindness is also regarded as the extension of peripheral conditions over the fovea.

This theory is even more unsatisfactory than the Young-Helmholtz theory. In addition to the [redacted] artificiality of the system of three substances, in addition to the difficulty of explaining how [redacted] ~~ability of one nerve~~ nerve-fibre, is able ~~to~~ carry all the variations which six different stimuli continually give off, we have the fact that there are two distinct types of 'red-green' blindness, which are sharply demarkated, so that Hering's makeshift hypothesis ~~of~~ that 'red-blindness' is to be explained through unusually slight pigmentation of the macula and lens will not work. Besides, blue and yellow are not the colors which, the monocularly color-blind say, correspond to the sensations of the defective eye, but red and blue-green or greenish yellow and blue-violet, as Von Kries has shown. The former difficulty could be removed by making the opposing processes processes of mutual central inhibition rather than chemical changes; the latter difficulties concerning color-blindness, taken together with the fact that the red and the green which are pure to the eye when taken together give yellow, not white, suggest a three-color theory for the peripheral phenomena.

In Hering's theory as it was first propounded, another difficulty was present. Whereas red and green, or blue and yellow seem to be mutually exclusive, ~~and~~ white and black are connected through the greys. The position of grey was a stumbling block in Hering's theory until Müller suggested that it was of central origin. The problem of the relation of light and color is ~~also~~ a ~~puz~~ puzzling one in other respects also. For instance, Hering explains the Purkinje phenomenon through the fact that the dissimilatory processes of red and yellow disappear as it grows dark, so that they do not tend to shift the point of maximum brightness towards the red end of the color scale, as they do in the light. That is, the dissimilatory processes have an intrinsic brightness in addition to the brightness caused by the stimulation of the white process. Between these two brightnesses, however, there seems to be no introspective difference.[1]

Both the theory of Hering and that of Helmholtz are untenable. On account of this, many compromise theories have grown up. Among the most important of these are those of Müller, Von Kries, Mrs. Ladd-Franklin, and Patten. Patten's theory explains the color-vision of the cones through the fact that they have a transverse fibrillation, which, he believes, acts as the receptive organs ~~for the stationary~~ acting in resonance to the waves of light ~~produced by the se interference of the light wave with its reflection from the end of the cone~~. They may be affected, however, by chemical changes resulting in fatigue, to which phenomena after-images are due. The rods can give only monochromatic vision, on account of the equal length of all the fibrils. The cones in the fovea see ~~to~~ colors best, because they are the

[1] Hering does not allow, as does von Kries, when his theory meets a similar difficulty, for a central synthesis.

longest, and have the most fibres, thereby being able to distinguish closer shades of hue. The fact that polarized light appears dull is accounted for on the basis that, since it vibrates in only one plane, it affects ~~no~~ the fibrils only in so far as they extend in that plane. White is produced through the nearly equal stimulation of all levels of the cone, and so any two stimuli which are at the right distance apart to produce a fairly smooth stimulation curve throughout the whole cone will produce white. ~~Color~~ Red-blindness is due to the absence of the base of the cone, cutting off the red end completely, while green-blindness is caused by the cylindricalness of the red end, assimilating the red sensations to the yellow-green. That the nerve-fibres must carry many impulses is regarded as the necessary consequence of the fact that there are fewer fibres in the optic nerve than ~~in th~~ retinal elements in the eye.

This theory has some serious difficulties to encounter, although it is of all the theories of vision the one which makes best use of our knowledge of the histology of the retina. In the first place, it is unable to explain the sensation of purple, ~~unless it has recourse to~~ which does not result from the stimulation of any single fibre, and yet is as introspectively simple as orange or blue-green, which do. In the second place, in ~~color~~ red blindness, not only red is lost, but also green, and in green-blindness, not only [redacted] green, but [redacted] red. The evidence on which he bases his argument that the fibrils of the optic nerve carry more than ~~two~~ one quality does not seem conclusive, because two layers of ganglions intervene between cone and nerve, and it is not inconceivable that in these two the red-sensation of an area covering many rods and cones might be concentrated and conveyed to the brain through a single fibre of the optic nerve.

Mrs. Franklin's theory is of quite a

different nature. She assumes that in the rod-cells there ~~are~~ is a chemical process taking place in the presence of light which gives the sensation grey. In the peripheral cones this single process is broken up into two, one of which ~~is~~ gives the sensation yellow, and the other the sensation, blue. These are stimulated, ~~by~~ the one by long waves, and the other by short waves. ~~In the fovea, the~~ When these two processes go on at once, they resynthetize grey. Red and green, which appear in and around the fovea, bear the same relation to yellow that yellow and blue bear to grey. Color-blindness is due to the absence of differentiation of the red and green processes. The facts of contrast and of after-images are explained by the fact that the visual substance, in which all these processes takes place, is extremely unstable after it has been partly broken down by any one of the processes, and tends to break down entirely, being carried, as it is broken down, through the ~~capp~~ capillaries of the retina to neighborthat each one of these can disturb the nerve fibres of the retina, optic nerve, and brain in a separate, clearly distinct way, that the relative strengths of stimulation of two different decompositions are kept constant until we reach the brain, and, most important of all, that the ganglionic layers of the retina and the optic centers in the brain are passive, or almost passive in color vision, the impulse being completed the moment it leaves the rod or cone. For these reasons, the theory can be regarded only as a very digrammatic schema, designed to correlate the known facts, but not to explain them in terms of other facts which are better known. For explanations we must turn to such theories as those of Müller and Von Kries.

G. E. Müller, in addition to his correction of Hering's theory by the addition of the central grey, regards each pure color ~~a~~ received through the peripheral sense-organ as exciting three different qualities centrally. Thus, peripheral ~~red~~ excites central red, yellow, and white, peripheral

~~green~~ yellow, yellow, green, and white, peripheral ~~blue~~ green, green, blue, and black, and peripheral ~~red~~ blue, blue, red, and black. The object we call yellow excites peripheral green and peripheral yellow, which excite, respectively, red, yellow, and white, and ~~red~~ yellow, green, and white, which give yellow and white, the red and green cancelling, and so on through the color-scale. By this means Hering's doctrine of the specific brightness of colors, as shown in his explanation of the Purkinje phenomenon, is done away with. Red-blindness is explained as due to the absence of the central factors for red and green, green-blindness to the absence of the peripheral factors.

Although this theory marks a great advance in its mode of explaining color vision through the introduction of central factors, it still retains the fundamental difficulty of most four-color theories in that the introspectively pure green and the pure red do not, as the theory requires, make white or grey, but yellow. In addition, although the theory is undoubtably too simple rather than too complex, its complexity carries further than the experimental or anatomical evidence justifies. Nevertheless, it seems to me that it is in this type of theory that the one which shall be at once plausible and adequate will be found.

Von Kries holds a theory in many ways resembling that of Mrs Franklin. He believes that the colored sensations given by the cones are formed by the various stages of the action of a unitary light-process. There are three processes which give the whole scale of colors, one of which determines the shade of a color, a second, its position on the red-green series, and a third, its place between yellow and blue. The white of twilight vision is an entirely separate process, and belongs to the rods. That is, the grey of twilight vision has different peripheral conditions from the grey formed by the mixture of red and green colours, and this is supposed to explain the Purkinje phenomenon.

This theory, it is true, retains

some of the difficulties of the Hering theory, in that it is a four-color theory. It is also vague, although, in a sphere where our knowledge is so inadequate, an honest confession of ignorance may be much more valuable than a specious certainty. But the point which its critics most emphasise, that ~~the~~ central processes need to be invoked to explain the similarity between twilight grey and daylight grey, rod grey and cone grey, is one of the most significant points in the whole theory, because, although it may be utterly incorrect in detail, and probably is, it offers a timely warning that we cannot afford to neglect the central factors in vision, and that any theory which does neglect them is _ipso facto_ inadequate.

There has been no really adequate theory of color-vision as yet propounded, and there probably will be none in the near future. The moral for the psychologist is the danger of premature

generalization. And yet, the problem of color-vision is no more complicated than many other psychological problems. The situation is one which leads to grave doubts as to the adequacy of modern psychological methods. The solution of the problem is far more likely to come to the physiologist or the histologist, in his investigation of the structure and function of the retina, than to the psychologist, whose evidence is liable to be entirely vitiated through the ~~prejy~~ prejudices
3, of the introspecting subjects. More darkness than light has been thrown on the problems of color-vision by the dispute between those that regard such colors as orange as introspectively simple, and those that regard them as complex.

The physiologist would have a sorry time of it, if it were not for the results of psychological investigation.

The solution – that is the physiological explanation will probably come from a physiologist, who takes into account all the data of psychological investigation. You are probably aware that Hering and von Kries are physiologists ing regions. The Ladd-Franklin theory has been modified so as to account for the Purkinje phenomenon, without recourse to the visual purple, by Schenck, who regards the primitive grey substance as complex in action, ~~and formed of~~ responding on the one hand to ~~green-yellow~~ blue-green colors, and then to green-yellow and yellow-red colors, but giving a grey stimulus to the nerve for all of them. (Not very clear) According to Schenk, the formation of color-reacting groupings in the partially sensitized grey molecule leads to those forms of vision in which the red end of the spectrum is shortened. The Purkinje phenomenon is due to the fact that in the rods only the green-blue reacting substance is present.

While the Ladd-Franklin theory is a very good hypothesis to summarise the facts known about ~~to~~ color-vision and color-blindness, it cannot claim to be more. It is based on the tremendously artificial assumption that there is a substance present in the foveal cones which can break down in any one of five ways (or more, if Schenk's modification be accepted), and

# Bibliography of Color Vision.

The bibliography of this subject is so tremendous that I can only give the books I have read and some of the chief books on the subject. I have not ~~sed~~ read the original works on the subject, because they are so voluminous that, in the brief time at my disposal, I could not have covered sufficient ground. For this reason I looked for articles which would give a clear and yet concise exposition of the principal facts and theories of color-vision. The paper does not pretend to give an adequate account of any one of the theories it discusses, for this would require a book in itself. It merely intends to bring up and summarize some salient points.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